# TRANSACTIONS

OF THE

# American Institute of Electrical Engineers

Vol. 49 JANUARY, 1930 No. 1

TABLE OF CONTENTS


Radio Interference from Line Insulators, by Ellis Van Atta and E. L. White ..... 1
Discussion ..... 5
Spray and Fog Tests on 220-Kv. Insulators, by R. J. C. Wood ..... 9
Discussion ..... 13
The Sixty-Cycle Flashover of Long Suspension Insulator Strings, by R. H. Angus ..... 15
Discussion ..... 19
Impulse Insulation Characteristics of Wood Pole Lines, by H. L. Melvin ..... 21
Discussion ..... 27
The Theory of Electrical Conductivity, Recent Developments, by William V. Houston ..... 30
Development of Insulating Oils, by C. E. Skinner ..... 35
Discussion ..... 39
Effect of Color of Tank on the Temperature of Self-Cooled Transformers under Service Conditions, by V. M. Montsinger and L. Wetherill ..... 41
Discussion ..... 50
Population as an Index to Electrical Development, by N. B. Hinson ..... 52
Discussion ..... 55
Flames from Electric Arcs, by J. Slepian ..... 56
Design Features that Make Large Turbine Generators Possible, by W. J. Foster and M. A. Savage ..... 60
Discussion ..... 67
Effect of Surges on Transformer Windings, by J. K. Hodnette ..... 68
Discussion ..... 75
An A-C. Low-Voltage Network without Network Protectors, by Lester R. Gamble and Earl Baughn ..... 82
Discussion ..... 92
High-Voltage Low-Current Fuses and Switches, by Roy Wilkins ..... 96
Motor Control for Wind Tunnel, by William A. Lewis ..... 99
The Electrical Engineering of Sound Picture Systems, by K. F. Morgan and T. E. Shea ..... 105
Discussion ..... 116
Dial Telephone System Serving Small Communities of Southern California, by F. O. Wheelock ..... 117
Discussion ..... 124
Parallel Operation of Transformers, by Mabel Macferran ..... 125
Progress in the Study of System Stability, by I. H. Summers and J. B. McClure ..... 132
Discussion ..... 159
Series Synchronous Condensers for Generation of Voltage Consumed by Line Inductance, by Theodore H. Morgan ..... 162
Discussion ..... 165
Recent Developments in Toll Telephone Service, by W. H. Harrison ..... 166
Discussion ..... 176
The Chicago Long Distance Toll Board, by E. O. Neubauer and G. A. Rutgers ..... 178
Discussion ..... 184
Air Transport Communication, by R. L. Jones and F. M. Ryan ..... 187
Discussion ..... 197
The Future of Higher Steam Pressures in Steam Electric Generating Stations, by Irving E. Moultrop ..... 198
The Fault Ground Bus, by R. M. Stanley and F. C. Hornibrook ..... 201
Discussion ..... 211
Increased Voltages for Synchronous Machines, by C. M. Laffoon ..... 213
Discussion ..... 221
Double Windings for Turbine Alternators, by P. L. Alger, E. H. Freiburghouse, and D. D. Chase ..... 226
A 40,000-Kw. Variable-Ratio Frequency Converter Installation, by E. S. Bundy, A. Van Niekerk, and W. H. Rodgers ..... 245
Discussion ..... 255
Theory of a New Valve Type Lightning Arrester, by J. Slepian, R. Tanberg, and C. E. Krause ..... 257
Discussion ..... 262
Low-Voltage A-C. Networks of the Standard Gas and Electric Company's Properties, by R. M. Stanley and C. T. Sinclair ..... 265
Discussion ..... 280
An Economic Study of an Electrical Distributing Station, by W. G. Kelley ..... 285
Experience with Carrier-Current Communication on a High-Tension Interconnected Transmission System, by Philip Sporn and Ray H. Wolford ..... 288
Discussion ..... 313
Automatic Regulation of Synchronous Condensers Equipped with Superspeed Excitation, by L. W. Thompson and P. J. Walton ..... 315
Discussion ..... 318
Polyphase Induction Motors, by W. J. Branson ..... 319
Discussion ..... 328
A Recording Torque Indicator that Records the Torsional Effort of Motors during Acceleration, by G. R. Anderson ..... 333
Discussion ..... 336
Stability of Synchronous Machines—Effect of Armature Circuit Resistance, by C. A. Nickle and C. A. Pierce ..... 338
Discussion ..... 350
Ionization Currents and the Breakdown of Insulation, by J. J. Torok and F. D. Fielder ..... 352
Discussion ..... 357
Dissipation of Heat by Radiation, by A. D. Moore ..... 359
Discussion ..... 364
Power Transients in A-C. Motors, by L. E. A. Kelso and G. F. Tracy ..... 366
The General Circle Diagram of Electrical Machinery, by F. E. Terman, T. L. Lenzen, C. L. Freedman, and K. A. Rogers ..... 374
Effect of Electric Shock, by W. B. Kouwenhoven and Orthello R. Langworthy ..... 381


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# PREFACE

This issue, Number 1 of Volume 49, contains the papers presented at the Pacific Coast Convention held at Santa Monica, California, September 3-6, 1929, and at the Great Lakes District Meeting, Chicago, Illinois, December 2-4, 1929.

Three miscellaneous contributions are also included: *Power Transients in A-C. Motors*, by L. E. A. Kelso and G. F. Tracy, *General Circle Diagram of Electrical Machinery*, by F. E. Terman, T. L. Lenzen, C. L. Freedman, and K. A. Rogers, and *Effect of Electric Shock*, by W. B. Kouwenhoven and Orthello Langworthy.

For the reader's convenience an index of the authors and discussors included in this issue is appended. The complete annual index will appear in the October Quarterly.

# TRANSACTIONS

OF THE

# American Institute of Electrical Engineers

Vol. 49 APRIL, 1930 No. 2

## TABLE OF CONTENTS


The Metal-Clad Switchgear at State Line Station, by A. M. Rossman ... 397
Discussion ... 401
Development of the New Autovalve Arrester, by J. Slepian, R. Tanberg, and C. E. Krause ... 404
Discussion ... 417
Thyrite, A New Material for Lightning Arresters, by K. B. McEachron ... 410
Discussion ... 417
Extinction of a Long A-C. Arc, by J. Slepian ... 421
Discussion ... 441
The Use of Oil in Arc Rupture, by B. P. Baker and H. M. Wilcox ... 431
Discussion ... 441
Calculation of Induced Voltages in Metallic Conductors, by Herbert Bristol Dwight ... 447
Discussion ... 452
Induced Voltage of Electrical Machines, by L. V. Bewley ... 456
A Cathode Ray Oscillograph with Norinder Relay, by O. Ackermann ... 467
Discussion ... 474
Submarine Telegraphy in the Post-War Decade, by I. S. Coggeshall ... 476
Discussion ... 484
Magnetic Circuit Units, by A. E. Kennelly ... 486
Discussion ... 494
Simulating Sunlight, by M. Luckiesh ... 511
Discussion ... 516
The Calorimetric Study of the Arc, by P. P. Alexander ... 519
Discussion ... 522
Resistance Welding, by Byron T. Mottinger ... 524
Starting Performance of Salient-Pole Synchronous Motors, by T. M. Linville ... 531
Discussion ... 546
Ventilation of Revolving-Field Salient-Pole Alternators, by Carl J. Fechheimer ... 548
Discussion ... 572
An Ultra Violet Light Meter, by H. C. Rentschler ... 576
Discussion ... 578
System Connections and Inter-Connections, Chicago District, by George M. Armbrust and Titus G. LeClair ... 581
Discussion ... 612
The Fundamental Plan of Power Supply of the Detroit Edison Company, by S. M. Dean ... 597
Discussion ... 612
Fundamental Plan of Power Supply in the Philadelphia Area, by Raymond Bailey ... 605
Discussion ... 612
Transoceanic Telephone Service—General Aspects, by T. G. Miller ... 621
Discussion ... 643
Transoceanic Telephone Service—Short-Wave Transmission, by Ralph Bown ... 624
Discussion ... 643
Transoceanic Telephone Service—Short-Wave Equipment, by A. A. Oswald ... 629
Discussion ... 643
Transoceanic Telephone Service—Short-Wave Stations, by F. A. Cowan ... 638
Discussion ... 643
The Conductivity of Insulating Oils, by J. B. Whitehead and R. H. Marvin ... 647
Discussion ... 656
High-Voltage Corona in Air, by Sigmund K. Waldorf ... 657
Discussion ... 665
Generalized Theory of Electrical Machinery, by Gabriel Kron ... 666
Discussion ... 683
Transient Torque-Angle Characteristics of Synchronous Machines, by W. V. Lyon and H. E. Edgerton ... 686
Discussion ... 698
Three-Phase Short Circuit Synchronous Machines—V, by R. E. Doherty and C. A. Nickle ... 700
Discussion ... 714
Operating Characteristics of Turbine Generators, by T. E. Purcell and A. P. Hayward ... 715
Discussion ... 719
Cathode Energy of the Iron Arc, by Gilbert E. Doan ... 723
Discussion ... 731
Electric Welding by the Carbon Arc, by J. C. Lincoln ... 735
Discussion ... 738
Behavior of Dielectrics, by R. R. Benedict ... 739
Discussion ... 750
Three Regions of Dielectric Breakdown, by P. H. Moon and A. S. Norcross ... 755
Discussion ... 763
Ionization Studies in Paper-Insulated Cables—III, by C. L. Dawes and P. H. Humphries ... 766
Discussion ... 773
Loading Transformers by Temperature, by V. M. Montsinger ... 776
Discussion ... 790
Operating Transformers by Temperature, by W. M. Dann ... 793
Discussion ... 796
Telephone Interference from A-C. Generators, by J. J. Smith ... 798
Discussion ... 805
Inversion Currents and Voltages in Auto-Transformers, by A. Boyajian ... 810
Discussion ... 819


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## PREFACE

The greater part of the papers and discussions presented at the Winter Convention in New York, January 27-31, 1930, are included in this issue, Number 2 of Volume 49 of the TRANSACTIONS.

The remaining Winter Convention papers, together with those presented at the North Eastern District Meeting held in Springfield, Massachusetts, May 7-10, will appear in the July Quarterly.

# TRANSACTIONS

OF THE

# American Institute of Electrical Engineers

Vol. 49 JULY, 1930 No. 3

TABLE OF CONTENTS


Controlling Power Flow with Phase-Shifting Equipment, by W. J. Lyman ..... 825
Discussion ..... 829
Electrically Welded Structures Under Dynamic Stress, by M. Stone and J. G. Ritter ..... 832
Discussion ..... 837
Tap Changing Under Load for Voltage and Phase-Angle Control, by H. B. West ..... 839
Discussion ..... 845
Quiet Induction Motors, by L. E. Hildebrand ..... 848
Discussion ..... 852
Symposium on Lightning ..... 857—948
Lightning on Transmission Lines—Cathode Ray Oscillograph Studies, by J. H. Cox and E. Beck ..... 857
Discussion ..... 928
Surge Characteristics of Insulators and Gaps, by J. J. Torok ..... 866
Discussion ..... 928
Lightning Laboratory at Stillwater, New Jersey, by R. N. Conwell and C. L. Fortescue ..... 872
Discussion ..... 928
Lightning Voltages on Transmission Lines, by R. H. George and J. R. Eaton ..... 877
Discussion ..... 928
Traveling Waves on Transmission Lines with Artificial Lightning Surges, by K. B. McEachron, J. G. Hemstreet, and W. J. Rudge ..... 885
Discussion ..... 928
Lightning Investigation on 220-Kv. System of the Pennsylvania Power & Light Company (1928 and 1929), by N. N. Smeloff and A. L. Price ..... 895
Discussion ..... 928
Lightning Investigation on the Ohio Power Company's 132-Kv. System, by P. Sporn and W. L. Lloyd, Jr ..... 905
Discussion ..... 928
Lightning Investigation on Transmission Lines, by W. W. Lewis and C. M. Foust ..... 917
Discussion ..... 928
A Self-Compensating Temperature Indicator, by I. F. Kinnard and H. T. Faus ..... 949
Phase Defect Angle of an Air Capacitor, by W. B. Kouwenhoven and C. L. Lemmon ..... 952
Transmission Research and Design with the Field as a Laboratory, by F. E. Andrews and C. L. Stroup ..... 959
Discussion ..... 969
Arcing Grounds and Effect of Neutral Grounding Impedance, by J. E. Clem ..... 970
Discussion ..... 988
Fused Grading Shields, by H. A. Frey and E. M. Skipper ..... 990
Discussion ..... 996
Reduction of Eddy Current Losses, by John M. Lyons ..... 998
Discussion ..... 1010
Effect of Armature Resistance upon Hunting of Synchronous Machines, by C. F. Wagner ..... 1011
Discussion ..... 1024
The Synchronous-Repulsion Motor, by H. C. Specht ..... 1027
Discussion ..... 1031
Synchronous Motor Effects in Induction Machines, by E. E. Dreese ..... 1033
Discussion ..... 1041
Transformer Ratio and Differential Leakage of Distributed Windings, by R. E. Hellmund and C. G. Veinott ..... 1043
Discussion ..... 1053
Induction Motor Performance Calculations, by P. L. Alger ..... 1055
Discussion ..... 1066
Voltage Irregularities in D-C. Generators, by J. T. Fetsch ..... 1068
Discussion ..... 1084
Cooperative Courses—Their Development and Operating Principles, by Karl L. Wildes ..... 1086
Discussion ..... 1093
Determination of Generator Speed and Retardation during Loss Measurements, by O. E. Charlton and W. D. Ketchum ..... 1095
Discussion ..... 1101
The M. I. T. Network Analyzer, by H. I. Hazen, O. R. Schurig, and M. F. Gardner ..... 1102
Discussion ..... 1113
Calculation of Protection of a Transmission Line by Ground Conductors, by Herbert Bristol Dwight ..... 1115
Discussion ..... 1118
A New Transmission Line Construction—Post Type Towers, by Percy H. Thomas ..... 1122
Discussion ..... 1127
The Calculation of Alternator Swing Curves—The Step-by-Step Method, by F. R. Longley ..... 1129
Discussion ..... 1150
Radio Telephone Service to Ships at Sea, by William Wilson and Lloyd Espenschied ..... 1152
Discussion ..... 1160
Shunt Resistors for Reactors, by F. H. Kierstead, H. L. Rorden, and L. V. Bewley ..... 1161
Discussion ..... 1177
Effect of Transient Voltage on Power Transformer Design, by K. K. Palueff ..... 1179
Discussion ..... 1190
Report of the Board of Directors for the Fiscal Year Ending April 30, 1930 ..... 1197


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## PREFACE

This issue, Number 3 of Volume 49, contains those papers presented at the Winter Convention, New York City, January 27-31, 1930, which were not included in the April Quarterly, as well as the papers of the North Eastern District Meeting held in Springfield, Massachusetts, May 7-10, 1930.

The report of the Board of Directors for the fiscal year ending April 30, 1930 concludes this number.

# TRANSACTIONS

OF THE

# American Institute of Electrical Engineers

Vol. 49 OCTOBER, 1930 No. 4

## TABLE OF CONTENTS


Transmission System Relay Protection, by William W. Edson ..... 1213
Discussion ..... 1224
Modern Requirements for Protective Relays on Important System Interconnections, by O. C. Traver and L. F. Kennedy ..... 1226
Discussion ..... 1239
High-Speed Protective Relays, by L. N. Crichton ..... 1232
Discussion ..... 1239
Directional Ground Relays, by E. E. George and R. H. Bennett, Jr ..... 1243
Discussion ..... 1254
Electric Power Consumption for Yard Switching, by P. H. Hatch ..... 1256
Control Systems for Oil and Gasoline Electric Locomotives and Cars, by N. L. Freeman ..... 1262
Discussion ..... 1269
Electric Transmission and Control of Power from Internal Combustion Engines for Transportation, by S. T. Dodd ..... 1271
Discussion ..... 1281
Auxiliaries for High-Voltage D-C. Multiple Unit Cars, by C. J. Axtell ..... 1282
Discussion ..... 1294
Auxiliary Circuits for High-Voltage D-C. Motor Car Equipments, by O. K. Marti and Walter Giger ..... 1287
Discussion ..... 1294
Railbonding Practise and Experience on Electrified Steam Railroads, by H. F. Brown ..... 1299
Discussion ..... 1314
An Electron Tube Telemetering System, by A. S. Fitzgerald ..... 1321
Discussion ..... 1335
Development of a Two-Wire Supervisory Control System with Remote Metering, by R. J. Wensley and W. M. Donovan ..... 1339
Discussion ..... 1342
Centralized Control of System Operation, by James T. Lawson ..... 1344
Discussion ..... 1349
Automatic Power Supply for Steel Mill Electrification, by Robert J. Harry ..... 1351
Discussion ..... 1356
1000-Kw. Automatic Mercury Arc Rectifier Substation of the Union Railway Company of New York, by W. E. Gutzwiller and O. Naef ..... 1357
Miniature Switchboards, by Philip Sporn ..... 1363
Discussion ..... 1367
Mutual Impedances of Ground-Return Circuits Some Experimental Studies, by A. E. Bowen and C. L. Gilkeson ..... 1370
Discussion ..... 1379
Effects of the Magnetic Field on Lichtenberg Figures, by C. Edward Magnusson ..... 1384
Discussion ..... 1391
A Survey of Room Noise in Telephone Locations, by W. J. Williams and Ralph G. McCurdy ..... 1393
The 220,000-Volt System of the Hydro-Electric Power Commission of Ontario, by E. T. J. Brandon ..... 1400
Discussion ..... 1417
The Analytics of Transmission Calculations, by T. R. Rosebrugh ..... 1419
Discussion ..... 1430
Study of the Effect of Short Lengths of Cable on Traveling Waves, by K. B. McEachron, J. G. Hemstreet, and H. P. Seelye ..... 1432
Discussion ..... 1441
Dancing Conductors, by A. E. Davison ..... 1444
Rationalization of Station Insulating Structures with Respect to Insulation of the Transmission Line, by C. L. Fortescue ..... 1450
Discussion ..... 1496
The Effect of Transient Voltages on Dielectrics—IV, by F. W. Peek, Jr ..... 1456
Discussion ..... 1496
Rationalization of Transmission Insulation Strength—II, by Philip Sporn ..... 1470
Discussion ..... 1496
Recommendations on Balancing Transformer and Line Insulations on Basis of Impulse Voltage Strength, by V. M. Montsinger and W. M. Dann ..... 1478
Discussion ..... 1496
Coordination of Insulation as a Design Problem, by G. D. Floyd ..... 1482
Discussion ..... 1496
Standards of Insulation and Protection for Transformers, by J. Allen Johnson and Edwin S. Bundy ..... 1486
Discussion ..... 1496
Essential Factors in the Coordination of Line, Station and Apparatus Insulation, by A. E. Silver and H. L. Melvin ..... 1491
Discussion ..... 1496
Long Distance Cable Circuit for Program Transmission, by A. B. Clark and C. W. Green ..... 1514
The Transmission Characteristics of Open-Wire Telephone Lines, by E. I. Green ..... 1524
A Study of Telephone Line Insulators, by L. T. Wilson ..... 1536
A General Switching Plan for Telephone Toll Service, by H. S. Osborne ..... 1549
Long Telephone Lines in Canada, by J. L. Clarke ..... 1558
Two-Way Television, by H. E. Ives, F. Gray and M. W. Baldwin ..... 1563
Discussion ..... 1576


(*Continued on next page.*)

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Effects of Lightning Voltages on Rotating Machines and Methods of Protecting Against Them, by F. D. Fielder and Edward Beck ... 1577
Discussion ... 1607
Voltage Oscillations in Armature Windings Under Lightning Impulses—I, by E. W. Boehne ... 1587
Discussion ... 1607
Vertical Shaft 25,000-Kv-a. Synchronous Condensers 25-Cycle, 500-Rev. per Min. Outdoor Type Units for Toronto Leaside Transformer Station, by H. A. Ricker, J. R. Dunbar and R. E. Day ... 1616
Discussion ... 1626
The East River Generating Station of the New York Edison Company, by C. B. Grady, W. H. Lawrence and R. H. Tapscott ... 1628
Discussion ... 1640
Present Day Hydro Power Practise in Central Europe, by A. V. Karpov ... 1642
Discussion ... 1657
Automatic Stations Committee Report, by F. Zogbaum, Chairman ... 1660
Electrical Communication Committee Report, by G. A. Kositzsky, Chairman ... 1671
Electrical Machinery Committee Report, by P. L. Alger, Chairman ... 1677
Electric Welding Committee Report, by A. M. Candy, Chairman ... 1699
Electrophysics Committee Report, by O. E. Buckley, Chairman ... 1702
General Power Applications Committee Report, by J. F. Gaskill, Chairman ... 1711
Instruments and Measurements Committee Report, by Everett S. Lee, Chairman ... 1728
Applications to Iron and Steel Production Committee Report, by M. M. Fowler, Chairman 1733
Production and Application of Light Committee Report, by G. S. Merrill, Chairman ... 1735
Application to Marine Work Committee Report, by W. E. Thau, Chairman ... 1739
Applications to Mining Work Committee Report, by Carl Lee, Chairman ... 1740
Power Generation Committee Report, by F. A. Allner, Chairman ... 1742
Power Transmission and Distribution Committee Report, by H. R. Woodrow, Chairman ... 1744
Protective Devices Committee Report, by E. A. Hester, Chairman ... 1754
Electrical Transportation Committee Report, by Sidney Withington, Chairman ... 1759
The Status of the Young Engineer, by Harold B. Smith, President's Address ... 1762

# PREFACE

This is the final number of Volume 49 of the Quarterly TRANSACTIONS of the American Institute of Electrical Engineers, and contains the papers and committee reports presented at the Summer Convention held at Toronto, Ontario, Canada, June 23-27, as well as *The Status of the Young Engineer*, the address delivered by President Smith at that convention.

Parts 1, 2 and 3 of Volume 49 contain the index of authors as published in each separate issue. An index of authors and a subject index to Volume 49 are complete in this number.

# SUBJECT INDEX

## PAPERS, DISCUSSIONS AND REPORTS

### Subject Classifications


American Institute of Electrical Engineers Affairs ..... 1765

Cables ..... 1765
Central Station Systems ..... 1765
Circuit Breakers and Switches ..... 1765
Communication ..... 1765
Condensers ..... 1765
Conductors ..... 1765
Control Devices ..... 1765
Conversion Methods and Equipment ..... 1766
Corona ..... 1766

Dielectric Phenomena ..... 1766
Distribution ..... 1766

Education ..... 1766
Electric Circuit Theory ..... 1766
Electrophysics ..... 1766

Generators, Alternating Current ..... 1766
Generators, Direct Current ..... 1766

Hydroelectric ..... 1766

Industrial Application of Power ..... 1766
Insulation ..... 1766
Insulators ..... 1766
Interconnected Systems ..... 1766

Lighting ..... 1766
Lightning Arresters ..... 1766
Loss and Efficiency Measurements ..... 1766

Magnetic Phenomena ..... 1766
Marine Applications ..... 1766
Measuring Instruments ..... 1766
Measuring Methods ..... 1767
Mining Applications ..... 1767
Motors, Alternating Current ..... 1767
Motors, Direct Current ..... 1767

Protective Devices ..... 1767

Radio Phenomena ..... 1767
Railways ..... 1767
Research ..... 1767

Stability ..... 1767
Substations ..... 1767
Switches ..... 1767

Technical Committee Reports ..... 1767
Telegraph ..... 1768
Telephone ..... 1768
Television ..... 1768
Transformers ..... 1768
Transients ..... 1768
Transmission Lines (Electrical Characteristics) ..... 1768
Transmission Lines (General) ..... 1768
Transmission Lines (Mechanical Features) ..... 1768

Ventilation ..... 1768

Welding ..... 1768


---


**AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS AFFAIRS**

Status of the Young Engineer, The, *Smith, Harold B.*, President's Address (October) ..... 1762

**CABLES**

Calculation of Cable Temperatures in Subway Ducts, The, *Kirke, W. B.*, October JOURNAL ..... 855
Ionization Studies in Paper-Insulated Cables—III, *Dawes, C. L. and Humphrics, P. H.* (April) ..... 766
Study of the Effect of Short Lengths of Cable on Traveling Waves, *McEachron, K. B., Hemstreet, J. G., and Seelye, H. P.* (October) ..... 1432

**CENTRAL STATION SYSTEMS**

Automatic Stations Committee Report (October) ..... 1660
Centralized Control of System Operation, *Lawson, J. T.* (October) ..... 1344
East River Generating Station of the New York Edison Company, The, *Grady, C. B., Lawrence, W. H., and Tapscott, R. H.* (October) ..... 1628
Essential Factors in the Coordination of Line Station and Apparatus Insulation, *Silver, A. E. and Melvin, H. L.* (October) ..... 1491
Fundamental Plan of Power Supply in the Philadelphia Area, *Bailey, R.* (April) ..... 605
Fundamental Plan of Power Supply of the Detroit Edison Company, The, *Dean, S. M.* (April) ..... 597
Future of Higher Steam Pressures in Steam Electric Generating Stations, The, *Moultrop, I. E.* (January) ..... 198
Lightning Investigation on the Ohio Power Company's 132-Kv. System, *Sporn, P. and Lloyd, W. L., Jr.* (July) ..... 905
Lightning Investigation on 220-Kv. System of the Penn. Power & Lt. Co., (1928 and 1929), *Smeloff, N. N. and Price, A. L.* (July) ..... 895
Low-Voltage A-C. Networks of the Standard Gas & Electric Company's Properties, *Stanley, R. M. and Sinclair, C. T.* (January) ..... 265
Miniature Switchboards. A Modernization in the Design of Operating Switchboards for Electric Power Stations and Substations, *Sporn, P.* (October) ..... 1363
Population as an Index to Electrical Development, *Hinson, N. B.* (January) ..... 52
Power Generation Committee Report (October) ..... 1742
Rationalization of Station Insulating Structures, *Fortescue C. L.* (October) ..... 1450

**CIRCUIT BREAKERS AND SWITCHES**

Conductivity of Insulating Oils, The, *Whitehead, J. B. and Marvin, R. H.* (April) ..... 647
Developments of Insulating Oils, *Skinner, C. E.* (January) ..... 35
Metal-Clad Switchgear at State Line Station, The, *Rossman, A. M.* (April) ..... 397
Use of Oil in Arc Rupture, The, *Baker, B. B. and Wilcox, H. M.* (April) ..... 431

**COMMUNICATION**

Electrical Communication Committee Report (October) ..... 1671
Experience with Carrier-Current Communication on a High-Tension Interconnected Transmission System, *Sporn, Philip and Wolford, Ray D.* (January) ..... 288
Long Distance Cable Circuit for Program Transmission, *Clark, A. B. and Green, C. W.* (October) ..... 1514

**CONDENSERS**

Phase Defect Angle of an Air Capacitor, *Kouwenhoven, W. B. and Lemmon, C. L.* (July) ..... 952
Series Synchronous Condensers for Generation of Voltage Consumed by Line Inductance, *Morgan, Theodore* (January) ..... 162

**CONDUCTORS**

Dancing Conductors, *Davison, A. E.* (October) ..... 1444

**CONTROL DEVICES**

Controlling Power Flow with Phase-Shifting Equipment, *Lyman, W. J.* (July) ..... 825
Control Systems for Oil and Gasoline Electric Locomotives and Cars, *Freeman, N. L.* (October) ..... 1262
Motor Control for Wind Tunnel, *Lewis, W. A.* (January) ..... 99

## CONVERSION METHODS AND EQUIPMENT

40,000-Kw. Variable-Ratio Frequency Converter Installation, A, *Bundy, E. S., Van Niekerk, A., and Rodgers, W. H.* (January) ..... 245

## CORONA

High-Voltage Corona in Air, *Waldorf, S. K.* (April) ..... 657

## DIELECTRIC PHENOMENA

Behavior of Dielectrics, *Benedict, R. R.* (April) ..... 739
Effect of Transient Voltages on Dielectrics—IV, The, *Peek, F. W., Jr.* (October) ..... 1456
Three Regions of Dielectric Breakdown, *Moon, P. H. and Norcross, A. S.* (April) ..... 755

## DISTRIBUTION

An A-C. Low-Voltage Network without Network Protectors, *Gamble, L. R. and Baughn, E.* (January) ..... 82
An Economic Study of an Electrical Distributing Station, *Kelley, W. G.* (January) ..... 285
Power Transmission and Distribution Committee Report (October) ..... 1744

## EDUCATION

Cooperative Courses—Their Development and Operating Principles, *Wildes, Karl L.* (July) ..... 1086

## ELECTRIC CIRCUIT THEORY

Analytics of Transmission Calculations The Theoretical Foundation of the Quaternary Linear Real Transformation Connecting Input and Output Quantities in the Gen. Elec. Circuit Together with Its Application by Algebraic and Geometrical Methods, *Rosebrugh, T. R.* (October) ..... 1419
Calculation of Induced Voltages in Metallic Conductors, *Dwight, H. B.* (April) ..... 447
Calorimetric Study of the Arc, The, *Alexander, P. P.* (April) ..... 519
Cathode Energy of the Iron Arc, *Doan, G.* (April) ..... 723
Effect of Surges on Transformer Windings, *Hodnette, J. K.* (January) ..... 68
Extinction of a Long A-C. Arc, *Slepian, J.* (April) ..... 421
Flames from Electric Arcs, *Slepian, J.* (January) ..... 56
Ionization Currents and the Breakdown of Insulation, *Torok, J. J. and Fielder, F. D.* (January) ..... 352
Mutual Impedances of Ground-Return Circuits Some Experimental Studies, *Bowen, A. E. and Gilkeson, C. L.* (October) ..... 1370

## ELECTROPHYSICS

Dissipation of Heat by Radiation, *Moore, A. D.* (January) 359
Electrophysics Committee Report (October) ..... 1702
Ionization Currents and the Breakdown of Insulation, *Torok J. J. and Fielder, F. D.* (January) ..... 352
Theory of Electrical Conductivity, Recent Developments, *Houston, W. V.* (January) ..... 30

## GENERATORS, ALTERNATING CURRENT

Design Features that Make Large Turbine Generators Possible, *Foster, W. J. and Savage, M. A.* (January) ..... 60
Determination of Generator Speed and Retardation during Loss Measurements, *Charlton, O. E. and Ketchum W. D.* (July) ..... 1095
Double Windings for Turbine Alternators, *Alger, P. L., Freiburghouse, E. H., and Chase, D. D.* (January) ..... 226
General Circle Diagram of Electrical Machinery, The, *Terman, F. E., Lenzen, T. L., Freedman, C. L., and Rogers, K. A.* (January) ..... 374
Generalized Theory of Electrical Machinery, *Kron, G.* (April) ..... 666
Induced Voltage of Electrical Machines, *Bewley, L. V.* (April) ..... 456
Operating Characteristics of Turbine Generators, *Purcell, T. E. and Hayward, A. P.* (April) ..... 715
Telephone Interference from A-C. Generators, *Smith, J. J.* (April) ..... 789
Ventilation of Revolving-Field Salient-Pole Alternators, *Fechheimer, Carl J.* (April) ..... 548

## GENERATORS, DIRECT CURRENT

Determination of Generator Speed and Retardation during Loss Measurements, *Charlton, O. E. and Ketchum, W. D.* (July) ..... 1095
Generalized Theory of Electrical Machinery, *Kron, G.* (April) ..... 666
Induced Voltage of Electrical Machines, *Bewley, L. V.* (April) ..... 456
Voltage Irregularities in D-C. Generators, *Fetsch, J. T.* (July) ..... 1068

## HYDROELECTRIC

Present Day Hydro Power Practise in Central Europe, *Karpov, A. V.* (January) ..... 1642
220,000 Volt System of the Hydro-Electric Power Commission of Ontario, The, *Brandon, E. T. J.* (October) .. 1400

## INDUSTRIAL APPLICATION OF POWER

Automatic Power Supply for Steel Mill Electrification, *Harry, R. J.* (October) ..... 1351

## INSULATION

Coordination of Insulation as a Design Problem, *Floyd, G. D.* (October) ..... 1482
Essential Factors in the Coordination of Line Station and Apparatus Insulation, *Silver, A. E. and Melvin, H. L.* (October) ..... 1491
Impulse Insulation Characteristics of Wood Pole Lines, *Melvin, H. L.* (January) ..... 21
Metal-Clad Gum-Filled Switchgear, *Chubbuck, L. B.*, November JOURNAL ..... 925
Rationalization of Station Insulating Structures, *Fortescue, C. L.* (October) ..... 1450
Rationalization of Transmission Insulation Strength—II, *Sporn, P.* (October) ..... 1470
Recommendations on Balancing Transformer and Line Insulations, *Montsinger, V. M. and Dann, W. M.* (October) ..... 1478
Standards of Insulation and Protection for Transformers, *Johnson, J. A. and Bundy, E. S.* (October) ..... 1486

## INSULATORS

Sixty-Cycle Flashover of Long Suspension Insulator Strings, *Angus, R. H.* (January) ..... 15
Spray and Fog Tests on 220-Kv. Insulators, *Wood, R. J. C.* (January) ..... 9
Study of Telephone Line Insulators, *Wilson, L. T.* (October) ..... 1536
Surge Characteristics of Insulators and Gaps, *Torok, J. J.* (July) ..... 866

## INTERCONNECTED SYSTEMS

Modern Requirements for Protective Relays on Important System Interconnections, *Traver, O. C. and Kennedy, L. F.* (October) ..... 1226
Simulating Sunlight, *Luckiesh, M.* (April) ..... 511

## LIGHTING

Production and Application of Light Committee Report (October) ..... 1735

## LIGHTNING ARRESTERS

Development of the New Autovalve Arrester, *Slepian, J., Tanberg, R., and Krause, C. E.* (April) ..... 404
Lightning Laboratory at Stillwater, New Jersey, *Conwell, R. N. and Fortescue, C. L.* (July) ..... 872
Lightning on Transmission Lines—Cathode Ray Oscillograph Studies, *Cox, J. H. and Beck, E.* (July) ..... 857
Theory of a New Valve Type Lightning Arrester, *Slepian, J., Tanberg, R., and Krause, C. E.* (January) ..... 257
Thyrite, A New Material for Lightning Arresters, *McEachron, K. B.* (April) ..... 410

## LOSS AND EFFICIENCY MEASUREMENTS

Determination of Generator Speed and Retardation during Loss Measurements, *Charlton, O. E. and Ketchum, W. D.* (July) ..... 1095
Reduction of Eddy Current Losses, *Lyons, J. M.* (July) .. 998

## MAGNETIC PHENOMENA

Effects of the Magnetic Field on Lichtenberg Figures, *Magnusson, C. E.* (October) ..... 1384
Magnetic Circuit Units, *Kennelly, A. E.* (April) ..... 486

## MARINE APPLICATIONS

Application to Marine Work Committee Report (October) 1739

## MEASURING INSTRUMENTS

An Ultra Violet Light Meter, *Rentschler, H. C.* (April) .... 576
Cathode Ray Oscillograph with Norinder Relay, A, *Ackermann, O.* (April) ..... 467

New Portable Oscillograph, *Hathaway, C. M.*, August JOURNAL ..... 646
Recording Torque Indicator that Records the Torsional Effort of Motors during Acceleration, A, *Anderson, G. R.* (January) ..... 333
Self-Compensating Temperature Indicator, A, *Kinnard, I. F. and Faus, H. T.* (July) ..... 949

## MEASURING METHODS

An Electron Tube Telemetering System, *Fitzgerald, A. S.* (October) ..... 1321
Development of a Two-Wire Supervisory Control System with Remote Metering, *Wensley, R. J. and Donovan, W. M.* (October) ..... 1339
Instruments and Measurements Committee Report (October) ..... 1728

## MINING APPLICATIONS

Applications to Mining Work Committee Report (October) ..... 1740

## MOTORS, ALTERNATING CURRENT

Effect of Electric Shock, *Kouwenhoven, W. B. and Langworthy, Orthello R.* (January) ..... 381
General Circle Diagram of Electrical Machinery, The, *Terman, F. E., Lenzen, T. L., Freedman, C. L., and Rogers, K. A.* (January) ..... 374
Generalized Theory of Electrical Machinery, *Kron, G.* (April) ..... 666
Induced Voltage of Electrical Machines, *Bewley, L. V.* (April) ..... 456
Induction Motor Performance Calculations, *Alger, P. L.* (July) ..... 1055
Polyphase Induction Motors, *Branson, W. J.* (January) ..... 319
Power Transients in A-C. Motors, *Kelso, L. E. A. and Tracy, G. F.* (January) ..... 368
Quiet Induction Motors, *Hildebrand, L. E.* (July) ..... 848
Starting Performance of Salient-Pole Synchronous Motors, *Linville, T. M.* (April) ..... 531
Synchronous Motor Effects in Induction Machines, *Dreese, E. E.* (July) ..... 1033
Synchronous-Repulsion Motor, The, *Specht, H. C.* (July) ..... 1027

## MOTORS, DIRECT CURRENT

Generalized Theory of Electrical Machinery, *Kron, G.* (April) ..... 666
Induced Voltage of Electrical Machines, *Bewley, L. V.* (April) ..... 456

## PROTECTIVE DEVICES

An A-C. Low-Voltage Network without Network Protectors, *Gamble, L. R. and Baughn, E.* (January) ..... 82
Directional Ground Relays, *George E. E. and Bennett, R. H., Jr.* (October) ..... 1243
Effects of Lightning Voltages on Rotating Machines and Methods of Protecting Against Them, *Fielder, F. D. and Beck, E.* (October) ..... 1577
Fault Ground Bus, The, *Stanley, R. M. and Hornsbrook, F. C.* (January) ..... 201
Fused Grading Shields, *H. A. Frey and Skipper, E. M.* (July) ..... 990
High-Speed Protective Relays, *Crichton, L. N.* (October) ..... 1232
High-Voltage Low-Current Fuses and Switches, *Wilkins, R.* (January) ..... 96
Low-Voltage A-C. Networks of the Standard Gas & Electric Company's Properties, *Stanley, R. M. and Sinclair, C. T.* (January) ..... 265
Metal-Clad Switchgear at State Line Station, The, *Rossman, A. M.* (April) ..... 397
Modern Requirements for Protective Relays on Important System Interconnections, *Traver, O. C. and Kennedy, L. F.* (October) ..... 1226
M. I. T. Network Analyzer, The, *Hazen, H. I., Schurig, O. R., and Gardner, M. F.* (July) ..... 1102
Protective Devices Committee Report, (October) ..... 1754
Shunt Resistors for Reactors, *Kierstead, F. H., Rorden, H. L., and Bewley, L. V.* (July) ..... 1161
Transmission System Relay Protection—III, *Edson, W. W.* (October) ..... 1213

## RADIO PHENOMENA

Air Transport Communication, *Jones, R. L. and Ryan, F. M.* (January) ..... 187
Electrical Engineering of Sound Picture Systems, *Morgan, K. F. and Shea, T. E.* (January) ..... 105
Radio Interference from Line Insulators, *Van Atta, E. and White, E. L.* (January) ..... 1
Radio Telephone Service to Ships at Sea, *Wilson, W. and Espenschied, L.* (July) ..... 1152

## RAILWAYS

Auxiliaries for High-Voltage D-C. Multiple Unit Cars, *Axtell, C. J.* (October) ..... 1282
Auxiliary Circuits for High-Voltage D-C. Motor Car Equipments, *Marti, O. K. and Giger, W.* (October) ..... 1287
Control Systems for Oil and Gasoline Electric Locomotives and Cars, *Freeman, N. L.* (October) ..... 1262
Electric Power Consumption for Yard Switching, *Hatch, P. H.* (October) ..... 1256
Electric Transmission and Control of Power from Internal Combustion Engines for Transportation, *Dodd, S. T.* (October) ..... 1271
Electrical Transportation Committee Report, (October) ..... 1759
1000 Kw. Automatic Mercury Arc Rectifier Substation of the Union Railway Co. of N. Y., *Gutzwiller, W. E. and Naef, O.* (October) ..... 1357
Railbonding Practise and Experience on Electrified Steam Railroads, *Brown, H. F.* (October) ..... 1299

## RESEARCH

1000 Kw. Automatic Mercury Arc Rectifier Substation of the Union Railway Company of New York, *Gutzwiller, W. E. and Naef, O.* (October) ..... 1357

## STABILITY

Calculation of Alternator Swing Curves—The Step-by-Step Method, The, *Longley, F. R.* (July) ..... 1129
Progress in the Study of System Stability, *Summers, I. H. and McClure, J. B.* (January) ..... 132
Stability of Synchronous Machines—Effect of Armature Circuit Resistances, *Nickle, C. A. and Pierce, C. A.* (January) ..... 338

## SUBSTATIONS

An Economic Study of an Electrical Distributing Station, *Kelley, W. G.* (January) ..... 285

## SWITCHES

Automatic Regulation of Synchronous Condensers Equipped with Superspeed Excitation, *Thompson, L. W. and Walton, P. J.* (January) ..... 315
Effect of Armature Resistance upon Hunting of Synchronous Machines, *Wagner, C. F.* (July) ..... 1011
High-Voltage Low-Current Fuses and Switches, *Wilkins, R.* (January) ..... 96
Increased Voltages for Synchronous Machines, *Laffoon, C. M.* (January) ..... 213
Metal-Clad Gum-Filled Switchgear, *Chubbuck, L. B.*, November JOURNAL ..... 925
Series Synchronous Condensers for Generation of Voltage Consumed by Line Inductance, *Morgan, Theodore* (January) ..... 162
Starting Performance of Salient-Pole Synchronous Motors, *Linville, T. M.* (April) ..... 531
Synchronous Motor Effects in Induction Machines, *Dreese, E. E.* (July) ..... 1033
Synchronous-Repulsion Motor, The, *Specht, H. C.* (July) ..... 1027
Three-Phase Short Circuit Synchronous Machines—V, *Doherty, R. E. and Nickle, C. A.* (April) ..... 700
Transient Torque-Angle Characteristics of Synchronous Machines, *Lyon, W. V. and Edgerton, H. E.* (April) ..... 686
Vertical Shaft 25,000-Kv-a. Synchronous Condensers, 25-Cycle, 500-Rev. per Min., Outdoor Type Units for Toronto to Leaside Transformer Station, *Ricker, H. A. Dunbar, J. R., and Day, R. E.* (October) ..... 1616

## TECHNICAL COMMITTEE REPORTS

Applications to Iron and Steel Productions Committee Report, (October) ..... 1733
Application to Marine Work Committee Report, (October) ..... 1739
Applications to Mining Work Committee Report (October) ..... 1740
Automatic Stations Committee Report (October) ..... 1660
Electrical Communication Committee Report (October) ..... 1671
Electrical Machinery Committee Report (October) ..... 1677
Electrical Transportation Committee Report (October) ..... 1759
Electric Welding Committee Report (October) ..... 1699
Electrophysics Committee Report (October) ..... 1702

General Power Applications Committee Report (October) 1711
Instruments and Measurements Committee Report (October) 1728
Power Generation Committee Report (October) 1742
Power Transmission and Distribution Committee Report (October) 1744
Production and Application of Light Committee Report (October) 1735
Protective Devices Committee Report (October) 1754

## TELEGRAPH

Submarine Telegraphy in the Post-War Decade, *Goggeshall, I. S.* (April) 476

## TELEPHONE

Air Transport Communication, *Jones, R. L. and Ryan, F. M.* (January) 187
Chicago Long Distance Toll Board, The, *Neubauer, E. O. and Rutgers, G. A.* (January) 178
Dial Telephone System Serving Small Communities of Southern California, *Wheelock, F. O.* (January) 117
General Switching Plan for Telephone Toll Service, A *Osborne, H. S.* (October) 1549
Long Telephone Lines in Canada, *Clarke, J. L.* (October) 1558
Radio Telephone Service to Ships at Sea, *Wilson W. and Espenschied, L.* (July) 1152
Recent Developments in Toll Telephone Service, *Harrison, W. H.* (January) 166
Study of Telephone Line Insulators, A, *Wilson, L. T.* (October) 1536
Survey of Room Noise in Telephone Locations, A, *Williams, W. J. and McCurdy, R. G.* (October) 1393
Telephone Interference from A-C. Generators, *Smith, J. J.* (April) 798
Transmission Characteristics of Open-Wire Telephone Lines, The. *Green, E. I.* (October) 1524
Transoceanic Telephone Service—General Aspects, *Miller, T. G.* (April) 621
Transoceanic Telephone Service—Short-Wave Equipment, *Oswald, A. A.* (April) 629
Transoceanic Telephone Service—Short-Wave Stations, *Cowan, F. A.* (April) 638
Transoceanic Telephone Service—Short-Wave Transmission, *Bown, Ralph* (April) 624

## TELEVISION

Two-Way Television, *Ives, H. E., Gray, Frank, and Baldwin, M. W.* (October) 1563

## TRANSFORMERS

Buried Distribution Type Transformer, *Schwenger, C. E.*, July JOURNAL 519
Conductivity of Insulating Oils, The, *Whitehead, J. B. and Marvin, R. H.* (April) 647
Developments of Insulating Oils, *Skinner, C. E.* (January) 35
Effect of Color of Tank on the Temperature of Self-Cooled Transformers under Service Conditions, *Montsinger, V. M. and Wetherill, L.* (January) 41
Effect of Surges on Transformer Windings, *Hodnette, J. K.* (January) 68
Effect of Transient Voltage on Power Transformer Design, *Palueff, K. K.* (July) 1179
Inversion Currents and Voltages in Auto-Transformers, *Boyajian, A.* (April) 810
Lightning Investigation on 220-Kv. System of the Penn. Power & Lt. Co. (1928 and 1929), *Smeloff, N. N. and Price, A. L.* (July) 895
Loading Transformers by Temperature, *Montsinger, V. M.* (April) 776
Operating Transformers by Temperature, *Dann, W. M.* (April) 793
Parallel Operation of Transformers, *Macferran, Mabel* (January) 125
Recommendations on Balancing Transformer and Line Insulations, *Montsinger, V. M. and Dann, W. M.* (October) 1478
Standards of Insulation and Protection for Transformers, *Johnson, J. A. and Bundy, E. S.* (October) 1486
Tap Changing Under Load for Voltage and Phase-Angle Control, *West, H. B.* (July) 839
Transformer Ratio and Differential Leakage of Distributed Windings, *Hellmund, R. E. and Veinott, C. G.* (July) 1043

## TRANSIENTS

Arcing Grounds and Effect of Neutral Grounding Impedance, *Clem, J. E.* (July) 970
Effects of Lightning Voltages on Rotating Machines and Methods of Protecting Against Them, *Fielder, F. D. and Beck, E.* (October) 1577
Effect of Surges on Transformer Windings, *Hodnette, J. K.* (January) 68
Effect of Transient Voltages on Dielectrics—IV, *Peek, F. W., Jr.* (October) 1456
Effect of Transient Voltage on Power Transformer Design, *Palueff, K. K.* (July) 1179
Lightning Investigation on the Ohio Power Company's 132-Kv. System, *Sporn, P. and Lloyd, W. L., Jr.* (July) 905
Lightning Investigation on Transmission Lines, *Lewis, W. W. and Foust, C. M.* (July) 917
Lightning Voltages on Transmission Lines, *George, R. H. and Eaton, J. R.* (July) 877
Power Transients in A-C. Motors, *Kelso, L. E. A. and Tracy, G. F.* (January) 366
Study of the Effect of Short Lengths of Cable on Traveling Waves, *McEachron, K. B., Hemstreet, J. G. and Seelye, H. P.* (October) 1432
Surge Characteristics of Insulators and Gaps, *Torok, J. J.* (July) 866
Traveling Waves on Transmission Lines with Artificial Lightning Surges, *McEachron, K. B., Hemstreet, J. G., and Rudge, W. J.* (July) 885
Voltage Oscillations in Armature Windings under Lightning Impulses, *Boehne, E. W.* (October) 1587

## TRANSMISSION LINES

### Electrical Characteristics

Essential Factors in the Coordination of Line, Station, and Apparatus Insulation, *Silver, A. E. and Melvin, H. L.* (October) 1491
Experience with Carrier-Current Communication on a High-Tension Interconnected Transmission System, *Sporn, Philip and Wolford, Ray H.* (January) 288
Lightning on Transmission Lines—Cathode Ray Oscillograph Studies, *Cox, J. H. and Beck, E.* (July) 857
Lightning Voltages on Transmission Lines, *George, R. H. and Eaton, J. R.* (July) 877
Rationalization of Transmission Insulation Strength—II, *Sporn, P.* (October) 1470
Transmission System Relay Protection—III, *Edson, W. W.* (October) 1213
Traveling Waves on Transmission Lines with Artificial Lightning Surges, *McEachron, K. B., Hemstreet, J. G., and Rudge, W. J.* (July) 885

## TRANSMISSION LINES

### General

Calculation of Protection of a Transmission Line by Ground Conductors, *Dwight, H. B.* (July) 1115
Impulse Insulation Characteristics of Wood Pole Lines, *Melvin, H. L.* (January) 21
Problem of Service Security in Large Transmission Systems, The, *Ackerman, P.*, September JOURNAL 767
System Connections and Inter-Connections, Chicago District, *Armbrust, G. M. and LeClair, T. G.* (April) 581
Transmission Research and Design with the Field as a Laboratory, *Andrews, F. E. and Stroup, C. L.* (July) 959

## TRANSMISSION LINES

### Mechanical Features

New Transmission Line Construction—Post Type Towers, *Thomas, Percy* (July) 1122
Rural Line Construction in Ontario, *Jones, R. E.*, July JOURNAL 550

## VENTILATION

Ventilation of Revolving-Field Salient-Pole Alternators, *Fechheimer, Carl J.* (April) 548

## WELDING

Electric Welding by the Carbon Arc, *Lincoln, J. C.* (April) 735
Electric Welding Committee Report (October) 1699
Electrically Welded Structures Under Dynamic Stress, *Stone, M. and Ritter, J. G.* (July) 832
Resistance Welding, *Mottinger, Byron, T.* (April) 524

# INDEX OF AUTHORS

## A


Ackermann, O., *Paper* (April) 467
Ackermann, O., *Discussion* (April) 475, (July) 933
Ackerman, P., *Paper*, September JOURNAL 767
Ackerman, P., *Discussion* (October) 1240
Adams, C. A., *Discussion* (April) 684, 733, 792
Alexander, P. P., *Paper* (April) 519
Alexander, P. P., *Discussion* (April) 523
Alger, P. L., *Paper* (July) 1055
Alger, P. L., E. H. Freiburghouse, and D. D. Chase, *Paper* (January) 226
Alger, P. L., *Committee Report* (October) 1677
Alger, P. L., *Discussion* (January) 221, (April) 807, (July) 1067
Allen, E. G., *Discussion* (April) 613
Allner, F. A., *Committee Report* (October) 1742
Allner, F. A., *Discussion* (October) 1657
Amberg, E. J., *Discussion* (July) 942
Amstutz, N. S., *Discussion* (October) 1576
Anderson, G. R., *Paper* (January) 333
Anderson, G. R., *Discussion* (January) 336
Andrews, F. E. and C. L. Stroup, *Paper* (July) 959
Andrews, F. E., *Discussion* (July) 939, 996, 1127
Angus, R. H., *Paper* (January) 15
Anissimoff, C. I., *Discussion* (January) 55
Armbrust, G. M. and T. G. LeClair, *Paper* (April) 582
Armbrust, G. M., *Discussion* (April) 618
Ashbaugh, J. H., *Discussion* (January) 318
Atkinson, R. W., *Discussion* (April) 763
Austin, A. O., *Discussion* (July) 944, (October) 1496
Axtell, C. J., *Paper* (October) 1282


## B


Bailey, B. F., *Discussion* (January) 336
Bailey, R., *Paper* (April) 605
Bailey, R., *Discussion* (April) 619
Baker, B. P. and H. M. Wilcox, *Paper* (April) 431
Baldwin, M. W., H. E. Ives, and Frank Gray, *Paper* (October) 1563
Bang, A. F. and L. G. Smith, *Discussion* (April) 614
Barker, J. W., *Discussion* (April) 731
Barns, B. L., *Discussion* (April) 574, 738, (July) 837
Baughn, Earl and Lester R. Gamble, *Paper* (January) 82
Beck, E. F. W., *Discussion* (April) 475
Beck, Edward, *Discussion* (January) 262, (April) 417, (July) 936, (October) 1507
Beck, Edward and J. H. Cox, *Paper* (July) 857
Beck, Edward and J. H. Cox, *Discussion* (July) 945
Beck, E. and F. D. Fielder, *Paper* (October) 1577
Beck, E. and F. D. Fielder, *Discussion* (October) 1613
Beckwith, Sterling, *Discussion* (April) 572
Bell, E. and A. L. Price, *Discussion* (July) 948
Benedict, R. R., *Paper* (April) 739
Benedict, R. R., *Discussion* (April) 753
Bennett, Edward, *Discussion* (April) 497
Bennett, J. W., *Discussion* (April) 402, 445, 618
Bennett, R. H., Jr., and E. E. George, *Paper* (October) 1243
Bennett, R. H., Jr., *Discussion* (October) 1254
Bergvall, R. C., *Discussion* (July) 1025, 1113
Bewley, L. V., *Paper* (April) 456
Bewley, L. V., F. H. Kierstead, and H. L. Rorden, *Paper* (July) 1161
Bewley, L. V., *Discussion* (April) 453, (July) 929, 988, 1042, 1084, 1118, (October) 1442, 1608
Binder, R. L., *Discussion* (January) 6
Blake, D. K., *Discussion* (January) 280
Blake, D. K., *Discussion* (April) 617
Blattner, D. G. and L. G. Bostwick, *Paper* (October) 1574
Boehne, E. W., *Paper* (October) 1587
Boehne, E. W., *Discussion* (July) 940, (October) 1614
Boothby, C. R. and P. H. Trickey, *Discussion* (July) 1041
Boothby, C. R. and C. G. Veinott, *Discussion* (January) 329
Bostwick, L. G. and D. G. Blattner, *Paper* (October) 1574
Bowen, H. E. and C. L. Gilkeson, *Paper* (October) 1370
Bowen, H. E. and C. L. Gilkeson, *Discussion* (October) 1382
Bown, R., *Paper* (April) 624
Bown, Ralph, *Discussion* (April) 646
Boyajian, A., *Paper* (April) 810
Boyajian, A., *Discussion* (April) 822, (July) 1093
Brandon, E. T. J., *Paper* (October) 1400
Brandon, E. T. J., *Discussion* (October) 1418
Branson, W. J., *Paper* (January) 319
Branson, W. J., *Discussion* (January) 331
Brinton, H. G., *Discussion* (October) 1441
Brookes, A. S., *Discussion* (July) 935
Brown, H. F., *Paper* (October) 1299
Brown, H. F., *Discussion* (October) 1320
Buckley, O. E., *Committee Report* (October) 1702
Buckley, O. E., *Discussion* (April) 484
Bundy, E. S., A. Van Niekerk, and W. H. Rodgers, *Paper* (January) 245
Bundy, Edwin S. and J. A. Johnson, *Paper* (October) 1486
Burbank, J. D., *Discussion* (January) 313
Buttolph, L. J., *Discussion* (April) 516, 579


## C


Calvert, J. F., *Discussion* (January) 223
Candy, A. M., *Committee Report* (October) 1699
Caparo, J. A., *Discussion* (January) 186
Chadbourn, R. W., *Discussion* (July) 1093
Chandler, F. H., *Discussion* (October) 1626
Charlton, O. E. and W. D. Ketchum, *Paper* (July) 1095
Charlton, O. E., *Discussion* (July) 1101
Chase, D. D., P. L. Alger, and E. H. Freiburghouse, *Paper* (January) 226
Chase, D. D., *Discussion* (January) 243
Chubbuck, L. B., *Paper*, November JOURNAL 925
Churchward, A., *Discussion* (April) 522
Clark, A. B. and C. W. Green, *Paper* (October) 1514
Clark, F. M., *Discussion* (April) 764
Clarke, J. L., *Paper* (October) 1558
Clem, J. E., *Paper* (July) 970
Clem, J. E., *Discussion* (April) 819, (July) 989, 996, 1119
Codding, H. W., *Discussion* (October) 1349
Coggeshall, I. S., *Paper* (April) 476
Colburn, W. H., *Discussion* (April) 402, (July) 996, 1127, (October) 1224
Coleman, J. O' R., *Discussion* (April) 805
Compton, K. T., *Discussion* (April) 733
Conwell, R. N. and C. L. Fortescue, *Paper* (July) 872
Coombs, R. D., *Discussion* (July) 1127
Cox, J. H., *Discussion* (April) 419, (July) 944, (October) 1499
Cox, J. H. and Edward Beck, *Paper* (July) 857
Cox, J. H. and Edward Beck, *Discussion* (July) 945
Cowan, F. A., *Paper* (April) 638
Cozzens, Bradley, *Discussion* (January) 5, 19
Crawford, M. T., *Discussion* (January) 283
Crawford, W. E., *Discussion* (April) 738
Cree, G. G., *Discussion* (April) 401
Creedy, F., *Discussion* (April) 734
Crichton, L. N., *Paper* (October) 1232
Crichton, L. N., *Discussion* (October) 1241
Curtis, H. L., *Discussion* (April) 506


## D


Daniels, R. S., *Discussion* (January) 6
Dann, W. M., *Paper* (April) 793
Dann, W. M., *Discussion* (April) 791, 797
Dann, W. M. and V. M. Montsinger, *Paper* (October) 1478
Davison, A. E, *Paper* (October) 1444
Dawes, C. L., *Discussion* (April) 495, 656, 753
Dawes, C. L. and P. H. Humphries, *Paper* (April) 766
Dawes, C. L. and P. H. Humphries, *Discussion* (April) 774
Day, R. E., H. A. Ricker, and J. R. Dunbar, *Paper* (October) 1616
Dean, S. M., *Paper* (April) 597
Dean, S. M., *Discussion* (April) 619
Del Mar, W. A., *Discussion* (April) 764
Doan, G. E., *Paper* (April) 723
Doan, G. E., *Discussion* (April) 734
Dodd, S. T., *Paper* (October) 1271
Dodds, G. B., *Discussion* (January) 212
Doggett, L. A., *Discussion* (April) 807
Doherty, R. E. and C. A. Nickle, *Paper* (April) 700
Donovan, W. M. and R. J. Wensley, *Paper* (October) 1339
Doolittle, F. B., *Discussion* (January) 5
Dorcas, M. J., *Discussion* (April) 516
Douglas, J. F. H., *Discussion* (January) 222, 330
Dreese, E. E., *Paper* (July) 1033

Dreese, E. E., *Discussion* (July) 1042
Dryer, W. P., *Discussion* (April) 719
Dudley, A. M., *Discussion* (January) 328
Dunbar, J. R., H. A. Ricker, and R. E. Day, *Paper* (October) 1616
Dunn, J. F., *Discussion* (January) 50
Dwight, Herbert Bristol, *Paper* (April) 447, (July) 1115
Dwight, Herbert Bristol, *Discussion* (April) 454, (July) 1121

## E

Eales, H. W., *Discussion* (January) 282
Eaton, J. R. and R. H. George, *Paper* (July) 877
Edgerton, H. E., *Discussion* (April) 698, (July) 1024
Edgerton, H. E. and W. V. Lyon, *Paper* (April) 686
Edson, W. W., *Paper* (October) 1213
Edson, W. W., *Discussion* (October) 1225
Erikson, H. A., *Discussion* (October) 1391
Espenschied, Lloyd and William Wilson, *Paper* (July) 1152
Espenschied, Lloyd, *Discussion* (July) 1160
Evans, R. D., *Discussion* (April) 441, 721

## F

Faus, H. T. and I. F. Kinnard, *Paper* (July) 949
Febrey, H. H., *Discussion* (October) 1314
Fechheimer, C. J., *Paper* (April) 548
Fechheimer, C. J., *Discussion* (January) 223, (April) 574, 791, 796, (July) 856
Ferris, L. P., *Discussion* (October) 1380
Fetsch, J. T., Jr., *Paper* (July) 1068
Fetsch, J. T., Jr., *Discussion* (July) 1085
Fielder, F. D., *Discussion* (January) 28
Fielder, F. D. and J. J. Torok, *Paper* (January) 352
Fielder, F. D. and E. Beck, *Paper* (October) 1577
Fielder, F. D. and E. Beck, *Discussion* (October) 1613
Fielder, F. D. and P. H. McAuley, *Discussion* (October) 1502
Fitzgerald, A. S., *Paper* (October) 1321
Fitzgerald, A. S., *Discussion* (October) 1239, 1337
Fleming, D. B., *Discussion* (April) 791
Fleming, G. A., *Discussion* (January) 13
Floyd, G. D., *Paper* (October) 1482
Floyd, G. D., *Discussion* (October) 1512, 1626
Fortescue, Cecil L., *Discussion* (April) 505, (July) 938, 946
Fortescue, C. L. and R. N. Conwell, *Paper* (July) 872
Fortescue, C. L., *Paper* (October) 1450
Fortescue, C. L., *Discussion* (October) 1503, 1509
Foster, W. J. and M. A. Savage, *Paper* (January) 60
Foust, C. M. and W. W. Lewis, *Paper* (July) 917
Foust, C. M., *Discussion* (October) 1391
Fowle, Frank F., *Discussion* (April) 807
Fowler, M. M., *Committee Report* (October) 1733
Freedman, C. I., K. A. Rogers, F. E. Terman, and T. L. Lenzen, *Paper* (January) 374
Freeman, N. L., *Paper* (October) 1262
Freiburghouse, E. H., D. D. Chase, and P. L. Alger, *Paper* (January) 226
Freiburghouse, G. H., *Discussion* (January) 243
Frey, H. A. and E. M. Skipper, *Paper* (July) 990
Frey, H. A., *Discussion* (July) 996

## G

Gage, H. P., *Discussion* (April) 579
Gamble, L. R. and Earl Baughn, *Paper* (January) 82
Gamble, L. R., *Discussion* (January) 27, 94, 159
Gardner, M. F., H. L. Hazen, and O. R. Schurig, *Paper* (July) 1102
Gaskill, J. F., *Committee Report* (October) 1711
Gati, Bela, *Discussion* (April) 751, 807
Gay, F. W., *Discussion* (April) 495, 546, 573, 790, (July) 845
George, E. E., *Discussion* (July) 931
George, E. E. and R. H. Bennett, Jr., *Paper* (October) 1243
George, R. B., *Discussion* (July) 1178
George, R. H., *Discussion* (January) 357, (July) 947
George, R. H. and J. R. Eaton, *Paper* (July) 877
Gherardi, B., *Discussion* (April) 643
Gibbs, G. S., *Discussion* (April) 505
Giger, W. and O. K. Marti, *Paper* (October) 1287
Gilkeson, C. L. and H. E. Bowen, *Paper* (October) 1370
Gilkeson, C. L. and H. E. Bowen, *Discussion* (October) 1382
Gilt, C. M., *Discussion* (April) 792
Gokhale, S. L., *Discussion* (April) 500
Goodale, J. E., *Discussion* (October) 1342
Goodman, Herman, *Discussion* (April) 518, 579
Gordon, E., *Discussion* (April) 578
Gorsuch, W. S., *Discussion* (October) 1640
Graham, Q., *Discussion* (July) 855
Grady, C. B., W. H. Lawrence, and R. H. Tapscott, *Paper* (October) 1628
Grady, C. B., *Discussion* (October) 1640
Gray, Frank, H. E. Ives, and M. W. Baldwin, *Paper* (October) 1563
Green, C. W. and A. B. Clark, *Paper* (October) 1514
Green, E. I., *Paper* (October) 1524
Guth, C. W., *Discussion* (October) 1609
Gutzwiller, W. E. and O. Naef, *Paper* (October) 1357

## H

Haberl, H. W., *Discussion* (October) 1240
Hagenguth, J. H., *Discussion* (July) 1192
Haglund, H. H., *Discussion* (April) 485
Hague, B., *Discussion* (April) 505
Halperin, H. and K. W. Miller, *Discussion* (October) 1441
Hamill, S. M., *Discussion* (January) 197, 212, 282
Harding, C. F., *Discussion* (October) 1442
Harris, H. A., *Discussion* (January) 176
Harrison, W. H., *Paper* (January) 166
Harrison, W. H., *Discussion* (January) 177
Harry, R. J., *Paper* (October) 1351
Harry, R. J., *Discussion* (October) 1356
Hartman, R. L., *Discussion* (January) 184
Hatch, P. H., *Paper* (October) 1256
Hathaway, C. M., *Paper*, August JOURNAL 646
Hayward, A. P. and T. E. Purcell, *Paper* (April) 715
Hayward, A. P., *Discussion* (April) 721
Hazen, H. L., O. R. Schurig, and M. F. Gardner, *Paper*, (July) 1102
Hellmund, R. E. and C. G. Veinott, *Paper* (July) 1043
Hellmund, R. E., *Discussion* (July) 853, 1031, 1042, 1053, 1066, (October) 1224
Hemstreet, J. G., W. J. Rudge, and K. B. McEachron, *Paper* (July) 885
Hemstreet, J. G., K. B. McEachron, and H. P. Seelye, *Paper* (October) 1432
Henderson, S. L., *Discussion* (January) 222, (April) 574, 806
Henningsen, E. S., *Discussion* (January) 67
Hester, E. A., *Committee Report* (October) 1754
Higgins, D. D., *Discussion* (January) 212
Hildebrand, L. E., *Paper* (July) 848
Hildebrand, L. E., *Discussion* (July) 856
Hinson, N. B., *Paper* (January) 52
Hinson, N. B., *Discussion* (January) 55
Hodnette, J. K., *Paper* (January) 68
Hodnette, J. K., *Discussion* (January) 80, (July) 942, 1190
Holladay, C. H., *Discussion* (January) 50
Holm, Ragnar, *Discussion* (April) 665
Hooper, S. C., *Discussion* (January) 197
Hornibrook, F. C. and R. M. Stanley, *Paper* (January) 201
Hornibrook, F. C., *Discussion* (January) 212
Houston, William V., *Paper* (January) 30
Howe, G. W. O., *Discussion* (April) 504
Huber, H. J. H., *Discussion* (April) 401
Humphries, P. H. and C. L. Dawes, *Paper* (April) 766
Humphries, P. H. and C. L. Dawes, *Discussion* (April) 774
Hunter, E. M., *Discussion* (July) 1120
Hunter, E. M. and J. B. McClure, *Discussion* (January) 160
Huntington, E. K., *Discussion* (July) 846

## I

Ives, H. E., Frank Gray, and M. W. Baldwin, *Paper* (October) 1563

## J

Jackson, D. C., Jr., *Discussion* (July) 1093
Jackson, R. P., *Discussion* (July) 1121
Jamieson, W. M., *Discussion* (January) 185
Jennings, C. H., *Discussion* (July) 837
Jewett, F. B., *Discussion* (April) 644
Johnson, J. A., *Discussion* (July) 1101
Johnson, J. A. and E. S. Bundy, *Paper* (October) 1486
Johnson, W. H., *Discussion* (January) 283
Jollyman, J. P., *Discussion* (January) 5, 159
Jones, R. E., *Paper*, July JOURNAL 550
Jones, R. L. and F. M. Ryan, *Paper* (January) 187
Jones, S. M., *Discussion* (October) 1496
Jordan, C. A., *Discussion* (July) 942

## K


Kalb, H. N., *Discussion* (January) 5
Karapetoff, V., *Discussion* (April) 496, 751
Karpov, A. V., *Paper* (October) 1642
Karpov, A. V., *Discussion* (October) 1658
Kositzky, G. A., *Committee Report* (October) 1671
Kehoe, A. H., *Discussion* (April) 612
Kelley, W. G., *Paper* (January) 285
Kelly, J. T., *Discussion* (July) 969
Kelso, L. E. A. and G. F. Tracy, *Paper* (January) 366
Kennedy, L. F. and O. C. Traver, *Paper* (October) 1226
Kennedy, L. F. and O. C. Traver, *Discussion* (October) 1241
Kennelly, A. E., *Paper* (April) 486
Kennelly, A. E., *Discussion* (April) 510, 645
Kenrick, G. W., *Discussion* (April) 645
Ketchum, W. D. and O. E. Charlton, *Paper* (July) 1095
Ketchum, W. D., *Discussion* (July) 1101
Kierstead, F. H., H. L. Rorden, and L. V. Bewley, *Paper* (July) 1161
Kierstead, F. H., *Discussion* (July) 1178
Kilgore, L. A., *Discussion* (January) 240, (April) 714
King, E. B., *Discussion* (October) 1379
Kinnard, I. F. and H. T. Faus, *Paper* (July) 949
Kirke, W. B., *Discussion* (July) 1160
Kirke, W. B., *Paper*, October JOURNAL 855
Knowlton, A. E., *Discussion* (January) 263
Koch, C. J., *Discussion* (July) 1041, 1067
Koontz, J. A., *Discussion* (January) 165
Kouwenhoven, W. B. and Orthello Langworthy, *Paper* (January) 381
Kouwenhoven, W. B. and C. L. Lemmon, *Paper* (July) 952
Kouwenhoven, W. B., *Discussion* (April) 656, 750, (October) 1335, 1640
Krape, R. D., *Discussion* (October) 1270
Krause, C. E., J. Slepian, and R. Tanberg, *Paper* (January) 257
Krause, C. E., J. Slepian, and R. Tanberg, *Paper* (April) 404
Kron, Gabriel, *Paper* (April) 666
Kron, Gabriel, *Discussion* (April) 685


## L


Laffoon, C. M., *Discussion* (January) 213, 225, 238
Langworthy, Orthello and W. B. Kouwenhoven, *Paper* (January) 381
Lawrence, W. H., Grady, C. B., and R. H. Tapscott, *Paper* (October) 1628
Lawson, J. T., *Paper* (October) 1344
LeClair, T. G. and G. M. Armbrust, *Paper* (April) 582
Lee, Carl, *Committee Report* (October) 1740
Lee, Everett S., *Committee Report* (October) 1728
Lee, E. S., *Discussion* (April) 474
Lemmon, C. L. and W. B. Kouwenhoven, *Paper* (July) 952
Lemp, H., *Discussion* (October) 1269
Lennox, J. S., *Discussion* (July) 845
Lennox, T. C., *Discussion* (April) 796
Lenzen, T. L., C. L. Freedman, K. A. Rogers, and F. E. Terman, *Paper* (January) 374
Lewis, William A., *Paper* (January) 99
Lewis, W. W. and C. M. Foust, *Paper* (July) 917
Lewis, W. W., *Discussion* (October) 1501
Lincoln, J. C., *Paper* (April) 735
Lincoln, J. C., *Discussion* (April) 522, 731, 733, 738 (July) 838
Linville, T. M., *Paper* (April) 531
Linville, T. M., *Discussion* (April) 547
Lissman, M. A., *Discussion* (January) 55
Lichtenberg, C., *Discussion* (October) 1241, 1335, 1350, 1356, 1368
Lloyd, M. G., *Discussion* (April) 494
Lloyd, W. L., Jr. and P. Sporn, *Paper* (July) 905
Longley, F. R., *Discussion* (July) 1129, 1151
Loughridge, D. H., *Discussion* (January) 116
Luckeish, M., *Paper* (April) 511
Luckiesh, M., *Discussion* (April) 518
Lyman, W. J., *Paper* (July) 825
Lyman, W. J., *Discussion* (April) 618, (July) 831
Lyons, John M., *Paper* (July) 998
Lyons, J. M., *Discussion* (July) 1010
Lyons, W. V. and H. E. Edgerton, *Paper* (April) 686
Lyons, W. V., *Discussion* (July) 1041


## M


Macferran, Mabel, *Paper* (January) 125
Macferran, Mabel, *Discussion* (January) 80
MacNeill, J. B., *Discussion* (April) 444
Magnusson, C. E., *Paper* (October) 1384
Marti, O. K. and W. Giger, *Paper* (October) 1287
Martin, S., Jr., *Discussion* (April) 738
Marvin, R. H. and J. B. Whitehead, *Paper* (April) 647
Mason, Hobart, *Discussion* (April) 484
Mason, R. C., *Discussion* (April) 732
Maurer, K. L., *Discussion* (October) 1381
Mayo, C. A., *Discussion* (October) 1343, 1349
Maxstadt, F. W., *Discussion* (January) 13
McAuley, P. H., *Discussion* (January) 20
McAuley, P. H. and F. D. Fielder, *Discussion* (October) 1502
McClure, J. B. and I. H. Summers, *Paper* (January) 132
McClure, J. B. and E. M. Hunter, *Discussion* (January) 160
McCurdy, R. G., *Discussion* (April) 806
McCurdy, R. G. and W. J. Williams, *Paper* (October) 1393
McDonald, H. G., *Discussion* (April) 442
McEachron, K. B., *Paper* (April) 410
McEachron, K. B., J. G. Hemstreet, and W. J. Rudge, *Paper* (July) 885
McEachron, K. B., *Discussion* (January) 263, 357, (April) 419, (July) 943, 947, (October) 1443, 1506, 1607
McEachron, K. B., J. G. Hemstreet, and H. P. Seelye, *Paper* (October) 1432
McFarlane, M. L. D., *Discussion* (April) 485
McKeehan, L. W., *Discussion* (April) 509
McMorris, W. A., *Discussion* (July) 1193
Melvin, H. L., *Paper* (January) 21
Melvin, H. L. and A. E. Silver, *Paper* (October) 1491
Melvin, H. L., *Discussion* (January) 28, (April) 617, (July) 939, (October) 1513
Merrill, G. S., *Committee Report* (October) 1735
Miller, K. W., *Discussion* (January) 364
Miller, K. W. and H. Halperin, *Discussion* (October) 1441
Miller, T. G., *Paper* (April) 621
Miller, T. G., *Discussion* (April) 646
Monteith, A. C., *Discussion* (July) 935
Montsinger, V. M., *Paper* (April) 776
Montsinger, V. M., *Discussion* (January) 51, (April) 792, (October) 1512
Montsinger, V. M. and W. M. Dann, *Paper* (October) 1478
Montsinger, V. M. and L. Wetherill, *Paper* (January) 41
Moon, P. H. and A. S. Norcross, *Paper* (April) 755
Moon, P. H., *Discussion* (April) 764
Moore, A. D., *Paper* (January) 359
Moore, A. D., *Discussion* (January) 328, 365
Morgan, K. F. and T. E. Shea, *Paper* (January) 105
Morgan, Theodore H., *Paper* (January) 162
Morgan, T. H., *Discussion* (January) 165
Morrill, W. J., *Discussion* (January) 328
Mottinger, B. T., *Paper* (April) 524
Moulton, J. S., *Discussion* (January) 51
Moultrop, Irving G., *Paper* (January) 198
Muller, G. H., *Discussion* (October) 1315
Murphy, T. H., *Discussion* (October) 1281


## N


Naef, O. and W. E. Gutzwiller, *Paper* (October) 1357
Nehler, J. H., *Discussion* (October) 1254
Neubauer, E. O. and G. A. Rutgers, *Paper* (January) 178
Neubauer, E. O., *Discussion* (January) 186
Neuman, L. J., *Discussion* (January) 67
Newman, S., Jr., *Discussion* (July) 1031
Nickle, C. A. and R. E. Doherty, *Paper*, (April) 700
Nickle, C. A. and C. A. Pierce, *Paper* (January) 338
Nickle, C. A., *Discussion* (January) 351, (April) 714
Norcross, A. S. and P. H. Moon, *Paper* (April) 755
Norcross, A. S., *Discussion* (April) 765
Norinder, Harold, *Discussion* (July) 937
Nyman, Alexander, *Discussion* (January) 80, 313, (April) 646


## O


Oesterreicher, S. I., *Discussion* (July) 1177
Ofverholm, Ivan, *Discussion* (October) 1316
Oliver, E. B., *Discussion* (April) 579
Opsahl, A. M., *Discussion* (April) 418
Osborne, H. S., *Paper* (October) 1549
Osborne, H. S., *Discussion* (January) 186
Oswald, A. A., *Paper* (April) 629


## P


Page, Leigh, *Discussion* (April) 506
Palueff, K. K., *Paper* (July) 1179
Palueff, K. K., *Discussion* (January) 75, (July) 1177, 1194, (October) 1497, 1610

Park, R. H., *Discussion* (April) ..... 683, 698
Parodi, M., *Discussion* (October) ..... 1294, 1316
Peck, E. P., *Discussion* (July) 929, (October) ..... 1379
Peek, F. W., Jr., *Discussion* (January) 79, (July) ..... 933
Peek, F. W., Jr., *Paper* (October) ..... 1456
Peek, F. W., Jr., *Discussion* (October) ..... 1511
Penney, G. W., *Discussion* (January) 336, (April) ..... 573
Peters, J. F., *Discussion* (October) ..... 1507
Peterson, L. C., *Discussion* (October) ..... 1380
Peterson, T. F., *Discussion* (April) ..... 773
Peterson, W. S., *Discussion* (January) ..... 159, 165
Pierce, C. A. and C. A. Nickle, *Paper* (January) ..... 338
Pierce, D. A., *Discussion* (October) ..... 1380
Pierce, R. T., *Discussion* (October) ..... 1336
Pilliod, J. J., *Discussion* (April) ..... 646
Plumb, H. T., *Discussion* (January) ..... 6
Porter, M. C., Jr., *Discussion* (April) ..... 763
Powel, C. A., *Discussion* (April) 721, (July) ..... 831
Powers, R. E., *Discussion* (January) ..... 241
Price, A. L. and Nicholas N. Smeloff, *Paper* (July) ..... 895
Price, A. L. and E. Bell, *Discussion* (July) ..... 948
Prince, D. C., *Discussion* (April) ..... 443
Proebstel, D. W., *Discussion* (January) ..... 40
Proebstel, D. W., *Discussion* (October) ..... 1350
Purcell, T. E. and A. P. Hayward, *Paper* (April) ..... 715

## Q

Quinan, G. E., *Discussion* (October) ..... 1392

## R

Race, H. H., *Discussion* (April) ..... 506
Randall, H. S., *Discussion* (July) ..... 930
Rapp, S., *Discussion* (January) ..... 124
Rathbone, T. C., *Discussion* (April) ..... 721
Rauth, A. W., *Discussion* (January) ..... 211
Rentschler, H. C., *Paper* (April) ..... 576
Rentschler, H. C., *Discussion* (April) ..... 580
Richter, H., *Discussion* (January) ..... 92, 280
Ricker, H. A., J. R. Dunbar, and R. E. Day, *Paper* (October) ..... 1616
Riggs, L. W., *Discussion* (October) ..... 1627
Riordan, J., *Discussion* (October) ..... 1382
Ritter, J. G. and Morris Stone, *Paper* (July) ..... 832
Ritter, J. G., *Discussion* (July) ..... 838
Robertson, B. L., *Discussion* (January) ..... 364
Robertson, B. L., *Discussion* (April) ..... 684
Robinson, P. W., *Discussion* (January) ..... 255
Rodgers, W. H., E. S. Bundy, and A. Van Niekerk, *Paper* (January) ..... 245
Rodgers, W. H. and A. Van Niekerk, *Discussion* (January) ..... 255
Rogers, K. A., F. E. Terman, T. L. Lenzen, and C. L. Freedman, *Paper*, (January) ..... 374
Roper, D. W., *Discussion* (April) 773, (July) ..... 929
Rorden, H. L., L. V. Bewley, and F. H. Kierstead, *Paper* (July) ..... 1161
Rosebrugh, T. R., *Paper* (October) ..... 1419
Rosebrugh, T. R., *Discussion* (October) ..... 1430
Rosenthal, H., *Discussion* (October) ..... 1281
Rossman, A. M., *Paper* (April) ..... 397
Rossman, A. M., *Discussion* (April) ..... 403
Rudge, W. J., K. B. McEachron, and J. G. Hemstreet, *Paper* (July) ..... 885
Rudge, W. J., *Discussion* (July) ..... 932
Rutan, E. J., *Discussion* (October) ..... 1335
Rutgers, G. A. and E. O. Neubauer, *Paper* (January) ..... 178
Ryan, F. M. and R. L. Jones, *Paper* (January) ..... 187
Ryan, F. M., *Discussion* (January) ..... 197

## S

Samuels, M. M., *Discussion* (April) 402, (October) 1417, 1500
Savage, M. A. and W. J. Foster, *Paper* (January) ..... 60
Savant, D. P., *Discussion* (April) ..... 506
Schirmer, A. H., *Discussion* (July) ..... 940
Schneider, M. S., *Discussion* (July) ..... 846
Schou, Theodore, *Discussion* (January) ..... 222
Schurig, O. R., M. F. Gardner, and H. L. Hazen, *Paper* (July) ..... 1102
Schurig, O. R., *Discussion* (July) ..... 996, 1114
Schwenger, C. E., *Paper*, July JOURNAL ..... 519
Scott, C. F., *Discussion* (July) ..... 1114
Seelye, H. P., J. G. Hemstreet, and K. B. McEachron, *Paper* (October) ..... 1432
Seelye, H. P., *Discussion* (October) ..... 1443
Sels, H. K., *Discussion* (July) ..... 939
Shackelton, W. J., *Discussion* (April) ..... 494
Shea, T. E. and K. F. Morgan, *Paper* (January) ..... 105
Shutt, C. C., *Discussion* (April) ..... 646
Silver, A. E. and H. L. Melvin, *Paper* (October) ..... 1491
Silver, A. E., *Discussion* (July) 928, (October) ..... 1512
Sinclair, C. T. and R. M. Stanley, *Paper* (January) ..... 265
Sinclair, C. T., *Discussion* (January) ..... 283
Sittinger, C. J., *Discussion* (July) ..... 829
Skinner, C. E., *Paper* (January) ..... 35
Skipper, E. M. and H. A. Frey, *Paper* (July) ..... 990
Slepian, J., *Paper* (January) ..... 56
Slepian, J., *Paper* (April) ..... 421
Slepian, J., R. Tanberg, and C. E. Krause, *Paper* (January) ..... 257
Slepian, J., R. Tanberg, and C. E. Krause, *Paper* (April) ..... 404
Slepian, Joseph, *Discussion* (January) 263, 364, (April) ..... 445, 452
Sloan, M. S., *Discussion* (October) ..... 1640
Smeloff, Nicholas N. and A. L. Price, *Paper* (July) ..... 895
Smith, B. H., *Discussion* (April) ..... 580
Smith, Burke, *Discussion* (January) ..... 177
Smith, Harold B., *President's Address* (October) ..... 1762
Smith, H. B., *Discussion* (January) ..... 39
Smith, J. J., *Paper* (April) ..... 798
Smith, J. J., *Discussion* (April) ..... 808
Smith, L. G. and A. F. Bang, *Discussion* (April) ..... 614
Smith, V. G., *Discussion* (October) ..... 1430
Smith, W. C., *Discussion* (January) ..... 50
Southgate, R. N., *Discussion* (July) ..... 930
Specht, H. C., *Paper* (July) ..... 1027
Specht, H. C., *Discussion* (July) ..... 852, 1032, 1053, 1066
Spencer, H. H., *Discussion* (July) 989, 1121, (October) 1224, 1239, 1254
Sporn, P. and W. L. Lloyd, Jr., *Paper* (July) ..... 905
Sporn, P. and Ray H. Wolford, *Paper* (January) ..... 288
Sporn, P., *Paper* (October) ..... 1363, 1470
Sporn, P., *Discussion* (January) 224, 314, (April) 401, 418, 442, (July) 948, (October) ..... 1368, 1511
Sprague, S. C., *Discussion* (January) ..... 357
Spraragen, William, *Discussion* (April) ..... 732
Spurck, R. M., *Discussion* (April) ..... 441
Stanley, R. M. and F. C. Hornibrook, *Paper* (January) ..... 201
Stanley, R. M. and C. T. Sinclair, *Paper* (January) ..... 265
Stanley, R. M., *Discussion* (October) ..... 1367
Starr, E. C., *Discussion* (January) ..... 165
Stoller, H. M., *Paper* (October) ..... 1571
Stone, E. C., *Discussion* (April) ..... 443, 616
Stone, Morris and J. G. Ritter, *Paper* (July) ..... 832
Stone, M., *Discussion* (April) ..... 738
Stroup, C. L. and F. E. Andrews, *Paper* (July) ..... 959
Stroup, C. L., *Discussion* (July) ..... 969
Summerhayes, H. R., *Discussion* (January) ..... 212
Summers, I. H. and J. B. McClure, *Paper* (January) ..... 132
Summers, I. H., *Discussion* (January) 160, (April) 546, 698, 819, (July) ..... 1010, 1113, 1150

## T

Tanberg, R., C. E. Krause, and J. Slepian, *Paper* (January) ..... 257
Tanberg, R., C. E. Krause, and J. Slepian, *Paper* (April) ..... 404
Tapscott, R. H., C. B. Grady, and W. H. Lawrence, *Paper* (October) ..... 1628
Tapscott, R. H., *Discussion* (October) ..... 1641
Terman, F. E., T. L. Lenzen, C. L. Freedman, and K. A. Rogers, *Paper* (January) ..... 374
Terman, F. E., *Discussion* (January) ..... 80
Terven, L. A., *Discussion* (July) ..... 930
Thau, W. E., *Committee Report* (October) ..... 1739
Thomas, Percy H., *Paper* (July) ..... 1122
Thomas, P. H., *Discussion* (July) ..... 1127
Thompson, L. W. and P. J. Walton, *Paper* (January) ..... 315
Torok, J. J., *Paper* (July) ..... 866
Torok, J. J. and F. D. Fielder, *Paper* (January) ..... 352
Torok, J. J., *Discussion* (January) 357, (July) 946, (October) ..... 1503
Tracy, G. F. and L. E. A. Kelso, *Paper* (January) ..... 366
Traver, O. C. and L. F. Kennedy, *Paper* (October) ..... 1226
Traver, O. C., *Discussion* (October) ..... 1241
Traver, O. C. and L. F. Kennedy, *Discussion* (October) ..... 1241
Treat, R., *Discussion* (October) ..... 1501
Trickey, P. H. and C. R. Boothby, *Discussion* (July) ..... 1041
Tronconi, G., *Discussion* (October) ..... 1320
Trueblood, H. M., *Discussion* (July) ..... 989
Tykociner, J. T., *Discussion* (January) ..... 357

## U

Urban, F. O., *Discussion* (July) ..... 1113

## V

Van Atta, Ellis and E. L. White, *Paper* (January) ..... 1
Van Atta, E., *Discussion* (January) ..... 8
Van Niekerk, A., W. H. Rodgers, and E. S. Bundy, *Paper* (January) ..... 245
Van Niekerk, A. and W. H. Rodgers, *Discussion* (January) 255
Veinott, C. G. and R. E. Hellmund, *Paper* (July) ..... 1043
Veinott, C. G. and C. R. Boothby, *Discussion* (January) .. 329
Vincent, H. B., *Discussion* (July) ..... 939
Vogel, F. J., *Discussion* (July) ..... 1177, 1192

## W

Wade, E. J., *Discussion* (April) 475, (July) ..... 932
Wagner, C. F., *Paper* (July) ..... 1011
Wagner, C. F., *Discussion* (January) 350, (July) ..... 1026
Waldorf, S. K., *Paper* (April) ..... 657
Waldorf, S. K., *Discussion* (April) ..... 665, 752
Wallau, H. L., *Discussion* (October) ..... 1500
Walters, W. W., *Discussion* (January) ..... 176
Walton, P. J. and L. W. Thompson, *Paper* (January) ..... 315
Walton, P. J., *Discussion* (January) ..... 318
Weber, C. A. M., *Discussion* (July) ..... 856
Wechmann, L. W., *Discussion* (October) ..... 1319
Weed, J. M., *Discussion* (April) ..... 733
Weichsel, H., *Discussion* (January) ..... 330
Wensley, R. J. and W. M. Donovan, *Paper* (October) ..... 1339
Wensley, R. J., *Discussion* (January) ..... 313
West, H. B., *Paper* (July) ..... 839
West, H. B., *Discussion* (July) ..... 847
Wetherill, L. and V. M. Montsinger, *Paper* (January) ..... 41
Wetherill, Lynn, *Discussion* (January) ..... 365
Wheelock, F. O., *Paper* (January) ..... 117
White, E. L. and Ellis Van Atta, *Paper* (January) ..... 1
Whitehead, J. B. and R. H. Marvin, *Paper* (April) ..... 647
Whitehead, J. B., *Discussion* (April) ..... 665, 751, 764, 774
Wieseman, R. W., *Discussion* (January) ..... 221
Wilcox, H. M. and B. P. Baker, *Paper* (April) ..... 431
Wilcox, H. M., *Discussion* (April) ..... 445
Wilcox, J. H., *Discussion* (January) ..... 39
Wildes, Karl L., *Paper* (July) ..... 1086
Wildes, Karl L., *Discussion* (July) ..... 1094
Willey, V. B., *Discussion* (January) ..... 92, 159
Wilkins, Roy, *Paper* (January) ..... 96
Williams, E. C., *Discussion* (April) ..... 401
Williams, W. J. and R. G. McCurdy, *Paper* (October) ..... 1393
Williamson, R. B., *Discussion* (January) ..... 224
Wilson, L. T., *Paper* (October) ..... 1536
Wilson, William and Lloyd Espenschied, *Paper* (July) ..... 1152
Winship, W. W., *Discussion* (April) ..... 579
Withington, Sidney, *Committee Report* (October) ..... 1759
Wolford, Ray H. and Philip Sporn, *Paper*, (January) ..... 288
Wood, H. B., *Discussion* (October) ..... 1368
Wood, R. J. C., *Paper* (January) ..... 9
Wood, R. J. C., *Discussion* (January) ..... 5, 14
Woodrow, H. R., *Committee Report* (October) ..... 1744
Woodrow, H. R., *Discussion* (April) ..... 614
Wright, Sherwin, *Discussion* (April) ..... 714

## Y

Young, R. L., *Discussion* (July) ..... 855

## Z

Zogbaum, F., *Committee Report* (October) ..... 1660

# Radio Interference from Line Insulators

BY ELLIS VAN ATTA[1] and E. L. WHITE[2]

Non-member Associate, A. I. E. E.

*Synopsis.—This paper presents a discussion of the causes of radio interference from insulators on high-voltage equipment. The present methods of eliminating this kind of disturbance are explained, and the question of future design is discussed.*

## Introduction

RADIO broadcasting has brought with it the problem of radio interference. The radio listener is, of course, the one most affected by interference; but the broadcasting companies, the manufacturers of electrical apparatus, and the producers of electrical energy are likewise concerned since the solution of the problem devolves upon them. During the past few years each of these interests has done much to eliminate unnecessary interference; and every kind of equipment used in the supply and consumption of electrical energy has been tried and tested for interfering qualities.

Their experience has shown that radio interference may be classified under five headings, with respect to its origin. These sources are as follows:

1. Consumers' equipment.
2. Low-voltage supply circuits and apparatus (110-550 volts).
3. Intermediate-voltage circuits and equipment (1100-7500 volts).
4. High-voltage equipment (11,000-220,000 volts).
5. Atmospheric disturbances.

Ways have been devised for eliminating practically all radio interference which originates on any of the first three classes of equipment. The last item is obviously beyond human control. The fourth classification includes numerous items of equipment which can be made free from radio interference, and a few other items for which no remedy has been devised as yet. The scope of this paper is limited to the latter group, particularly line insulators of the pin and suspension types.

## General

The principles underlying radio interference are similar to those of spark telegraphy and carrier current telephony. In brief, a spark occurring on electrical equipment of any kind sets up a wave train which produces damped oscillations at a multitude of frequencies. The predominating frequencies are the resonant frequencies of the associated lines and equipment, and their harmonics, including those in the radio broadcasting band.

Since the electrical constants which determine the above frequencies are distributed, and several kinds of equipment may be concerned, the resonant peaks are usually broad and overlapping. Consequently a broadcast receiver which has radio interference is usually affected over the entire broadcasting range, with occasional points of greater disturbance.

The extreme sensitiveness of modern receivers, and the use of a-c. supply, make them very susceptible to radio interference. The comparatively small amounts of energy involved in the electrical discharges described later are therefore sufficient to produce a great amount of disturbance in broadcast receivers, particularly when the discharges occur along high-voltage lines.

The distinction between corona and brush discharge should be kept in mind when radio interference from line insulators is considered. Corona discharge usually occurs at lower voltages than brush discharge, and appears as a bluish glow when viewed in a dark room. Brush discharge occurs after corona discharge, and takes the form of fine white streamers. This condition is usually considered as another form of corona discharge, but will be classed separately in this case because of the different interfering characteristics of the two discharges. In a broadcast receiver, corona discharge produces a soft, hissing sound which is not ordinarily objectionable. Brush discharge, however, produces a crackling, frying noise which is very annoying.

## Pin-Type Insulators

Corona and brush discharges may occur on high-voltage lines in any or all of the following ways:

1. Between metallic surfaces.
2. Between insulating surfaces.
3. Between metallic surfaces and insulating surfaces.

To entirely free a line of radio interference, all discharges must be stopped. In order to accomplish this purpose, all hardware must be tight; adjacent pieces of hardware must either have sufficient separation to prevent discharges, or must be bonded together; conductors and tie-wires must make perfect electrical contact with the tops of the insulators; and the pins must make perfect electrical contact with the entire surface of the thread in the pin holes. On lines using pin-type insulators these requirements can be met with the exception of the last two. Conductors, tie-wires, and pins do not make good electrical contact with the surfaces of the insulators, and every insulator is therefore a potential source of radio interference.

For the purpose of this discussion, a pin-type insulator

1. Radio Engineer, Pacific Power & Light Company, Walla Walla, Wash.

2. Communication Engineer, Puget Sound Power & Light Company, Seattle, Wash.

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29-132

will be considered as the dielectric of a condenser, with the conductor and tie wire acting as one plate and the pin acting as the other. When potential is applied to the plates, a charging current, the magnitude of which is determined by the reactance of the condenser and the applied voltage, will flow into the condenser. Since the reactance of a condenser is a function of its electrostatic capacity and the frequency of the applied voltage, it follows that the charging current is affected by the three factors, voltage, frequency, and capacity.

Consider a 66-kv. pin-type insulator, whose electrostatic capacity is approximately 10 $\mu\mu$f. A charging current of 0.14 milliamperes will flow into it when used on a line operated at a voltage of 38.1 kv. to ground and a frequency of 60 cycles per second. If the conductor, tie-wire, and pin all made perfect electrical contact with the insulating surfaces, this charging current could easily flow into the insulator. Unfortunately, resistance is offered to the flow of charging current by insufficient contact between the wires, pins, and insulating surfaces. Due to the fact that the dielectric strength of air is lower than that of the insulator material, the potential differences at these points of poor contact are sufficient to ionize the adjacent air, with resultant corona and brush discharges.

The problem of radio interference from pin-type insulators is thus reduced to the matter of overcoming resistance to the flow of charging current into the insulator.

Since the magnitude of the charging current into the insulator is determined by the voltage and the frequency applied, and by the electrostatic capacity of the insulator, a reduction in any of these factors will decrease the charging current. In practise, the voltage and frequency are fixed, but the capacity can be reduced by overinsulating the lines. This method has been tried with only partial success, particularly on lines operated at 55 and 66 kv. If larger pin-type insulators are used, the problem of insufficient contact between wire, pin, and insulator is still present.

The best solution of the problem appears to be some method of insuring good contact between the conductors, tie-wires, and insulating surfaces. On existing pin-type insulators, this result can probably be secured by treating the insulator heads and pin-holes in some manner which will eliminate the poor contact between the wires, pins, and insulators.

Metallic paints have been tried, without success, because such paints form a coating of metal particles suspended in varnish and do not offer a good conducting surface. Metal disks, attached to the conductors above the insulators, have proved partially successful, due to the reduction in current density where the conductors and tie-wires contact the insulators. Tests have shown that the same result may be accomplished by looping the tie-wire to form a ring several inches in diameter over the head of the insulator. Tests have also shown that discharges to the heads of insulators are materially reduced by the addition of several extra turns of tie-wire in the insulator grooves. Metal gauze, placed in the tie-wire groove, has proved effective in some cases, and seems to be the best solution of the problem at the present time. Experiments are still being conducted, however, and it is hoped that a compound can be found which will fill in the air spaces between wires and insulators, will be unaffected by weather conditions, and will not be expensive to apply.

The problem of new pin-type insulators is being attacked in several ways. Some manufacturers employ a metal cap cemented on the head of a standard insulator. Another one uses solder-impregnated gauze in the tie-wire groove. Other insulators have layers of metal applied to the heads and the wire grooves. These metals are of various kinds and varying thicknesses. Most of them are too thin to be practical but all have a good contact surface. Still another insulator is treated in the wire grooves and the pin-hole with a special glaze. This last insulator proved to be the best of all when subjected to rated voltage in a comparative test.

Obviously, the use of metal-coated heads and metal caps on pin-type insulators will result in an increase in the electrostatic capacity of such insulators. The charging current will be increased and consequently the current density at the surface of the pin-hole will be increased. Tests have shown that this point is a very important one. It is therefore imperative that the pin-hole be treated in some manner to insure good contact between the pin and the insulator. Metal threads, cemented into the insulator, are being used in most cases, while one insulator is treated with a special glaze, as mentioned before.

At the beginning of this discussion it was stated that corona and brush discharges may occur between insulating surfaces such as the petticoats of pin-type insulators. The presence of such discharges is an indication of faulty design or too high an applied voltage. The remedy is obvious in either case.

## Suspension Insulators

Suspension insulators can be classified under three general types, cap-and-pin, link, and spider. The cap-and-pin type, as the name implies, consists of a porcelain disk with a cap cemented to one side, and a pin to the other. Two kinds of hardware are used for attaching adjacent units, the clevis type and the ball-and-socket type. The link type of insulator consists of porcelain disks connected together by loops of metal, so that the porcelain is in compression. The spider type consists of extra-heavy porcelain disks, with the connecting hardware imbedded in both sides in the form of a spider, and secured by a metal alloy instead of cement.

Until recently, suspension insulators as a group have been considered free from radio interference. The potential impressed upon individual disks of a string, as they are used in practise, is comparatively low. On

55-kv. lines, using three units per phase wire, the maximum duty is about 11,000 volts. For 110-kv. lines using six or seven units per string, the maximum potential per unit is 14,000 volts. On 220-kv. lines, using fourteen units per string, the maximum voltage per unit is 23,000 volts without grading rings or shields, and about 15,000 volts with such devices.

When individual ball-and-socket-type insulators are tested in a dark room corona discharge appears at the cap and at the pin when potentials as low as 18,000 volts are applied. Brush discharge occurs at voltages as low as 26,000. This type of insulator, therefore, should not cause interference under ordinary conditions.

Corona and brush discharges also appear on clevis-type insulators at the above voltages when the cotter key is removed from the clevis bolt. With the cotter key in place, and the pointed ends turned upward, brush discharges occur between the points of the key and the innermost petticoat at potentials as low as 11,000 volts. The cotter keys on clevis-type insulators which have been in service on 110-kv. lines for only short periods, show unmistakable evidence of brush discharge, not only from the pointed ends but from the round ends as well. Cotter keys on the units next to the line are affected most, but the keys on other units also show signs of discharge. Obviously the cotter key is at fault on the clevis-type of insulator, and ways of eliminating this source of interference will be taken up later.

Insulators of the link type are even more liable to cause interference than clevis-type insulators. In the older models, no attempt is made to obtain good contact between the links and the porcelain, and brush discharges take place at potentials as low as 2000 volts per unit. When weights are used to simulate line loading, the brush-discharge potential rises to 4000 volts.

The newer models of link-type insulators employ lead shims, soft copper links, etc., in order to get better contact between the metal and the porcelain. Without loading, radio interference starts at 6000 volts per unit. Under 340-lb. tension, interference does not begin until 14,000 volts are impressed. Since the potential across the line unit of a string of six link-type insulators used on a 110-kv. line is about 20,000 volts, interference will be present under those or similar conditions.

On the spider-type of insulator, corona discharge does not start until potentials of 21,000 volts are applied across individual disks. Brush discharge occurs at 26,000 volts. Both discharge points are higher than the corresponding points for either cap-and-pin or link-type insulators, a fact which is accounted for by the heavy mass of porcelain used in this type of insulator, and the absence of sharp points or rough edges at points of high electrostatic flux density.

Both the spider type and the ball-and-socket type of insulator are designed to have certain values of mechanical strength, flashover voltage, and leakage distance, rather than high values of corona or brush discharge voltage. Fortunately these discharge points are higher than the usual operating voltages, and the insulators are satisfactory from the point of view of radio interference.

Clevis-type insulators are also satisfactory when the cotter key is properly designed. One manufacturer has designed a clevis-type insulator in which the cap is recessed to overlap the cotter key and prevent it from turning. One of the large power companies is replacing the regular cotter key with a circular key, so designed that the ends are concealed inside the clevis bolt when in place. Comparative tests show that clevis-type insulators equipped with circular cotter keys are on a par with ball-and-socket insulators.

The link type of insulator is satisfactory if sufficient loading is applied to keep the porcelain and the links in intimate contact, and the voltage per unit does not exceed 14,000 volts. Much of the discussion pertaining to pin-type insulators is also applicable to link-type insulators. The problems involved are similar and can probably be solved by using similar methods.

Many lines using suspension insulators also use arcing horns to protect the insulator disks during flashover and to prevent burning of the conductor. Grading rings, shields, etc., also accomplish this purpose and change the potential distribution along the insulator string, so that the maximum voltage per unit is very much reduced. Tests show that the arcing horn is the only one of the above devices which ordinarily causes radio interference. Brush discharges take place at the ends of the horns, which produce an interference similar in sound to that of pin-type insulators. These discharges can be eliminated in the present design of arcing horn by adding a small metal ball to the end of the horn. The surface area is thus increased, and sharp points are avoided.

### Other Sources of Interference

Pin-type and suspension insulators behave alike when subjected to moisture and dirt. The presence of either of these factors will usually increase the amount of interference, particularly on pin-type insulators. Tests in the laboratory show differences of 50 per cent or more in interference caused by insulators when dirty and the same insulators when cleaned. Moisture has a similar effect as shown by the curves of Fig. 1 where the noise level is three times as high for a line with insulators wet as it is for the same line when dry.

Defective, cracked, and broken insulators of either kind set up a disturbance which often affects radio receiving sets several miles away. Small projections on the surface of the porcelain sometimes create interference, especially when they are located in a heavy electrostatic field. Discharges frequently occur from the ends of tie-wires which are not bent closely enough to the conductor.

The remedy in each case is clear. Defective insulators must be replaced. Dirty insulators can be cleaned.

Wet-weather conditions are sometimes minimized by overinsulation, and tie-wire ends should always be bent back as closely to the conductor as possible. Proper inspection and maintenance are therefore essential to the elimination of radio interference from high-voltage lines.

## Curves

The curves in Fig. 1 are intended to show the effect of attenuation on radio interference which is being propagated along a transmission line, to give an idea of

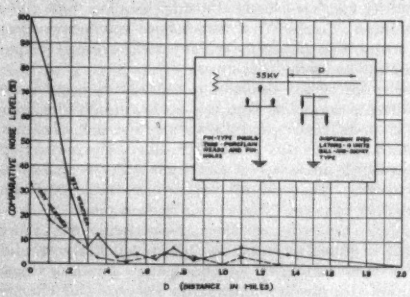


Fig. 1—Attenuation of Interference Along a Transmission Line

the distances to which interference will travel before it is reduced to a non-interfering level, and to show the effect of overinsulation. The observations were made on a 55-kv. line, one mile of which is constructed with pin-type insulators, and the remainder, about 20 miles, with ball-and-socket type suspension insulators.

The origin of the curves is taken at the point where the two types of construction join, and the abscissas are measured from that point along the section using suspension insulators. The ordinates are measured by means of a milliameter coupled to the output circuit of a superheterodyne receiver through a transformer. Although the readings of this meter have no absolute value, their significance becomes apparent when it is known that signals from a 5000-watt radio broadcasting station 75 miles away could not be heard with noise levels of ten per cent or more. At ten per cent the signals were about equal in intensity to the interfering noise. At five per cent the signals were stronger than the interference. With a zero-reading on the meter the interference was not objectionable, although it could still be heard along with the signals from the broadcasting station.

The readings for the upper curve were taken during a rain-storm. The lower curve was taken about thirty minutes after the storm ceased. In the case of the upper curve, a slight amount of interference could still be heard at a distance of four miles, which was attributed to the effect of rain on the suspension insulators.

The curves of Fig. 2 are similar to those of Fig. 1. These curves show the attenuation of radio interference at right-angles to a 55-kv. line for two conditions, (1) with no distribution circuits to radiate the disturbance, and (2) with distribution circuits paralleling the 55-kv. line and connected to other circuits at right-angles to the 55-kv. line. The latter condition is one which occurs frequently in cities and towns, but no way of overcoming it has been devised yet. The most effective method of minimizing this kind of radio interference is the elimination of the interference at its source. In many cases, however, the cheapest remedy for the situation may be the use of radio-frequency choke coils inserted in the distribution circuits where they leave the high-voltage line. Standard lightning-arrester choke coils have been tried, but were not successful because their inductance is too low. One company is successfully preventing radio interference on high-tension lines from following its telephone circuits by inserting choke coils in the telephone leads at points where they leave the high-voltage lines. Another company is experimenting with carrier current choke coils, and still another one is trying specially constructed choke coils of about 0.5 millihenry inductance. No reports are available on these tests, however.

## Conclusions

Radio interference is one of the problems which must be considered in future insulator designs. On pin-type

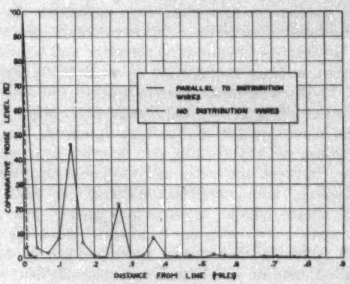


Fig. 2—Attenuation of Interference Perpendicular to a Transmission Line

insulators, corona and brush discharges can be eliminated by proper design of the petticoats, by using metal-coated or metal-capped heads, by using metallic threads in the pin-holes, and in some cases, by using a special glaze on the head and in the pin-hole. Suspension insulators can be improved by changing the design of the cotter key in the clevis type, by eliminating discharges between the links and the porcelain in the link type, and by redesigning all arcing horns to eliminate discharges at the ends. The corona-discharge point on cap-and-pin insulators can be raised by proper

design of hardware, by elimination of sharp points, by insuring adequate clearances at the cap and the pin, and by making the shape of the porcelain conform more closely to the lines of electrostatic flux.

Existing pin-type insulators present the most difficult problem of all. Copper mesh placed under the tie-wires has proved fairly successful in eliminating discharges at the head of the insulator, but experiments are still being made to discover a process which can be easily applied, is not too expensive, and which will stand up under operating conditions during the life of the insulator.

Radio interference from line insulators will always be a problem, because corona and brush discharges occur so readily on high-voltage equipment. Much work has been done to minimize this type of disturbance, and more is contemplated. Adequate maintenance and good construction are essential to the solution of the problem, but the greatest needs are for improved designs and continued experimenting.

## Discussion

**R. J. C. Wood:** At Redondo Beach we have a number of insulators hanging up under tests where they may become as dirty as possible with ocean spray and fog. They are not cleaned at all; they are left to accumulate all the spray and dirt that will come. Several times we have tried to detect radio interference from that lot of insulators. There are 16 strings of insulators, of which 3 are post assemblies and the rest are suspension, including 2 dead ends, all under test at 150 kv. to ground. We have never been able to find any radio interference although the insulators are visibly sparking over underneath around the pin of each when the air is damp. So it seems that there might be something more involved than just the design of the insulator string itself; possibly the attachment of a long line with its inherent capacity is necessary to form an oscillating circuit which would give rise to radio interference.

**J. P. Jollyman:** The experience in respect to radio interference of the several companies operating transmission systems on the Pacific Coast seems to vary considerably. Apparently the greatest difficulty exists in the regions having the heaviest rainfall and hence the cleanest insulators. Less difficulty seems to be experienced in the regions having less rain and a longer dry but partly foggy season. Under these conditions dirt accumulates along an overstressed leakage path and becomes so firmly attached from the effect of leakage currents that a conducting path is built up which is not removed by rain. This conducting path reduces the arcing at overstressed points and apparently reduces the radio interference.

**H. N. Kalb:** In connection with the bushing that Mr. Jollyman spoke of, we have had the same trouble with arcing between the conductor and the inner portion of the bushing surface and we have installed a screen, using either copper screen or galvanized-iron screen wire, attaching it to the upper part of the conductor, the screen being allowed to spread out and make contact with the inner surface of the bushing throughout the entire length.

With pin-type insulators, we have a great deal of that same trouble that was described in Mr. Van Atta's paper. We use both three-piece and four-piece pin-type insulators, and have found nothing as yet that would clear up the interference entirely. We have tried, in an experimental way, using both the copper gauze that was mentioned in the paper, and screen and different materials of that kind.

So far as the suspension insulators are concerned, we have made some tests on them and find very little interference, if any. I wish to emphasize the word "if" for this reason: We have lines with different sized conductors on which we have found that the noise was of different volume on the different lines. On a 110-kv. line with 7 units in suspension, a line having 0000 aluminum wire was much more noisy than a line of the same voltage with a conductor of 397,530-cir. mil aluminum. Also we arranged for a field test by connecting one of those lines to one unit in the generating plant, starting in with zero voltage and building it up and then lowering it, and at the same time taking a reading of the noise level. We found that the line which ordinarily operated at 120,000 volts still had points of visible corona, at 100,000 volts. Those were few and scattered, of course, but appeared even on the arcing horns. We still had noise at a voltage as low as 70,000 volts. Contrasting with that, we completed a line to operate at 70,000 volts, which had 397,500-cir. mil aluminum conductors, and from the radio interference standpoint, that is probably the most quiet line on which we have ever made any tests.

I simply wish to make that statement because probably a great deal of our trouble is due not to the insulators alone, but to the size of conductors and the voltage impressed on them.

**Bradley Cozzens:** I was very much interested in the fact that the authors brought out the problem of voltage distribution on insulator strings. With dry insulators, the values which were given are undoubtedly correct. However, on the Pacific Coast, we always find fog, and with the fog comes a wetting of the insulators, and a very marked change in the voltage distribution from that which is found in dry weather. A good example of this changed distribution is the 9- or 10-unit string on 110,000-volt lines, in which two units of the string may be carrying 90 per cent of the applied voltage. Thus there is in excess of 30 kv. on each of the overstressed units. This is made evident by sparking over the under side, and occasionally over the top surfaces of these units. These static sparks develop at times into an arc discharge. At this time the current is limited only by the wet resistance of that portion of the string which is not partially short-circuited by the arcs.

I should like to ask Mr. Van Atta if he has experienced this arc condition, and if so, how serious it is from a radio interference standpoint.

I should like to stress this point further, that other voltage distributions than those normally assumed for dry conditions practically always exist on wet insulator strings, and should be borne in mind when considering interference as caused by line insulators.

**F. B. Doolittle:** I was interested to note that Mr. Jollyman brought up the subject of radio interference caused by bushings because we have experienced trouble from 66-kv. transformer, oil-switch, and wall-type bushings. These particular bushings consist primarily of a central porcelain tube, the 1-in. bore of which is of considerably larger diameter than the bare copper conductor which passes through it. Consequently it was necessary for the charging current of the porcelain to jump the air-gap between the conductor and the porcelain. This sparking not only caused radio interference but also broke down the air and caused the formation of cupric nitrate on the copper lead. The cupric nitrate was formed in such large quantities in some of the oil-switch bushings that it dropped to the bottom of the switch tanks and ate holes through them, causing oil leaks which led to the discovery of the trouble.

We found that a very simple remedy for this trouble is to insert a split brass sleeve the full length of the hole through the bushing which makes close contact with the porcelain. The sleeve consists of 24-gage brass tubing of slightly larger diameter than the bore of the bushing, the tubing being split lengthwise so that it springs tightly against the porcelain when inserted in the bore. One end of the sleeve is, of course, bonded to the conductor.

In regard to radio interference from line insulators, the Southern California Edison Company is particularly fortunate in that most of the lines are considerably over-insulated. This over-insulation is necessary because of the accumulation of dirt on the insulators during the dry season which would otherwise cause flashovers in fog. Five suspension units are used on most of our 66-kv. lines, which results in such a low voltage stress per unit that no radio interference is produced under ordinary conditions.

We operate a few miles of 33-kv. line on pin-type insulators and have looked for radio interference on them but so far have found none traceable to the insulators. This seems surprising in view of the possibilities for interference with this type of construction as pointed out in the foregoing paper.

Our 11-kv. and 16-kv. lines are in general free from radio interference, I believe largely due to the fact that the insulators used are rated at considerably higher voltage than that on which they are operated.

**H. T. Plumb:** I was interested to hear the opinion that only clean insulators give radio interference, and that western lines do not interfere. The line of which the gentleman spoke is unknown but there is a line at about 110 kv. between here and San Diego which does interfere. I can vouch for the fact that there is so

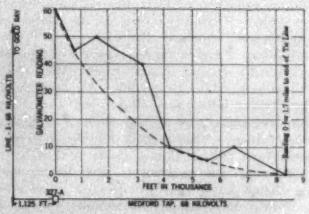


FIG. 1—RADIO INTERFERENCE READINGS

Taken along the Medford Tap of Line 19, 12-21-28, beginning at Sw. 327-A, using radio frequency galvanometer with radio test set. Lapp insulators, 66 kv. No. 6173 had been previously re-tied beyond O. C. B. No. 327-A, using copper web under the tie wire. The web reduced the readings to zero within a distance of 8300 ft. from the switch, and readings remained 0 for 1.7 mile to end of single pole line at junction with 2-pole line insulated 130 kv. and operating at 68 kv.

Started taking readings at Sw. 327-A at 9:20 A. M., arrived at end of 130 kv. line at 10:45 a. m.

much noise from that line, not only radio noise but real sound noise, that it once woke me up in the middle of the night. The line voltage may have increased in the night, or sea fog may have deposited on the insulators so that there was actual arcing between petticoats. An engineer who lives in San Diego and whose home this line passes stated that it causes excessive interference. He has purchased a $600 radio instrument which is practically worthless. He lives within three blocks of that line.

**R. S. Daniels:** A serious situation at Medford, Oregon, has been remedied by the use of heavy copper braid on pin-type insulators used on 66-kv. wood-pole lines. Seven miles of line have been retied, using not gauze, but a pad of heavy copper braid, No. 4 B & S gage, placed under the tie wire.

Fig. 1 shows relative attenuation along the 3¼-mi. section of line where the braid was used.

We have found that the disturbance originating from discharges between the tie wire and the procelain is greatly affected by (1) rain or snow, (2) clouds, (3) temperature of the air, (4) time of day. The first two are probably due to humidity. Noise is at its worst in hot weather and least in either rainy or cloudy weather.

Fig. 2 shows relative change in noise level throughout the day between the hours of 7:00 a. m. and 10:00 p. m., which shows much more disturbance during clear weather than cloudy. The copper braid as used at Medford for over a year has reduced the noise level to a point which gives practically no interference to radio sets which are near the 66-kv. wires, or near distribution lines, part of which have been carried on the same poles with the high-tension wires.

Fig. 3 shows the application of the braided pad.

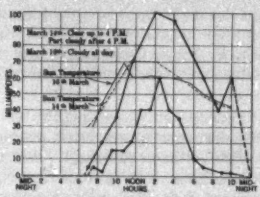


FIG. 2—RADIO GALVANOMETER READINGS AT MEDFORD SUBSTATION

**R. L. Binder:** (communicated after adjournment) The authors have undoubtedly grasped the essential features of the cause of static on insulators and bushings, but they do not give any information on methods for overcoming the difficulty nor have they mentioned other important considerations in connection with brush and corona discharge on high-tension lines. Not only do corona and brush discharge affect radio transmission but by the generation of ozone, they cause rapid deterioration of insulation and also a high rate of oxidation of conductors.

As far back as 1912, the writer was brought into contact with this condition on what were then considered high-voltage transmission lines and was able to overcome some of the difficulties by cementing metal foil to various parts of high-tension insulators. Such methods, however, did not afford permanent means for overcoming the trouble, because with the breakdown of the cementing medium, part of the foil would separate and that which remained attached to the insulator would increase the static discharge.

FIG. 3

We have called attention to the use of sprayed molten metal coatings on various parts of petticoat insulators and insulator bushings and in every instance where such coatings have been used, entirely satisfactory results have been obtained.

The accompanying report shows exhaustive tests which were made on porcelain bushings.

Sprayed molten metal coatings of lead, tin, zinc, or copper, or combinations of them, have been used with equal success. Where it is desired to place them on the glazed parts of insulators, such surfaces are first sand-blasted and a permanent bond of the sprayed molten metal is readily secured. On clean unglazed surfaces, no sand-blasting is necessary.

The cost of applying the coating is entirely within commercial limits.

*Tests on Porcelain Bushings.* A series of tests was made to determine a satisfactory method for decreasing the static leakage on some bushings used in circuit breakers. These bushings illustrated in Fig. 4 were used on 2000-ampere circuit breakers. They were normally subjected to a stress of 7700 volts to ground. In the test at 60 cycles, voltage was applied across the brass collar of the bushing and the bus bar through the bushing. The voltage was increased gradually from zero to a value at which static appeared and sometimes to flashover.

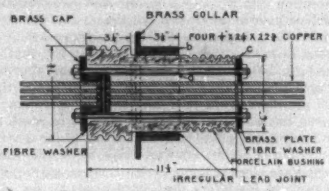


FIG. 4—BUSHING AS RECEIVED FROM FACTORY

The first appearance of static occurred between the through-bolt and the inside cylindrical surface. See (a) on Fig. 4. As the air gradually became ionized the static spread and flowed very violently between the main copper conductor and the inside cylindrical surface. When the air within the bushing became entirely ionized and the voltage had increased, static occurred about the alloy fill. With increased voltage the static at (a) became violent and gradually crept over the porcelain causing a breakdown at 52,000 volts.

*Voltages at which static occurred.*

| | |
|---|---|
| Audible | 8000 to 9000 |
| Visible inside | 13,500 volts |
| Visible outside | 19,000 volts |
| Flashed over | 52,000 volts |

*Methods of Eliminating Static.* 1. Filled bushing with steel wool and poured a ring of compound consisting of beeswax and rosin over the visible ends of the metal alloy between bushing and sleeve.

Results—Satisfactory if wool is properly packed.

2. Filled bushing with beeswax and rosin.

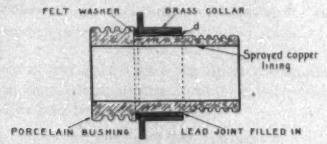


FIG. 5—BUSHING WITH SPRAYED COPPER LINING

Results—Static eliminated until 12,000 volts was reached. Then it appeared on outside from porcelain to metal alloy.

3. Bushing filled with compound. Metal alloy covered with compound.

Results—Very satisfactory. No static at 25,000 volts. Not considered because flexibility of bushing was destroyed.

4. Painted inside of bushing with aluminum paint. Alloy covered with porcelain.

Results—Static at 15,000 volts. Not considered because aluminum paint flaked off.

5. Sheet-metal tube placed inside of bushing and alloy covered with compound.

Results—Very satisfactory. Not considered because method was thought undesirable.

6. Brass through-bolts removed and bakelite substituted, no compound used.

Results—Static occurred at 9000 to 10,000 volts.

7. Inside of bushing coated with 0.006 in. of sprayed molten copper. Alloy covered with compound.

Results—Static occurred at 16,000 volts. Flash point reduced to 46,000 volts. This method adopted to eliminate the static on these bushings.

The inside of the bushing was sand blasted and cleaned. Next a coat of lead 0.004 in. thick was put on to provide a proper base. Over the lead a coat of copper 0.006 in. thick was sprayed. This metal coating is firm and will not flake or peel off. The work was done by the Metals Coating Company of America, at Philadelphia.

Since discovering static on the FH9 bushings, tests were made with a compact superheterodyne radio set on various other types of bushings and the results indicated various amounts of static on practically all of them. This radio set is moved slowly along the compartment doors and the static is picked up even though very slight.

Further tests were made on an untreated bushing and on treated bushings. The results of these tests were as follows:

| Specimen tested | Voltages | | | Remarks |
|---|---|---|---|---|
| | Audible | Visible | Flashover | |
| (Fig. 4) Untreated | 8,000 | 11,000 | 52,500 | Discharge first became visible at *a* between the bus copper and porcelain bushings. This discharge gradually increased until flashover occurred from *b* to *c*. |
| (Fig. 5) Inside of porcelain bushing coated with sprayed molten lead 0.004 in. thick. Covered with sprayed molten copper 0.006 in. thick. With irregular lead seal. | 8,500 | 14,000 | | Visible discharge took place from irregular lead seal to porcelain bushing at *d*. No discharge audible or visible inside bushing. |
| (Fig. 5) Inside of porcelain bushing coated with sprayed molten lead 0.004 in. thick. Covered with sprayed molten copper 0.006 in. thick. With lead seal smoothed off. | 10,000 | 17,000 | | Visible discharge at *d*. No discharge inside porcelain bushing. |
| (Fig. 6) Inside of porcelain bushing coated with sprayed molten lead 0.006 in. thick. Covered with sprayed molten copper 0.006 in. thick. Specimen No. 1, end of lead seal covered with insulating compound. | 16,500 | 29,000 | | A very slight visible discharge occurred at *e* between collar and porcelain bushing. |
| (Fig. 6) Inside of porcelain bushing coated with sprayed molten lead 0.004 in. thick. Covered with sprayed molten copper 0.006 in. thick. Specimen No. 2, with end of lead seal covered with insulating compound. | 15,000 | 29,000 | 45,700 | A greater visible discharge occurred at *c* and gradually increased until flashover occurred from *c* to *f*, *i. e.*, from collar to end plate. |

*Conclusions.* The results of the tests brought out the following points:

1. Application of sprayed molten metal coatings on the inside of the porcelain bushings transfers the leakage from the inside to the outside of the insulator. It also slightly increases the value at which leakage becomes audible, but materially increases the stress on the porcelain bushing.

2. Smoothing off the lead seal between the bronze collar and the porcelain bushing on one of the sprayed types definitely increases the resistance to audible leakage.

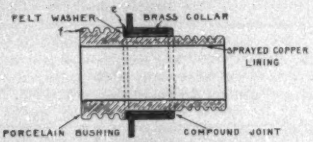


FIG. 6—BUSHING WITH SPRAYED COPPER LINING AND COMPOUND-FILLED JOINT

3. Removing some of the lead seal, and replacing it with an insulating compound, and smoothing it over the entire end of the brass collar, appreciably increases the resistance to audible leakage and transfers the discharge to the large end of the brass collar. Under these conditions, audible leakage occurs at a minimum voltage of 15,000 volts, which is about twice the normal voltage stress of 7700 volts to which these bushings are subjected.

4. The greatest safety factor is therefore obtained by coating the inside of the bushing with sprayed molten metal, and finishing off the end of the lead seal with insulating compound in such a manner as to completely cover the small end of the brass collar.

**E. Van Atta:** Regarding the voltage on strings of insulators on 220,000 volts, I gave only the maximum voltages. The paper takes care of that; that was given as 23,000 volts without grading rings, but with these it is down to 15,000 volts.

Now regarding dirt and moisture on insulators: There is a question as to whether the distribution of voltage over the insulators isn't changed by these factors. It certainly is. And, as a matter of fact, all of our experience has shown that during wet weather conditions of reception are very greatly improved along high-voltage lines.

In connection with whether a certain line gives interference or not, I think we have to take into consideration the location of that particular line with respect to the broadcasting stations to which you happen to be listening. We know that if a station has a signal strength 100 or 1000 times greater than the disturbing field strength that we are going to get reception and there isn't any radio interference on that line *in that particular location.* If we moved the same line out where we had to reach out 1000 mi. to get reception, it would be as bad as any of the others.

The condition of corona on wires may have something to do with interference along a line. In fact, there are a great many things outside of insulators that have a lot to do with radio interference.

Regarding bushing trouble, we have had a great deal of that. In one instance, on a 66,000-volt bushing, we filled the bushing with compound. In other instances on 25,000-volt transformers with hollow bushings, we have simply wrapped the wire running through the bushing with 10 or 12 thicknesses of Empire tape and this has taken care of the trouble and relieved the radio interference. Incidentally, that same idea may be worth something on pin-type insulators.

# Spray and Fog Tests on 220-Kv. Insulators

BY R. J. C. WOOD[1]

Associate, A. I. E. E.

***Synopsis.***—*To determine insulation for an outdoor 220-kv. station on the coast subject to ocean spray, an insulator test rack was installed at Redondo, California.*

*Ten types of insulator, including widely different designs, were tested continuously for two years and a half at 150 kv. to ground. Comparative results were obtained by adding or subtracting units in suspension strings until an equality against arc-over was approximated. Ninety arc-overs occurred.*

*The surface leakage resistance was found to be a fair index of the resistance to arc-over under salt spray conditions. The shape of the insulator made no difference as long as the total surface resistance of the string remained the same.*

*The surface resistance is that calculated upon the assumption of a uniform conducting coating upon all the exposed surface of the insulator and is the line integral of distance divided by circumference along the shortest surface path from cap to pin.*

*Accidental differences of conditions are such that one insulator string would not consistently arc-over in preference to another unless its surface resistance were less than 80 per cent of the other.*

*Suspension strings having a total surface resistance of 11.0, using inch units, were found satisfactory for a steady 150 kv. to ground under the conditions at Redondo.*

*A spray method of cleaning insulators while energized was devised.*

## Introduction

In the latter part of 1926 it was seen that it would soon become necessary to decide upon the kind of insulation to be used in the Southern California Edison Company's 220-kv. outdoor station that was to be built at Long Beach, on the coast south of Los Angeles.

A test rack was therefore set up at Redondo on the coast, the location being chosen as one of the most subject to ocean spray and fog upon the system, and where considerable insulator trouble on both 66-kv. and 16-kv. lines had been experienced.

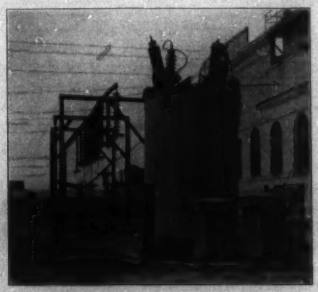

Fig. 1—Test Rack, Energizing Transformer, and Two Small Transformers Used as Reactors. Looking North

## Climatic Conditions

The storm winds are westerly and drive the spray from the ocean surf directly into the test rack, the accumulation of salt upon the insulators having been such at times that during the heat of the day small crystals of salt have been observed scattered all over the surface of the porcelain. At night the deposition of moisture upon the insulators is frequently sufficient so that they drip and the sandy soil underneath is all pock marked from the dropping water. In addition to the salt deposit there is a certain amount of dust and sufficient soot to blacken any rag used for cleaning.

The time of year during which arc-overs are most prevalent is from March or April until the first rains of the season, which may come in September or October.

## Description of Apparatus

The rack illustrated in Figs. 1, and 2, was situated about 500 ft. from the ocean front. The pipe bus was energized to 150 kv. to ground.

Electrical connections were as in Fig. 3, the two 150-kv-a. banks of transformers in series with the 4500-kv-a. transformer being used as reactors to limit the short-circuit current to 10 amperes over an insulator and 100 amperes on the station bus.

Fig. 2—Test Rack. Looking Southwest

To indicate which of the insulator strings had arced-over, a one-ampere enclosed fuse was connected between each insulator string and the bus. These fuses were further protected against weather and corona by short lengths of one-inch pipe and may be seen in Figs. 1 and 2.

The types of insulator tested are shown in Fig. 4;

1. Research Engineer, Southern California Edison Co., Los Angeles, Calif.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.*



29-139

some of their physical constants in Table I. The quantity called "Surface Resistance" is not any measured resistance, but is the calculated surface leakage resistance from cap to pin of a single insulator unit, assuming the exposed porcelain surface to be uniformly coated with a conducting layer. Should the conducting layer have a resistance of one megohm per

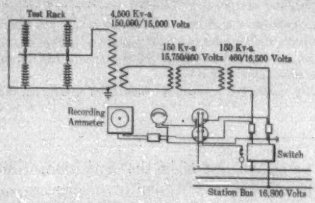


FIG. 3—DIAGRAM OF CONNECTIONS BETWEEN STATION BUS AND TEST RACK

square inch, then the figures of Table I give the surface resistance from cap to pin in megohms.

The rack was kept energized both day and night whenever possible; an arc-over would cause the relays to open the main 16-kv. switch; the operator would at once close the switch again; if upon the third trial the arc-over still persisted the switch would be left open until the next day. Arc-overs practically always occurred during the night when fog or dew was heaviest.

## PROGRAM OF TESTS

During the period from January 1, 1927, to June 1, 1928, a number of rather long suspension strings was under test, no changes being made except to disconnect two short strings of 13 Type *A* and 13 Type *D* which arced-over.

The strings under test during this period are detailed in Table II. They were all washed by hand on February 9, 1927. 6-*E* and 6-*J* were washed immediately after each arc-over, and 5-*J* was washed frequently as described later.

Beginning June 1, 1928, the program was changed. Strings 8-*E*, 7-*E*, 6-*E*, were removed (the number and letter designating the number of units of a certain type).

The other types in service had the effective number of units in a string reduced by short-circuiting any required number of units, at the upper end of the string, with wire.

The general practise was then followed of adding a unit, by moving the short-circuiting wire, on any one string after it had arced-over on two separate days. This wire device enabled units to be added or subtracted without handling the units and changing their surface condition.

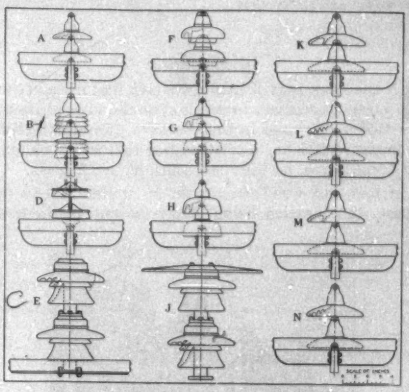


FIG. 4—TYPES OF INSULATOR UNDER TEST

It was expected in this way to arrive gradually at an equality in the different strings.

Types *H* and *G* were not put on test until October 15, 1928; Types *C* and *F* were added January 10, 1929.

In order to get comparative results, types *C*, *F*, *G*, *H*, *N*, *M*, were all washed by hand on January 15, 1929, so as to have them in the same condition as the recently added types. None of the other suspension strings had

TABLE I
PHYSICAL CONSTANTS OF INSULATORS: INCH UNITS

| Type | Diameter | Leakage distance | Surface resistance | Resistance per inch leakage | Axial length per unit | Resistance per axial inch |
|---|---|---|---|---|---|---|
| A | 10 | 10.75 | 0.651 | 0.0605 | 5.75 | 0.1132 |
| B | 9 | 20.0 | 1.062 | 0.0531 | 6.5 | 0.1634 |
| C | 9 | 18.25 | 0.955 | 0.0523 | 6.5 | 0.1468 |
| D | 10 | 11.0 | .. | .. | 5.37 | .. |
| E | 17 | 33.0 | 1.163 | 0.0352 | 14.5 | 0.0802 |
| F | 11 | 16.5 | 0.811 | 0.0492 | 5.75 | 0.1411 |
| G | 10 | 13.12 | 0.715 | 0.0545 | 5.75 | 0.1244 |
| H | 10 | 15.5 | 0.837 | 0.0540 | 5.75 | 0.1455 |
| J | 17 | 33.0 | 1.163 | 0.0352 | 14.5 | 0.0802 |
| K | 14 | 16.5 | 0.848 | 0.0514 | 6.6 | 0.1285 |
| L | 14 | 19.0 | 0.908 | 0.0478 | 6.6 | 0.1375 |
| M | 14 | 16.5 | 0.848 | 0.0514 | 8.0 | 0.1060 |
| N | 14 | 19.0 | 0.908 | 0.0478 | 8.0 | 0.1135 |

Note: Resistance is not easily calculated for Type D. From test results it seems to have approximately the same resistance as Type A.

been washed, except by natural rains, since February 9, 1927, and they were now left in that state but reduced in number of units per string and the process of building up to an equality started in again.

On June 15, 1929 the program was again changed and all types, except the posts *J*, had units added until

TABLE II

INSULATOR STRINGS UNDER TEST 1-1-27 TO 6-1-28

| Number in string | Type and position | Leakage distance | Surface resistance | Period under test |
|---|---|---|---|---|
| 13 | A suspension | 140 | 8.47 | 1-1-27 to 3-12-27 |
| 17 | A " | 183 | 11.06 | 1-1-27 to 6-1-28 |
| 15 | AA dead end | 161 | 9.77 | 1-14-27 to 6-1-28 |
| * | | | | |
| 15 | AA " " | 161 | 9.77 | 1-14-27 to 6-1-28 |
| 12 | B suspension | 240 | 12.75 | 1-1-27 to 6-1-28 |
| 13 | D " | 143 | | 9-23-27 to 2-1-28 |
| 6 | E " | 231 | 6.98 | 1-1-27 to 6-1-28 |
| 7 | E " | 231 | 8.14 | " " " |
| 8 | E " | 264 | 9.30 | " " " |
| 5 | J post | 165 | 5.81 | " " " |
| 6 | J " | 198 | 6.98 | " " " |
| 7 | J " | 231 | 8.14 | " " " |
| 15 | K suspension | 248 | 12.72 | " " " |
| 12*L* + 3 | K " | 278 | 13.43 | 2-10-27 " " |
| 12 | M " | 198 | 10.17 | 1-1-27 " " |
| 12 | N " | 228 | 10.89 | 2-10-27 " " |

there was one more unit in each string than the maximum number that had arced-over at any time.

## Arc-Overs

The first period of the test showed that neither the five- nor six-unit post, type *J*, would be satisfactory without periodic cleaning; it was found feasible, however, to spray the five-unit post with water, while energized, without danger of its arcing-over, provided the spraying were done frequently. Cleaning once a week apparently kept this post in good condition. The special spray nozzle used washed practically the entire porcelain surface.

13-*A*, 13-*D* proved inadequate, each arcing over twice. There were six arc-overs on 6-*E* in suspension and three on 6-*J* as a post, in each case the insulator being hand washed immediately after arcing-over. This difference in behavior between post and suspension may have been due to the slight difference in the shielding, or to the cap in one case and the pin of the insulator in the other being at bus potential or, what seems most probable, that at the greater elevation above ground of the suspension string there was a greater wind velocity and more spray and dirt were deposited upon the porcelain; heat radiation would also be greater in the more exposed position and deposition of dew greater,—all of which would render the suspension string more liable to arc-over than the post. The post 5-*J* arced-over four times but not after regular washings were inaugurated. No relative values for the remaining suspension strings were obtained as none arced-over. Altogether there were 17 arc-overs in this period.

From June 1, 1928 to September 30, 1928 there were 30 arc-overs. The first rain of the season occurred October 11, 1928, and no further arc-overs took place until March 4, 1929. From March 4, 1929 to July 19, 1929 there were 43 arc-overs, giving a total of 73 arc-overs from which to analyze the relative performance of the different types of insulator.

## Analysis of Arc-Overs

In Fig. 5 each flashover has been plotted with a view to seeing whether the leakage distance might not be the controlling factor in arc-over; if so, the string arcing over should have the least leakage distance of all under test. When this was the case it was plotted as a circle at 100 per cent. When, however, there were one or more strings having lower leakage distances than the one arcing-over, then they were plotted as crosses showing their leakage distances as a per cent of that of the string that arced. Thus in Fig. 5 any type which has many low-percentage plots is apparently not so good as one in which the plots are of a higher percentage, remembering

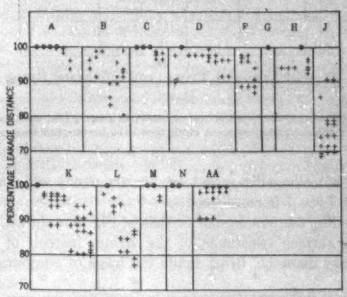


Fig. 5—Comparison of Types upon a Leakage Distance Basis

The insulator string having the shortest leakage distance is not always the one to arc-over. Each cross shows the percentage leakage length of a string that was shorter than the one arcing-over. A circle shows the shortest arcing-over.

that the comparison is not unit per unit, but is based upon strings of equal leakage distance.

It is seen at once that this basis of comparison is not entirely satisfactory. Due to the unavoidable variations in amount of deposit, dew, wind, no two strings of insulators subjected to field conditions would ever behave exactly in accordance with any of their physical dimensions, except by accident. It would, however, be expected that they would average in some relation to some measuring stick, each exhibiting departures on either side of a mean. When these departures from the mean were the same for each, then they would be considered as equal, according to the particular basis of measurement chosen. Extending this argument to a number of different types of insulator, a true basis of comparison will have been found if in such a plot as Fig. 5 all the types exhibit equal divergencies. It is seen at once that Fig. 5 fails chiefly with respect to Type *J*, which by reason of its position should show up

better than all others. Fig. 5 shows it as the worst. The intercomparison of the other types is fair in view of the fact that *C, F, G, H, N, M,* were all washed January 15, 1929, and would be expected to show up better than the others last washed February 9, 1927. It will be found significant that the ratio of surface resistance to

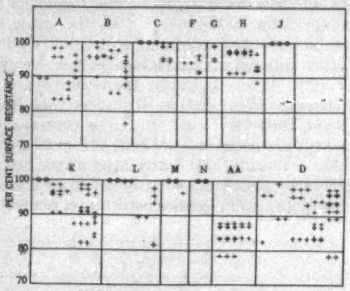


FIG. 6—COMPARISON OF TYPES UPON A SURFACE RESISTANCE BASIS

Each cross shows the percentage resistance of a string that was less than that of the one arcing-over. A circle shows the lowest resistance arcing-over

inch of leakage distance does not vary over a wide range until Type *J* is considered.

In Fig. 6 a plot similar to that of Fig. 5 is shown, the total surface resistance of the string, instead of the leakage distance, being made the basis of comparison.

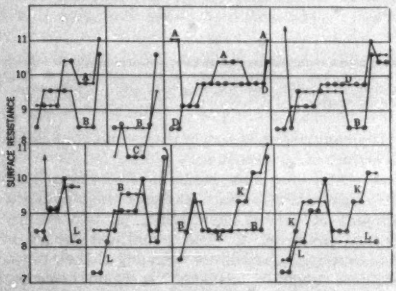


FIG. 7—COMPARISON OF TYPES BY PAIRS UPON A SURFACE RESISTANCE BASIS

The string arcing-over is marked with a circle vertically over or under the one not arcing. Insulators not washed since Feb. 9, '27

Type *D* is given an arbitrary resistance per unit equal to that of Type *A* for reasons referred to later. This plot exhibits a much greater uniformity than Fig. 5. Types *A, B, K, L, AA, D* are practically identical as to the range covered and are all types not washed since February 9, 1927. Types *C, F, G, H,* also have about the same range; *M* and *N* are restricted in range but the number of observations is small for each. The same qualification applies to type *J*; however, *J* is now in its proper place, not having arced-over unless it had the lowest resistance, which is as it should be considering its preferred position near the ground.

As a further test of the supposition that the surface resistance is a comparative measure of the resistance to arc-over, a direct comparison between types, taken in pairs, covering the whole period January 1, 1927 to July 19, 1929 is given in Figs. 7 and 8.

Comparing for instance Types *A* and *B*, each arc-over that has occurred upon either one of these is plotted, showing in the same vertical line the surface resistance of the two strings, the one that arced-over marked with a circle, and the one that did not, with a dot. Drawn lines connect points of the same type and do not represent any relation between coordinates.

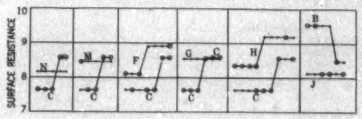


FIG. 8—COMPARISON OF TYPES BY PAIRS UPON A SURFACE RESISTANCE BASIS. INSULATORS NOT WASHED SINCE JAN. 15, '29

Type *D* has arbitrarily been assigned such a resistance per unit as would make it best fit the comparisons *A-D* and *D-B*, *A* and *B* being radically different designs. This arbitrary resistance of *D* turns out to be the same per unit as the calculated value for *A*.

If there were none of the accidental variations previously referred to and the surface resistance were an exact measure of the arc-over resistance, then the circle points would always be on the lower line. This is not the case, considering those pairs of points where the higher resistance string has arced-over. The amount of the discrepancies is shown in Table III.

TABLE III
PERCENTAGE DISCREPANCIES OF FIGS. 7 AND 8

| Pair of types considered | Average difference in surface resistances as per cent of the greater | Period of test |
|---|---|---|
| A–B | 5.38 | 1– 1–27 to 7–19–29 |
| B–C | 7.07 | " " " |
| A–D | 6.15 | " " " |
| D–B | 2.76 | " " " |
| A–L | 4.17 | " " " |
| B–L | 4.40 | " " " |
| B–K | 8.60 | " " " |
| K–L | 8.22 | " " " |
| B–J | 0.00 | " " " |
| N–C | 3.72 | 1–15–27 to 7–19–29 |
| M–C | 1.28 | " " " |
| F–C | 5.80 | " " " |
| G–C | 0.12 | " " " |
| H–C | 8.23 | " " " |

It will be noted that the discrepancies are not large after all, considering the nature of the original data, and it is certainly impossible to assign to any one type

rather than another any materially greater liability to arc-over when equal surface resistances of each are taken and exposed to the same conditions.

It therefore appears that the surface leakage resistance is a close measure of the ability of these types of insulators to stand up under such conditions as are found at Redondo and that there is no particular virtue in one shape over another, except in so far as it may afford more surface resistance and enable a fewer number of units to provide the total required.

There is a limit to the reduction in number of units per string imposed by ordinary dry and wet arc-over requirements and the danger of puncture when too few thicknesses of porcelain are used between line and ground. It would seem conservative to satisfy the ordinary line conditions as to number of units and then choose the type and perhaps greater number of units which will furnish the necessary surface resistance to suit the locality at the minimum of cost for both insulators and supporting structures.

The final results of the elimination contest are shown in Table IV.

TABLE IV
LIMITS REACHED IN ARC-OVER, LEAKAGE, AND RESISTANCE

| Type | Max. number arced-over | Min. number not arced | Leakage arced-over | Distance not arced | Surface arced-over | Resistance not arced |
|---|---|---|---|---|---|---|
| A | 16 | 17 | 172 | 183 | 10.41 | 11.06 |
| B | 10 | 11 | 200 | 220 | 10.62 | 11.69 |
| C | 9 | 10 | 164 | 183 | 8.59 | 9.55 |
| D | 16 | 17 | 176 | 187 | 10.41 | 11.06 |
| E | 7 | 8 | 231 | 264 | 8.14 | 9.30 |
| F | 11 | 12 | 182 | 198 | 8.92 | 9.73 |
| G | 12 | 13 | 158 | 171 | 8.58 | 9.30 |
| H | 11 | 12 | 171 | 186 | 9.21 | 10.04 |
| J | 7 | .. | 231 | .. | 8.14 | .. |
| K | 12 | 13 | 198 | 215 | 10.17 | 11.01 |
| L | 11 | 12 | 209 | 228 | 9.99 | 10.89 |
| M | 10 | 12 | 165 | 198 | 8.48 | 10.17 |
| N | 9 | 11 | 171 | 209 | 8.17 | 9.99 |

Note: Resistance per unit of "D" assumed equal to that of "A".

It is seen that strings having a surface resistance of from 9.99 to 10.62 have arced over, these strings having gone through the whole period of the test from 1-1-27 to 7-19-29 without being artificially washed, but that the strings washed 1-15-29 had in competition with them arced-over resistances of from 8.17 to 9.21, showing to some extent quantitatively how the washing done by natural rains compares with careful artificial cleaning. It further seems that a string with surface resistance of 11.0 will satisfactorily insulate against a steady 150 kv. to ground for three years under climatic conditions similar to those encountered at Redondo.

Acknowledgments are due practically all the insulator manufacturers for their ready response with samples of "fog type" insulators without which it would have been impossible to arrive at such definite results.

## Conclusions

1. Insulators may be compared, as to their ability to withstand arc-over under spray and fog conditions, by their surface leakage resistance, calculated as the line integral of length divided by circumference along the shortest surface path from cap to pin.

2. There is no virtue in any particular shape except as it provides surface leakage resistance.

3. One insulator string will not consistently arc over in preference to another unless its surface leakage resistance is less than 80 per cent of that of the other.

4. A surface leakage resistance of 11.0, in inch units, per string, appears sufficient for a steady voltage of 150 kv. to ground with conditions as at Redondo, Calif. On a line, allowance may have to be made for surges.

5. It has been found practical to clean some insulators, while energized, with a water spray and thus use a smaller number of units than would otherwise be safe.

## Discussion

**G. A. Fleming:** The 220-kv. insulators at Long Beach Steam Plant were selected on the basis of Mr. Wood's tests. Six type *J* units are used for the bus supports and 15 type *B* units for the strain insulators. A spray system for washing the insulators while energized was also installed. All of this equipment has now been in service for about 15 months and verifies Mr. Wood's conclusion to a very great extent.

The bus supports have one more unit or 20 per cent more insulation than has been found entirely satisfactory at stations away from the sea coast, but have less surface resistance than Mr. Wood's tests show desirable at Redondo without frequent cleaning. A spray-nozzle system was therefore installed and the insulators are washed once each day from two nozzles placed 10 ft. from the bus supports. The cleaning secured has been very satisfactory and leaves only a small deposit on the under side of the porcelain petticoats to be removed by hand when found convenient.

To determine the factor of safety against arc-over when the washing is being done, a series of laboratory tests was made on insulators which had been covered with sea water and sand. It was found that the bus supports stood 325 kv. without arc-over and the strain insulators in a horizontal position stood an even higher voltage. But the factors of safety on the same strain insulator in a vertical position and on the equipment bushing, were found to be considerably lower. This characteristic of the strain insulators is attributed to the distance between units being so small that a continuous stream of water is formed by the run-off from the spray. The surface resistance of these units is so high that no trouble is expected on the transmission line where washing is impractical, but the added safety of clean insulators is obviously desirable at such an important station and it is now planned to change the vertical strain insulators to type *L*.

The bushings were found to have a low surface resistance which makes frequent cleaning imperative, so they are being washed while energized, even though the concentration of salt in the test covering had to be reduced to 1/10 that of sea water and only one spray nozzle used to stand 325 kv. without arc-over. Sparking is of course more noticeable when washing the bushings than the bus supports, but no trouble has been experienced. Larger bushings will of course be specified for all future equipment.

**F. W. Maxstadt:** Some dry flashover tests on glass cylinders in electric fields between parallel plates where the electric lines are parallel to the surface of the insulator have been in progress in our laboratory and Mr. Wood's first conclusion suggested that we try wet flashover tests on the same apparatus.

The following r. m. s. voltages were obtained:

| | Flashover | Surface resistance on 150-kv. basis |
|---|---|---|
| (a) Two-in. long by 1-13/16 in. diameter glass cylinder, treated with three successive coats of sea water dried between each coat.—Dry 25 deg. cent. | 12,500 | 4.2 |
| (b) Same sample with a fourth coat of sea water.—Dry | 10,300 | 5.1 |
| (c) Same sample with 3 coats dried and one wet. | 5,000 | 10.5 |
| (d) Sprayed with fresh water (fine mist) but many times as much water as natural mist and sprayed from 3 sides at once: some salt remaining | 7,500 | 7.0 |
| (e) Spray reduced to half of former amount | 8,300 | 6.3 |
| (f) Corona and streamers but no flashover: spray in action as in (d) | 4,200 | 12.5 |

Test (e) is under conditions most nearly duplicating Mr. Wood's worst weather at Redondo and the agreement is quite satisfactory.

The fact that this test is on an insulator of a shape radically different from those used by the author, a shape intended to eliminate some of the uncertainties such as flux refraction and non-uniform surface-current density, strengthens his second conclusion.

Test (d) indicates the factor of safety that may be expected when spraying salty insulator surfaces with fresh water.

The values above given are reproduceable within 10 to 15 per cent. The source of test voltage was a 250-kv., 400-kv-a. transformer with only 15,000 ohms resistance in the high-voltage circuit, a voltmeter coil being used for the readings.

**R. J. C. Wood:** It may be of interest to bring the Redondo tests up to date.

Referring to Table IV of the paper, string *D* has been increased to 17 units and has subsequently arced over twice. String *G* arced once, was increased to 14 units and has not arced over since. One unit was added to string *H* which now has 13 units that have not arced over. In other respects Table IV remains unchanged.

Mr. Maxstadt's results in the laboratory, giving the same order of results as those obtained outdoors, are very gratifying and important as so much of the difficulty of research work lies in the proper coordination of laboratory results and field experience.

# The Sixty-Cycle Flashover of Long Suspension Insulator Strings

BY R. H. ANGUS*

Enrolled Student, A. I. E. E.

***Synopsis.***—*This is a study of the 60-cycle flashover of strings up to voltages of 1100 kv., undertaken at the Ryan High-Voltage Laboratory, Stanford University. Investigation was made of the variations in flashover voltage for similar horizontal and vertical strings, with and without shields and tower members. An attempt has been made to correlate these flashover voltages with the point-to-point and point-to-grounded-plane arc-over voltages established in 1928 at the Laboratory.* [1]

## Introduction

THE dry 60-cycle flashover voltage of long strings of cap-and-pin porcelain insulators, is of some importance in the design and selection of the insulation for any particular project. There are authorities who advocate the adoption of a wet flashover as the criterion;[2] but the difficulties which have been encountered in the standardization of a suitable "rain" or "mist" make it inadvisable to accept this as the only test of insulator strings.[3] Further, if Dr. L. B. Loeb's[4] theory of breakdown is established, it may be that power frequency arc-over voltages will be a measure of impulse voltage flashover of insulator strings, provided arcing-rings are designed and fitted to prevent cascading arcs.[5]

In all the publications dealing with the flashover of insulator strings, which the writer has seen, no reference was found to tests on strings in a horizontal position. Judging by the large numbers of strain strings in any high-voltage line, this would appear to be an important omission, which may be filled by the tests on horizontal strings to be described in this paper. Only one article mentioned flashovers of more than 750 kv.[6] Because deviations from a straight line flashover-distance relation only begin to appear above 600 kv., the experimental work was continued up to flashovers of 1100 kv., which is the maximum voltage to ground available at the Ryan High-Voltage Laboratory.

Doubt has been expressed as to the necessity of increasing the number of insulators in strain strings, by one or two, over the number in a normal suspension string. This seems to be standard practise to attempt to overcome the deterioration of insulation due to the accumulation of dirt and the heating effects of sunlight. But the flashover of similar clean strings in the two positions was not thought to be different,[2] although the form of the electrostatic field about vertical and horizontal strings cannot be the same.

## The Nature of Flashover

The flashover of an insulator string is the breakdown of the surrounding air, and consequently follows the laws of conduction of electricity through gases, which have been formulated by Paschen, J. J. Thomson, J. S. Townsend, L. B. Loeb, F. W. Peek, and others. The process of breakdown is thought to consist of ionization of the air and disturbance of the electronic orbits, consequent on the applied voltage gradient, till the air attains a conducting or chemically reactive state. When this occurs a sharp spark takes place, the spark having many of the characteristics of a condenser discharge. The power arc immediately follows. In the preparation for breakdown, ionization is dependent on voltage gradient and therefore on the form of the electrostatic field. Previous to power-frequency point-gap arc-overs of above 500 kv., long "streamers" sparks reach out from the electrodes. The air in the paths of these sparks is conducting and their presence must influence the distribution of the field. It is conceivable that their influence is the main cause of the widely varying arc-over values which are observed.[7]

The field about an insulator string is, as is well known, by no means uniform. The equal capacities of the units, as they are in series, give a higher stress at the line end of the string than at any other place. Equalizing shields do much to unify the distribution of stress along a string, but they and grounded tower structures complicate the form of the field, so that the effect of their presence on the flashover of a string can hardly be accurately anticipated for any particular case. All that can be done is to discover the variations in flashover values due to surrounding objects, for some extreme cases.

## The Test Insulators

Only two types of insulators were used in the tests. Both were standard ball-and-socket cap-and-pin porcelain insulators, whose principal dimensions are: insulator "A", diameter 10 in., pitch 5.75 in.; insulator "B" diameter 10 in., pitch 5.0 in.

It is hoped that the selection of this type of insulator will in no way prejudice the possibilities of other types, including that evolved by Dr. H. B. Smith.[8] Only ring shields at the line end and arcing-rings at the ground end of the strings were used, as arcing horns appear unsatisfactory.[9] The shields were to attempt

*Commonwealth Fund Fellow at Stanford University, Palo Alto, Calif.

1. For reference see Bibliography.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.*

to equalize the electrostatic stress on individual units, and the arcing rings were to insure that the arc clears the string at the ground end. The dimensions are below.

*Shields.* Single String; a circular torus, internal diameter 22 in. of 2.5-in. circular metal material, mounted from the line clamp so that the central plane of the torus was one inch below the top of the cap of the line unit. The whole shield was in metallic contact with the high-voltage line.

Double String; an oval ring, internal diameters 33 and 20 in., of oval material 1 in. by 0.5 in., mounted in a similar way to the single string shield with the 33-in. diameter in the plane containing the axes of the two strings. The 1-in. diameter of the material was parallel to the axes of the strings.

*Arcing-rings.* Single String; circular ring, internal diameter 20 in. of 1-in. by 0.25-in. flat material, mounted in metallic connection to ground, the 1-in. dimension parallel to the axis of the string. The ring was level with the porcelain of the ground unit.

Double String; similar in every way to the double string shield.

Flashover voltages of vertical and horizontal strings of both types of insulators, were measured for the following cases:

1. Strings without shields or arcing-rings.
2. Strings fitted with shields and arcing-rings.
3. Strings fitted with shields and arcing-rings, tower structures being present at the ground end of the string.

In each case the nearest object, other than these mentioned above together, with the high-voltage and ground cables was over 18 ft. from the string.

## Method of Conducting Tests

As the flashover of any gap is dependent on ionization, the maximum voltage reached before spark-over is the value that must be measured. With an alternating voltage, the required value is that of the crest immediately previous to spark-over. Thus, a satisfactory method of measuring this value must be devised; either the crest value or the wave form must be known, and the use of an oscillograph is obviously desirable. The technique of voltage measurement by means of an oscillographic record of the current through a water resistor, as developed in 1928 at the Ryan High-Voltage Laboratory,[1] proved to be invaluable. This method was used to calibrate the voltmeter coil of the high-voltage transformers, for each type of set-up, as differing capacities to ground and differing corona loads affect the constancy of the voltmeter coil's transformation ratio.

Five separate oscillograph measurements were made for each of a number of typical set-ups. The results so obtained were compared with voltmeter coil readings of other flashovers of the same strings. This led to a calibration curve for each type of string, so that voltmeter coil readings could be used for similar strings of different lengths.

Results were thus achieved more quickly than if an oscillograph had been used for every measurement.

No temperature or pressure connections of flashover voltages were made, as at no time during the tests were the conditions sufficiently far from the standard of 760 mm. and 25 deg. cent. to warrant such connections.

## Comparison of Flashover Voltages

There are certain principles which must be accepted before flashover values of different strings may be compared; these are:

1. Flashover values should be referred to the arc-over distance and not to the number of units in the string. The arc-over distance is the length of the shortest path in air which arc can take from the line to the ground end of the string.
2. Comparison of the flashovers of complete strings under working conditions should be made only with each other, or some standard, and not with the flashover value of one unit of the string.[9]
3. The lowest observed flashover is the important value. Proceeding on these lines, an attempt has been made to relate the lowest flashovers of suspension and strain strings with the standards of the point-to-point and point-to-grounded-plane arc-overs.

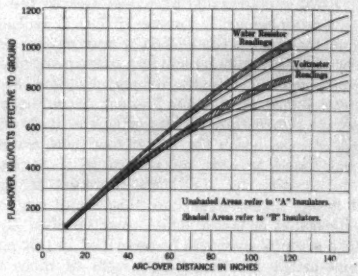


Fig. 1—Flashover of Suspension Insulators, Strain Position, Unshielded

## Discussion of Results

As the flashover of a string of insulators to a certain extent is dependent upon the initial state of ionization of the surrounding air, a constant flashover voltage cannot be expected, and the values may be represented rather by an area than by a line curve. This is done in Fig. 1. The areas denote the range within which the flashover of a strain string may occur, for the two types of insulators which were tested. A comparison is also made between the values derived by the water resistor method and the direct voltmeter readings. This shows the necessity for calibration of any particular arrangement of apparatus.

With "B" insulators, the calibration ratio increases steadily with the string length, which is a result of the increasing corona load as the flashover voltages grow larger. With "A" insulators a greater change in the ratio sets in at 550 kv. This is due, first, to the increasing corona, and second, to priming which occurs with more than six of this type of unit. "Priming" is a term applied to the short, snapping sparks over the

Fig. 2—Non-Cascading Flashover of Vertical String of 10 "A" Insulators

line units, occurring before arc-over. It is the direct translation of the French expression for this phenomenon,[9] and should, in the opinion of the writer, be used in preference to "cascading," which should de-

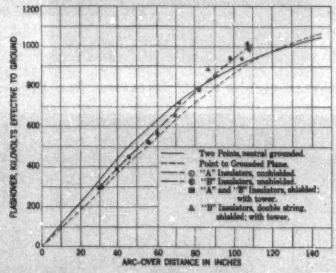


Fig. 3—Flashover of Suspension Insulators, Vertical Position, Lowest Observed Values

scribe only the type of arc that clings close to the porcelain in its passage from one cap to the next.

## Lowest Observed Values

*1. Strings in the Vertical Position.*

(a). "A" and "B" insulators, unshielded.

In this position, the conductor has a very considerable shielding effect on the string; so much so that no priming took place, and only 108 in. could be arced over with the 1100 kv. available. There was some cascading with "A" insulator strings of above ten units. Fig. 2 is a typical non-cascading arc-over.

(b). "A" and "B" insulators, with shields, arcing-rings, and tower members.

The lowest flashover voltages for the same arc-over distances are very similar to those for unshielded strings; the effect of the conductor is nearly as much as that of the shields in equalizing the stresses on individual units and preventing both priming and cascading. This is especially noticeable with the smaller pitched "B" insulators.

The values for shielded and unshielded strings are so equal that one curve serves for both sets. (Fig. 3.) The curve is approximately midway between the point-to-point and point-to-plane curves; the deviation from this position at above 750 kv. is due to the effect of the capacity-to-ground on a vertical gap, which causes about 20 per cent increase in the arc-over value of a 110-in. point-gap when the lower point is moved from ground level to 15 ft. above it.[1]

In order to discover any effect of the vertical part of

Fig. 4—Flashover of 20 "B" Insulators, with Shields and Tower Members in Position

towers on flashover values, a large wire screen was erected 10 ft. 10 in. from the nearest point of the shield of a string of 20 "B" insulators, and the screen was connected to ground. (Fig. 4.) Voltmeter readings of flashovers were taken with and without the screen in place. The averages of the two sets of readings were equal, showing that the voltmeter coil calibrations of the two set-ups were the same. But the lowest observed values were 900 kv. with the screen and 930 kv. without. It is probably safe to infer that the exploring streamer sparks were influenced by the presence of the screen, resulting in a 3 per cent lower flashover. This is barely greater than the limits of experimental error. Consequently it may be said that the important part of the tower, as regards flashovers, is the member at the ground end of the insulators.

The flashover voltage of a double string when

shielded, is sufficiently near to that of a similar single string to assume that they are equal, provided they have equal arc-over distances, (Fig. 3).

*2. Strings in the Horizontal Position.*

In the horizontal position the conductor provides no shielding effect. In actual transmission lines, the jumper at anchor towers would give some shielding; but it was decided to use an extreme case, as might be found at a terminal point, where the lead to the transformers or switchgear is in such a position as to shield the insulators but little.

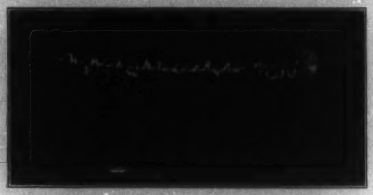

FIG. 5—FLASHOVER OF 25 "A" INSULATORS, STRAIN POSITION

(a) "A" insulators, unshielded.

The lowest flashover voltages of unshielded strings of "A" insulators are mid-way between the point-to-point and point-to-plane values, up to about 750 kv. Above this, both priming and cascading (Fig. 5) become very marked, and the curve runs below those of the two standards. (Fig. 6.) It should be noted that 25 "A" units were arced over only because priming and cascading occurred. The flashover of 25 of the closer pitched "B" units was beyond limits of the high-voltage transformers, for with them there was less priming and cascading. (Fig. 7.)

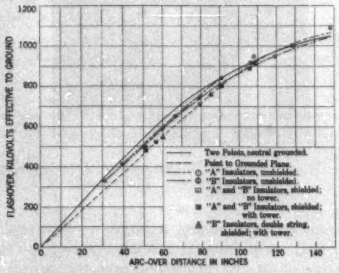


FIG. 6—FLASHOVER OF SUSPENSION INSULATORS, STRAIN POSITION, LOWEST OBSERVED VALUES

Fig. 8 is interesting, as it visibly demonstrates the need of shields and arcing-rings; corona from the high-voltage lead has shielded the first nine units, but cascading has occurred on the ground unit.

(b) "B" insulators, unshielded.

The smaller amount of priming with "B" insulators results in a higher flashover for a given arc-over distance than with the "A" insulators, although there is hardly any difference between the flashovers of the two types for strings of less than 15 units.

(c) "A" and "B" insulators, with shields, arcing-rings, and tower members.

Fig. 9 shows a typical arc-over. An arc to the tower sometimes occurred, and the flashover was frequently below the string but in every case the arc cleared the units.

The flashover voltages were the lowest of all those measured. They agree very closely with the point-to-grounded-plane values, as might have been anticipated from the position of the high-voltage lead with respect to the grounded tower.

FIG. 7—FLASHOVER OF 22 "B" INSULATORS, STRAIN POSITION

FIG. 8—FLASHOVER OF 10 "A" INSULATORS, STRAIN POSITION

FIG. 9—FLASHOVER OF 20 "A" INSULATORS, WITH SHIELDS AND TOWER MEMBERS IN POSITION. WATER COLUMN RESISTOR IN FOREGROUND

## CONCLUSIONS

*1. Variation in Pitch.* With strings in any position which are shielded (either by the conductor or by

shields) a 15 per cent variation in pitch does not affect the arc-over.

With strings which are not shielded cascading and priming may result on an increase in pitch. This will lower the flashover value.

The 5-in. pitch of the "B" insulators seems to be as large as a 10-in. diameter unit will stand without cascading. This is in close agreement with the results of G. Viel[9] for cap-and-pin insulators 11.4 in. in diameter and 5.9 in. pitch. In other words, for unshielded strings the pitch should not be more than about half the diameter of the unit.

*2. Shielding.* All strings (except perhaps those below 15 in. long) should be shielded. With vertical strings the conductor may provide sufficient shielding if the pitch and therefore the variation in stress on individual units, is not too great; though to be certain that the flashovers clear the string, arcing-rings should be used.[5] In other positions the conductor may not provide sufficient shielding; then ring shields must be fitted.

*3. The Flashover Voltage-Distance Relation* is not straight line, but lies between the point-to-point and point-to-ground-plane curves.

*4. The Lowest Flashovers* are obtained with strain strings. But these values are not below the point-to-grounded-plane arc-overs for the same distances.

*5. Length of Strain Strings.* These need not be more than five per cent longer than suspension strings; that is, one unit in twenty should be added to the normal vertical string to guard against the capacity effect of the strain towers. Additional units may also be necessary to overcome special local atmospheric or dirt conditions.

*6. Double Strings* have the same flashover as single strings of the same length, if both are adequately shielded.

*7. Calibration of Voltmeter.* Voltmeter-coil (or potential-transformer) readings should be calibrated by some suitable method for each particular type of set-up.

ACKNOWLEDGMENTS

The author is deeply indebted to Dr. H. J. Ryan for his helpful criticisms and to Professor J. S. Carroll and the other members of the laboratory staff whose experience and assistance, both mental and physical, were invaluable.

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3. R. T. Fleming, "Testing of Insulators under Artificial Rain," *Electric Rev.* (Lond.), Vol. 98, 1926, pp. 612 and 651.

Note. As reported on page 260 of Volume 48 of the A. I. E. E. JOURNAL for April 1929, it seems as though Viel advocates the increased separation of both cap-and-pin and link type insulators. Actually these remarks apply only to the link type with which he experimented; he says that his cap-and-pin type should not have a greater separation.

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## Discussion

**Bradley Cozzens:** It has been pointed out that the condition for the maximum field intensity on a point having a definite distance clearance, is to place that point at the center of a sphere. It is practically impossible to have the point at the center of a hemisphere. The point-to-plane condition approaches this latter setup, and is the practical condition that gives the lowest

FIG. 1

arc-over voltage for a given distance between electrodes. The value of point-to-plane arc-over voltage is thus the safe value to use in that portion of tower design which is based on flashover distance. The results of Mr. Angus show that the insulator string flashover values approach the point-to-plane arc-over voltage as a minimum.

Mr. Angus states that double strings have the same value of flashover voltage as do single strings of the same length. It has been the practise in past years to use the double string in prac-

tically every place where especially high strength is necessary. These have been replaced in some cases by the new high-strength units, but there are still many places where the double string is used. The wet arc-over of an insulator string is quite different from the dry condition which Mr. Angus has considered.

The voltage distribution on a wet insulator string is anything but uniform. Taking a double string that is wet, the voltage may pile up on the two or three line units of one of the strings; so that the remaining portion of the string is practically entirely at ground potential. On the other string of the pair the high-voltage stress may be on the tower end of the string. This means that the entire string with the exception of the two or three units at the tower end of the string will be at line potential. The fourth unit in this string will be at line potential, while the fourth unit in the paralleling string is at ground potential. This high potential difference between the two strings is in many cases sufficient to break down the air between the two strings, and result in a complete arc-over of the string.

It has been found in practise that double suspension strings do have a higher rate of failure in dust and fog conditions than do the single suspension strings.

Mr. Angus has given some valuable information in this paper in regard to the two conditions which he has investigated. There are, undoubtedly, many other conditions which might be considered, but it is of the utmost importance to the man who is designing towers to have definite values upon which to base judgment in regard to the value of pitch as affecting the string flashover.

**P. H. McAuley:** (communicated after adjournment) Mr. Angus has studied the 60-cycle flashover characteristics of suspension insulators of two different pitches or spacings. The longer spaced units showed a greater tendency to cascade. It is inferred that cascading flashovers will not occur if the pitch of the insulators is sufficiently small. These conclusions seem perfectly valid in so far as the effect of cascading on the magnitude of the 60-cycle flashover voltage of a given string is concerned.

However, from a service point of view we are interested in cascading because of the liability of damage to the porcelain disks. Apart from foreign conducting material, perhaps most line flashovers are caused by surge voltages. Hence, we are really more interested in the nature of the surge flashover, because it seems reasonable to assume that the power current will follow the arc path established by the surge. Laboratory tests indicate that surge voltages invariably cascade insulator strings that are not protected by arcing rings. Fig. 1 shows a surge flashover of a 12-unit string of suspension insulators of 10-in. diameter disks and 4¾-in. spacing. It is noticed that the arc clings to the porcelain surface of every unit in the string. In our experience this is characteristic of surge voltage flashovers regardless of insulator pitch of spacing.

# Impulse Insulation Characteristics of Wood Pole Lines

BY H. L. MELVIN*
Member, A. I. E. E.

***Synopsis.***—*This paper gives the results of a rather comprehensive series of tests on the impulse insulation characteristics of wood and on combinations of insulators and wood as used in wood pole transmission line construction; and suggested methods of protecting wood from damage due to lightning discharges; also a brief discussion on the application of the data.*

## I. Introduction

WOOD poles and crossarms have been used in transmission line construction since the beginning of electric power transmission. That wood has insulating value has been recognized through these years both in the field and laboratory and it has been utilized to a greater or less degree either intentionally or accidentally as a part of the insulation for transmission lines on practically every power system. In some localities it has been possible to use treated wood as a part of the normal line voltage insulation but frequently it is not even practicable to have wood in the insulating circuit, between phases at least, on account of the possibility of crossarm and pole burning caused by leakage currents.

With steadily applied voltages the insulating value of wood varies over a very wide range depending upon the treatment, kind of wood, moisture content, and amount of contamination. Ordinary types of line insulation are also affected by moisture and contamination; however, it has been learned that these factors do not influence their impulse insulation characteristics materially. It has also been observed, from analyses of operating performance of transmission lines from a lightning standpoint, that those utilizing some part of the wood apparently have better records than lines with the same amount of porcelain insulation but with the hardware bonded and grounded.

Consideration of these factors made it desirable to undertake a special study of the impulse insulation characteristics of wood for its practical value in the design and operation of wood pole lines, to provide a means of placing some measure of value upon the many schemes being proposed and tried which use wood as insulation, and as a supplement to the rather intensive investigation of the lightning problem being conducted in the field and laboratory. Accordingly a rather comprehensive series of tests was undertaken for the purpose of obtaining some fundamental data on the insulating value of poles, crossarms, and combinations of insulators, crossarms, and poles to impulse voltages, also on methods of protecting wood from damage due to lightning. With these data available it should be possible to use wood in a more intelligent manner in design and better understand the performance of various types of construction where wood constitutes part of the line insulation.

*Engineering Department, Electric Bond & Share Company, New York, N. Y.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.*

## II. Test Impulse Wave

The impulse voltage wave used for all the tests can be described as one reaching its maximum value in approximately one-fourth of a microsecond and then decreasing to one-half of its maximum in approximately twenty microseconds. The voltages recorded are the minimum crest values required for sparkover on the tail of the wave.

While the sparkover voltage values would vary with the type of impulse wave used, it was not considered practicable to extend the tests to cover other types of voltage waves, particularly since no actual determinations of the character of lightning voltages had been made at that time. These tests should be interpreted as not necessarily representing actual lightning conditions but as giving comparative sparkover voltage values for the particular voltage wave.

Voltages having maximum values of 400 kv. to 3000 kv. were employed. Several shots were required in making each point determination and as would be expected in testing insulation having the characteristics of ordinary wood, the test points were rather erratic. The actual test points have not been shown on the curves in the various figures, but rather they represent averaged results. The dashed curves and portions of curves are interpolations and extensions.

## III. Impulse Sparkover Voltages

*General.* Sparkover voltage tests were made on cedar, chestnut, and treated pine poles; fir and treated pine crossarms; treated hardwood and pine sticks; and combinations of insulators and crossarms; insulators and poles; and insulators, crossarms, and poles. The poles and crossarms were of dimensions that might be used on a line except that the poles were shorter. The dimensions of the sticks were about those considered suitable for use as long wood guy insulators. The combinations of insulators and wood tested were as might be used in 66 kv. to 132 kv. construction.

To study the influence of moisture, conductivity, and contamination on the impulse sparkover values, one each of the different varieties of poles was kept under



29-137

cover for over two weeks so they contained the usual amount of moisture in a dry pole, another set was kept in a similar way but their surfaces were wet before testing as would be the case in a heavy shower, a third group was soaked in a vat of ordinary tap water for about two weeks to thoroughly wet the wood fibers, the fourth soaked in a vat of salty water (about one-fourth as salty as sea water) for about two weeks to increase their conductivity, and to other samples a coating of wet cement was applied to simulate contamination. The crossarms and sticks were prepared in a similar manner, several similar samples being given the same treatment.

Fig. 1—Impulse Sparkover of Wood Pole

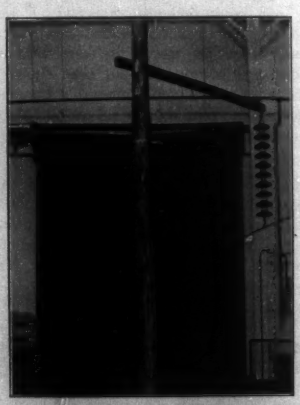

Fig. 2—Typical Test Assembly

*Poles, Crossarms, and Sticks.* Tests were made on the dry, surface wet, tap water soaked, salt water soaked, and cement coated poles in varying lengths from 4 ft. to 14 ft. The results indicated that the impulse sparkover values are not materially affected by the variety of wood, treatment, moisture content, contamination, or salt water absorption. The salt water soaked cedar pole, however, did give values lower than any of the others, probably on account of its very low conductivity, but since it did not represent any probable field condition, it was not included in the results. Many values obtained from the wet and salt water soaked samples were higher than those from corresponding dry samples. Adding a 200-ohm resistance in series with a pole, simulating high ground resistance, did not measurably affect the sparkover value.

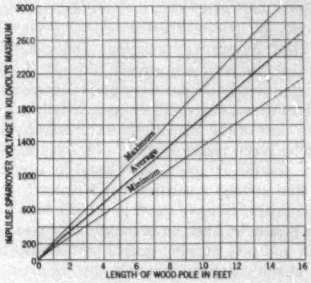


Fig. 3—Sparkover Voltage of Wood Poles

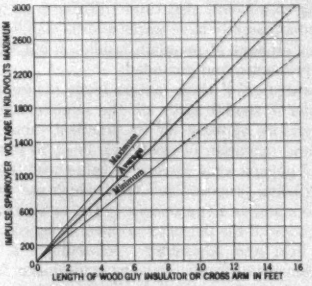


Fig. 4—Sparkover Voltage of Wood Guy Insulators and Wood Crossarms

Fig. 3 gives the results of the tests on poles. The test points fall between the maximum and minimum curves which vary about 20 per cent above and below

the average value of approximately 170 kv. per ft.

Similar results were obtained from tests of crossarms and wood guy insulator sticks, little difference being found as between hardwood, fir, or pine and the treatment or moisture content. A slightly higher insulating value than that obtained for poles was indicated, however, probably due to their smaller cross-section and the better class of wood. The results are shown by the curves in Fig. 4.

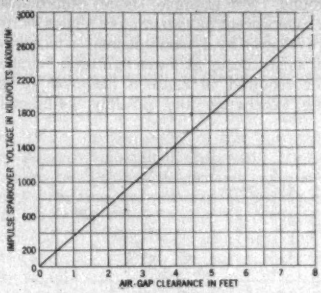


FIG. 5—SPARKOVER VOLTAGE OF AIR-GAPS

*Air-Gaps.* Sparkover voltage measurements were made for air-gaps such as obtain between conductors and guys or grounded parts of structures and across horn-gaps. These gaps are somewhat similar to needle-gaps but usually, on account of the hardware and configurations involved, should have slightly higher sparkover values than needle-gaps. It is believed the test set up was fairly representative of actual conditions and the resulting values are given by the curve in Fig. 5.

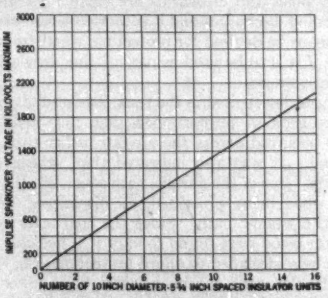


FIG. 6—SPARKOVER VOLTAGE OF SUSPENSION INSULATORS

*Insulators.* Fig. 6 gives the sparkover voltages for 10-in. diameter 5¾-in. spaced suspension units of the ordinary design for the 20-microsecond wave, as taken from the recent paper on *Lightning* by F. W. Peek, Jr.* All tests were made with this type of unit with the exception of those using a 70-kv. pin type insulator of usual design.

*Combinations of Insulators, Crossarms, and Poles.*

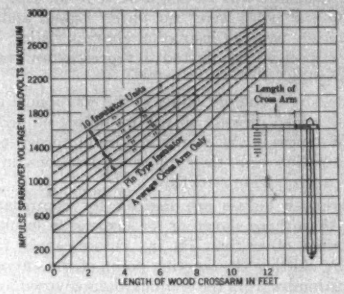


FIG. 7—SPARKOVER VOLTAGE OF INSULATORS AND WOOD CROSSARM

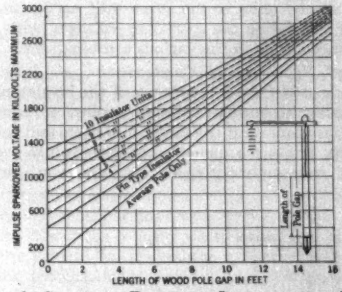


FIG. 8—SPARKOVER VOLTAGE OF INSULATORS AND WOOD POLE

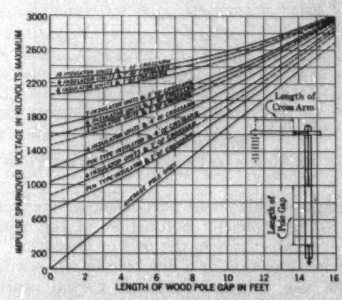


FIG. 9—SPARKOVER VOLTAGE OF INSULATORS, WOOD CROSSARM, AND WOOD POLE

Figs. 7, 8, and 9 give the average sparkover voltages for combinations of insulators and varying length of crossarm, insulators, and varying length of pole and different combinations of insulators and cross-

*See Bibliography for references.

arms with varying length of pole respectively. The suspension units were hung from the crossarm by means of an ordinary eye bolt as illustrated by Fig. 2, and the pin type insulator was mounted on a 13-in. pin. The crossarms and poles were tap water soaked and had approximately average insulation characteristics; however, all curves were adjusted to represent an average of the samples.

The sparkover voltage values of the component parts cannot be added directly as will be noted, on account of the differences in the characteristics of porcelain and wood insulation and their physical relations in the ordinary transmission structure.

If sparkover values are desired for combinations different than those shown or for suspension insulators with spacings other than 5¾ in., values can be interpolated by shifting the starting point of the curves or making estimates from the combinations covered by the tests. For example, eight 5-in. spaced units have approximately the same impulse sparkover as seven 5¾-in. spaced units so the seven unit curves may be used for estimating the sparkover voltages with eight short spaced units in the various combinations.

*Partial Sparkover of Combinations of Insulators, Crossarms, and Poles.* Sparkover of the insulators only may occur with impulse voltages applied to combinations of insulators and crossarms, insulators and poles, or insulators, crossarms, and poles, at lower values than are required to completely spark over the combinations.

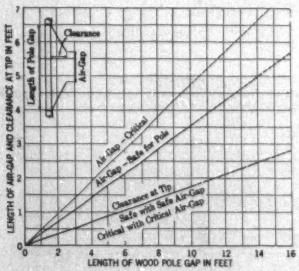


Fig. 10—Horn-Gap Protection of Wood Poles

The voltages at which these partial sparkovers occurred seemed to be primarily a function of the moisture content or conductivity of the pole or crossarm. With a dry or wet crossarm or a dry pole in series with the insulators, the voltages at which partial sparkover occurred were about the same as required for complete sparkover of the assembly. However, with a soaking wet pole the voltages at which partial sparkover occurred approached the sparkover value of the insulators or insulators and crossarm only. The intensity of the partial sparkover arc was very much lower than that for normal discharge of the lightning generator.

The results of these tests are not included in curve form as they were very erratic, depending upon the condition of the poles; also direct practical application could not be made of the data. They did, however, indicate possible limitations in the effective use of poles to increase the insulation of all three power conductors from ground. For example, should simultaneous partial sparkovers occur on two or more phases on the same structure followed by dynamic current, a phase-to-phase flashover might occur at lower lightning voltages than would be required to cause a flashover to ground. Operating experience and possibly additional tests

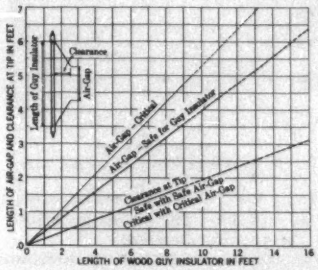


Fig. 11—Horn-Gap Protection of Wood-Guy Insulators

having available 60-cycle dynamic voltage on which the impulse wave is superimposed will be required before the possible effect of partial sparkovers on line operation can be estimated.

## IV. Protection of Wood from Damage

Wood poles and crossarms are frequently damaged by lightning discharges and it is therefore essential that some means be devised for protecting wood from such damage if it is to be used as part of line insulation to lightning voltages.

A simple device used in the tests consisted of protecting horn-gaps so proportioned that the impulse discharges occurred across the air-gap rather than along the wood. It was also indicated that, whenever the sparkover value of the parallel path was lower than that of the wood being protected, all discharges occurred across the weaker path. Since the sparkover voltage values for wood were found to vary it is necessary that the gap be so designed to afford protection even though the particular wood specimen might have lower than average insulation strength.

Figs. 10 and 11 give the controlling dimensions for designing horn-gap protection for wood poles and guy insulator sticks respectively. Dimensions taken from the "safe" curves should protect poles and sticks having insulation strengths corresponding to the low samples tested and the margin between the "critical" curves and "safe" curves indicates the factor of safety under average conditions. Not only must the air-gap

be of the proper relative length but the clearances from all points of the horns to the wood must be such that arcs will not occur from the horn to the wood and then along the surface of the latter.

Another method of protecting guy insulators from damage in the event of structure flashover is by means of a parallel gap, having a lower sparkover value than the insulator, installed on the pole. Fig.12 illustrates this scheme and gives the relation between pole-gap and guy insulator lengths. To provide for the possibility of a high insulation strength pole being combined with a low insulation strength guy insulator it is necessary to allow a differential as shown by the "safe" curve. Damage will, of course, occur in this pole-gap in the event of flashover unless it is protected. If protecting horns are to be installed, the critical curve should be used in determining the pole-gap and the protecting horn-gap dimensions should then be proportioned as shown by Fig. 10, otherwise by using the "safe" pole-gap curve and the "safe" air-gap curve a double factor or safety would be provided.

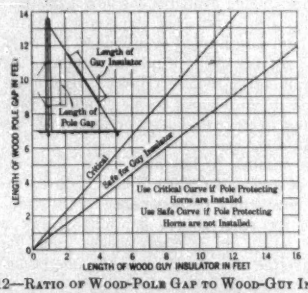


Fig. 12—Ratio of Wood-Pole Gap to Wood-Guy Insulator for Guy Insulator Protection

To determine whether an ordinary differential in ground resistance between pole and guy would make such a protective scheme unstable, a 50-ohm resistance was inserted in series with the pole-gap and this amount of resistance did not affect the relations.

Protecting gaps for crossarms must be designed for each combination of insulators and crossarm length as the voltage appearing on the crossarm is dependent upon the relations in the particular combination and the protecting air-gap must be so proportioned that it will have a sparkover value lower than the voltage appearing on the crossarm. Actual tests were not made to determine controlling dimensions for crossarm protecting horns; however, a suggested procedure is as follows, from Fig. 7 obtain the sparkover voltage of the particular insulator and crossarm combination, interpolating if necessary, then determine the increase in sparkover voltage effected by the crossarm by subtracting the sparkover voltage of the insulators alone, take 80 per cent of the resulting value to allow for variations in crossarms, determine the air-gap length from Fig. 5, and then obtain the clearance between the horn tip and crossarm directly from Fig. 11, using the clear length of crossarm to be protected as the abscissa.

The use of two or more shorter gaps in series might seem preferable and this scheme was also experimented with, but the sparkover value of gaps in series is rather indefinite unless all gaps are identical. The single gap would also seem less objectionable and more practicable of application even up to dimensions for protecting wood pole gaps longer than 20 ft. Whether protecting horns for poles, wood guy insulators, and crossarms designed with these dimensions will be effective for actual lightning must be demonstrated by field application, or when more is learned about lightning, including direct strokes, it may be possible to more nearly simulate the conditions in the laboratory and devise improved methods for protecting wood or modify the dimensions given by the curves.

## V. Application of Data

*General.* This investigation and discussion should not be interpreted as a recommendation for the general utilization of wood to increase the impulse insulation strength of lines. It is not always practicable to use wood in this manner on account of the possibility of crossarm and pole fires. The values of increased impulse insulation as reflected in the improved performance of transmission lines has not been definitely established. Furthermore, in some cases it may not be effective or advisable to increase the impulse insulation strength of lines materially above that of the substations and terminal apparatus.

In sections of the country where lightning is regarded as severe, several lines have been constructed and existing lines modified using wood in the various ways decribed below, from which some actual operating experience should soon be available. It must be remembered, however, that considerable time may be required to obtain authentic and conclusive confirming results from operating experience, since lightning storms must occur at the particular installations and careful analyses be made of what actually occurred from the evidence left by the storms.

The surge voltage investigations conducted during the past few years, which have included some lines using wood to a limited degree and one section of line in particular using long wood guy insulators have, however, yielded a few lightning voltage records of the order indicated by these tests. The plan for protecting long wood guy insulators by means of a parallel gap on the pole, as illustrated by Fig. 12, also seems to be effective from the limited operating data now available.

*Present Conventional Designs.* An analysis of the insulation strength of conventional wood structures in existing lines, using the wood to some extent as insulation, will no doubt reveal inconsistencies which might readily be corrected. Clearances between conductors and guys or other grounded parts of structures and the

amount of insulation wherever the insulator hardware is grounded should be checked in particular. It may also be practicable and should be very desirable to make the impulse insulation strength of all structures in a line uniform or at least design them for a uniform minimum value. Damage to wood from lightning may be reduced in particular cases if simple protecting horn-gaps can be applied to the affected parts of the structures.

The data can also be used to compare the relative impulse insulation strengths of different lines, also the insulation strengths of lines with that of terminal substations and apparatus.

*Modified Designs.* Where practicable to use wood as part of the line impulse insulation, the crossarms and poles can be employed in varying degrees in combination with the insulators. In designs of lines with conventional overhead ground wires and those with pole ground wires, installed for protecting poles from damage, the crossarms can frequently be used to increase the insulation strength. Attention must, of course, be given to those structures where the insulator hardware is grounded to provide the additional porcelain necessary to make them the equivalent of the other structures in the line. Whether crossarm protecting horns should be used or not would depend upon the particular combination of insulators and crossarm as well as past experience in the territory with similar construction.

It was observed during the tests that with four or more suspension units or a 70-kv. pin type insulator and about two feet of crossarm, the arc would usually strike to the ground connection clear of the arm, but with longer lengths of crossarm the arc usually cascaded the insulators and arm. Actual lightning may not perform in the same manner but it has been observed that relatively little damage is done to short crossarms or arms with crossarm braces which short circuit all but about two feet of their length. On the other hand, long crossarms are frequently damaged.

The impulse insulation strength of the conductors to ground, on lines not employing overhead ground wires, can be materially increased by utilizing the crossarms and a considerable portion of the poles. Long wood guy insulators are required in such designs to increase the insulation of the guyed structures. If bonding of the insulator hardware is necessary on account of burning due to leakage currents, the poles only can be used, increasing the insulation of the three conductors as a group to ground. There are several factors to be taken to account in preparing these designs, particularly at angle, dead end, and special structures and for lines having communication or distribution circuits on the same poles, which cannot be properly treated in this paper.

An example of a rather favored experimental design for H frame 66-kv. to 132-kv. lines, employs wood guy insulators about 20 ft. long, (usually two 10-ft. insulators in series); the end sections of the crossarm are either bonded to the top section of the pole grounding wire or crossarm protecting gaps are installed on the end sections; no bonding wire is placed along the crossarm between the poles increasing the phase-to-phase insulation, also there is little probability of severe damage in this section of the crossarm; pole gaps with protecting horns are installed at the guyed structures to protect the guy insulators and poles; the unguyed structures may not have any bonding or pole ground wires installed in order to obtain the maximum possible insulation, or unprotected gaps may be cut in the pole grounding wires such that their insulation strength will be equivalent to the guyed structures; or in severe lightning territory protecting horns may be used on all pole-gaps. The lower ends of the guy insulators and pole-gaps are kept about 10 ft. from the ground. Such designs will have from 2500-kv. to 3000-kv. impulse insulation strength to ground based on the results of these tests.

A line immune from lightning flashover cannot be built in this fashion as the small amount of operating experience already available has demonstrated. Experience has also shown that structures without the insulator hardware bonded or grounded frequently flash over and are damaged. If present reasoning is correct, however, it should require a direct stroke to the line or structures or an induced stroke of approaching maximum value to cause flashovers on lines with insulation strengths of the above order.

To be immune to lightning a line must either be capable of receiving a direct or branch stroke terminating on conductors or structures, with some means provided for relief of the lightning energy without dynamic follow up, or direct strokes must be effectively diverted from the line and the line insulation be such that flashover will not occur due to the voltages which can appear on the line conductors when lightning discharges occur to the diverting structures.

A general design along these lines might consist of a wood tower line constructed about as described above, using long wood guy insulators, with direct stroke protecting wire or wires erected over, or over and to one side, or possibly on both sides of the line, at a height such that direct strokes will occur to the protecting wire or wires rather than to the line conductors or structures. The protecting wire or wires might be grounded at two or more points in each span to reduce the impedance voltage drops to earth. Sufficient insulation through the air paths between the direct stroke protecting wires and the line conductors would of course be necessary, so that side flashing would not occur to the line. The impulse insulation strength of the line or combination of insulation with conventional overhead ground wires must be such that insulation sparkover will not occur for the induced voltages appearing on the line conductors. Instead of the overhead direct stroke protecting wire or wires, tall masts might be substituted so arranged as to divert direct strokes from the

line. Experimental applications of schemes of this kind are expensive; considerable time might be required to demonstrate their merit conclusively, and at the present time there is hardly sufficient information available for the preparation of designs, which would offer promise of functioning, without providing unreasonable factors of safety and at undue expense.

How important a part the use of wood may play in the insulation of lines for lightning voltages in future designs cannot be predicted, but it would seem probable that it may be used quite extensively in experimental installations and in connection with field research and lightning investigations.

*Substation Protection.* When transmission line impulse insulation strengths are increased above what is now regarded as normal for lines or for substations and terminal apparatus, as would seem possible if wood is utilized to any appreciable degree, attention must be given to substation protection from surges originating on the lines. Spillway or protective gaps set at substation insulation levels or slightly lower, or reduced insulation adjacent to substations, lightning arresters, or combinations of the above should provide the desired protection. Furthermore, lightning voltages seem to attenuate very rapidly in traveling along transmission lines so high impulse insulation should usually be effective over the major portion of lines between substations and the protective devices should only be called upon to function for some of the surges originating relatively near the terminal equipment.

## Conclusions

Wood seems to have quite definite impulse insulation strength which is fairly uniform, within practical limits, for the different varieties of wood used in transmission line construction; also it is not materially affected by moisture or contamination.

It should seem practicable to utilize wood to increase the impulse insulation strength of lines in many situations and these test data should be an aid in designing the structures so they will each have the desired uniform minimum insulation strength.

The impulse sparkover voltages of combinations of insulators and wood are not equal to the sum of the sparkover values of the component parts on account of their physical arrangement and the differences in their characteristics.

Partial sparkovers may occur, where poles and crossarms are used as part of the impulse insulation, particularly when the wood is wet, at lower lightning voltages than are required for complete sparkover to ground, possibly resulting in phase-to-phase flashovers.

The normal amounts of porcelain insulation required to successfully insulate normal line voltages cannot be reduced by utilizing wood on account of the probability of crossarm and pole fires; also, wet wood has very low insulating strength to steadily applied voltage.

Wood can evidently be protected from damage due to lightning discharges by providing a parallel air-gap of lower sparkover voltage value than the section of wood being protected.

Any application of these data should be regarded as experimental until such time as they have been demonstrated as applicable to actual lightning conditions. A definite statement cannot be made at this time regarding the value of increased impulse insulation as measured by improved line performance.

The voltage values given by the curves are for the particular impulse wave used in the tests and represent average values for the given test conditions.

These tests, while quite comprehensive, should not be considered as complete. Further tests would be very desirable, particularly if the impulse wave were superimposed upon normal 60-cycle voltage so that the effects of partial sparkovers could be studied as well as the behavior of 60-cycle voltages in following up long impulse arcs. Tests utilizing impulse waves of varying types would also yield valuable data and possibly the studies should be extended to cover these when more definite data are obtained on the characteristics of actual lightning and switching surges.

## Acknowledgments

The tests which form the basis of this paper were conducted in the High-Voltage Laboratory of the General Electric Company under the direction of the engineering department of the Electric Bond & Share Company for the Carolina Power & Light, Florida Power & Light, and Texas Power & Light Companies.

Mr. A. E. Silver, Mr. C. A. Jordan, and Mr. L. B. Cowgill of the Electric Bond & Share Company participated in the planning of the tests and preparation of the paper. Mr. Cowgill also assisted at the laboratory and in the analysis of the data.

The co-operation of the General Electric Company and valuable suggestions from Mr. F. W. Peek, Jr. in planning and arranging the tests as well as the assistance of Mr. W. L. Lloyd, Jr. in conducting the laboratory work are very much appreciated.

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## Discussion

**L. R. Gamble:** Following up the tests recently made in Pittsfield on the insulating value of wood poles, the Washington Water Power Company has incorporated a few of the ideas that seem to be reasonable in the use of wood insulation for protection against lightning impulses, and has redesigned its 110-kv. wood-pole structures to take advantage of wood insulation. We did not use wood guy insulators, but moved all guys to a position on the pole to give greater clearance to conductor and introduce a

section of wood-pole insulation in every instance, the guy where the strain really should be put, but in no case is it sufficiently far away from that point to weaken the construction.

We used cross-arm braces to stiffen our two-pole structures against the prevailing winds in the eastern part of Washington. If we do not use the brace the structures will take a leaning position. Nevertheless, when it was found the brace was depriving us of two feet of insulation in the cross-arm itself, we decided to omit the brace.

Our older lines were insulated with six disks, which gave us about 900-kv. impulse breakdown with the cross-arm braces used, and with 30-in. clearance to guys. By removing the braces and increasing clearance to guys to 4 ft. 6 in. we get about 1600-kv. To have obtained this by additional insulators would have meant the addition of two more disks in each string.

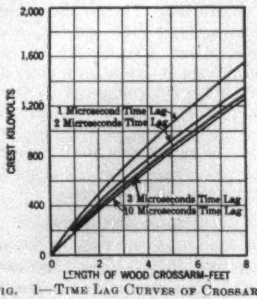


Fig. 1—Time Lag Curves of Crossarm

A wood brace from the cross-arm to the pole could have been used, but it was felt this expense was not justified.

To make the line symmetrical throughout in regard to the impulse insulation of 1600-kv. would have required eleven disks in every string on angle structures. To obviate this the guying of angle structures was arranged to get the equivalent insulation in the pole itself.

The tests as covered in Mr. Melvin's paper indicate that each foot of wood insulation is equivalent to one disk of insulation on the conductor.

**F. D. Fielder:** Tests on wood insulation have been made at the Westinghouse High Voltage Laboratory with an approximately flat-topped wave; it is believed that a comparison of some of these results will show the relative variation obtained with different impulse waves.

The wave used at Trafford rises to its crest in approximately ¾ microsecond and decreases to half of this value in 50 microseconds. It is practically a flat-topped wave to the breakdown point in most tests. By varying the crest value of this wave it is possible to obtain a wide range of breakdown voltages at different time lags. Such a process provides data which completely show the characteristics of the insulation under test. Cathode ray oscillograms of each test furnish a means of accurate measurement and analysis.

Two series of curves which are directly comparable with Fig. 7 of the paper are shown. The first set, Fig. 1 herewith, presents a series of time lag curves obtained on a 5 in. by 5 in. dry oak cross-arm, and shows voltage crest measurements corresponding to 1, 2, 3, and 10 microsecond time lags. The second set, Fig. 2 shows similar data obtained with five standard suspension insulators suspended from the end of a horizontal cross-arm. Thus a considerable variation in flashover voltage is shown for identical conditions. Similarly, tests have shown that 16 standard suspension units will flashover in 10 microseconds on impulse waves with a crest value as low as 1450 kv. Also, a 5-ft. needle gap in air will break down on surge voltages of 1000 kv. in approximately 20 microseconds. Actually, the surge breakdown voltage for any piece of insulation is represented by a time lag curve and not by a single value, and it is necessary to study the effect of different voltage waves to obtain complete information. It is hoped that the above comparative results will indicate the order of the variation which may be expected with different waves.

**H. L. Melvin:** From these tests it would seem that the impulse insulation strength of conventional wood-pole lines, where it is not necessary to bond the insulator hardware to prevent cross-arm burning, could frequently be increased 50 per cent or more by consistent use of a part of the wood in the structures and providing adequate clearances to guys and grounded parts. On lines not employing overhead ground wires, the insulation strength can be materially increased by the use of long wood guy insulators. The relative decrease in the number of transmission-line interruptions which may be experienced with increased insulation cannot be stated. It is very difficult to obtain authentic data of this kind from actual operating experience as lines of different impulse insulation strengths must be available which are subjected to the same lightning influence and comparisons should be made for several seasons. Even when parallel lines are compared, the prevailing direction of storm travel may influence their relative performance.

The results of these tests have been applied experimentally in the construction of a number of lines from which one to two seasons operating experience has been obtained. From these it

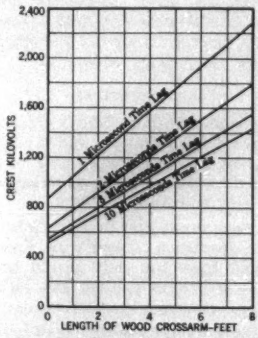


Fig. 2—Time Lag Curve of Cross-Arm and Five Standard Units

has been learned, that lines with insulation built up as high as 3000 kv. based on the test voltage wave, are by no means immune to lightning flashover. The scheme of protecting the wood guy insulators by means of the shorter parallel path on the pole, as illustrated by Fig. 12 in the paper, has been fairly successful though in a number of cases the wood guy insulators have been damaged. Numerous discharges across the unprotected pole gaps have been experienced and in several instances the poles have been severely damaged. The by-pass protecting horn gaps using the dimensions given, have evidently functioned to protect the wood though the operating experience covering this feature is at present quite limited.

The discussion and data given by Mr. Fielder are very interesting and illustrate the variation in voltage values which may be

expected by varying the duration of application of the crest value of the impulse voltage. It will be noted that the tail-of-wave spark-over values, obtained with the test wave used in the paper, give values approximating those for a one-microsecond to a two-microsecond time lag and the more nearly flat-topped impulse wave. The variation in impulse insulation strength of the wood specimen with varying time lags corresponds fairly well with the variation in the insulation strength of insulators, so it would seem that the curves in the paper can be used in estimating the relative impulse insulation strengths of insulators, air-gaps, and combinations of insulators and wood, even though the type of impulse wave be varied over quite a wide range.

This assumption is probably sufficiently accurate for practical purposes as the insulation strength of wood is not uniform, also extreme precision in the impulse insulation design of wood-pole lines does not seem warranted. Lightning voltages having equivalent durations considerably over 10 microseconds may be experienced and it is also possible with the longer durations that moisture, contamination, and the resistance of the wood may influence the sparkover voltage values to a greater extent than with the laboratory test wave employed. The actual voltage values do not mean a great deal except for making comparisons and in so far as they may be correlated with actual lightning voltage values.

# The Theory of Electrical Conductivity

## Recent Developments

BY WILLIAM V. HOUSTON*

Non-member

*Synopsis.—This paper explains the electrical conductivity of metals in light of recent discoveries regarding the behavior of electrons. It is claimed that these discoveries have made possible a satisfactory theory of conduction. The more important discovery is that of the wave nature of the electrons. The other new discovery is known as Pauli's "exclusion principle" which states that no two electrons in a wire can have exactly the same velocity and direction of motion. In working out the theory, the statistical method of the Fermi distribution function is employed.*

*The paper shows that the theory satisfactorily explains how there may be emissions of electrons from a hot wire in spite of the fact that very little energy is put into the electrons by raising the temperature; it explains relative resistances of metals and their alloys, the contact potential between metals, the thermoelectric effect, the Peltier effect, and the change in resistance due to a magnetic field.*

* * * * *

FOR the past 30 or 40 years the attempt has been made in the study of physics to explain all of the properties of matter on the basis of ultimate electrical particles. It has been assumed that a piece of material is made up of a very large number of positively charged particles called protons, and of negatively charged particles called electrons. This assumption is based on the experimental fact that it is possible to separate positive and negative particles from all kinds of matter. The numerical value of the charge on one particle is found to be the same as that on the other. Furthermore, the total numbers of protons and electrons are the same, so that there is no electrical charge on the body; but the mass of a proton is some 1840 times as large as that of an electron, so that the weight of a body is essentially that of the protons. It is found that all of the protons and about half of the electrons are gathered together into small clusters which are the atomic nuclei. These nuclei then have a resultant positive charge, and are surrounded by enough negative electrons to make a neutral atom. The number of positive charges on the nucleus, which is the same as the number of electrons around the nucleus, is equal to the atomic number of the element and determines its position in the periodic system of the elements. This method of interpreting experimental facts has had such tremendous success in so many fields that it seems almost certain that, in its broad outline, it represents correctly the constitution of matter.

With this picture, it is relatively easy to account qualitatively for the electrical conductivity of metals. When the atoms are packed as closely together as they are in a metal, the outer and more loosely attached electrons come under the influence of more than one atom and become free. In other words, they cannot be identified as belonging to one atom or another, and they move about between the atoms with very little restraint. Under these conditions, the application of e. m. f. causes these electrons to filter between the fixed atoms, and so, to constitute a current. On the other hand, an insulator is a substance in which all of the electrons are tightly bound to individual atoms.

This idea was given a quantitative treatment by Drude,[1] Lorentz,[2] and others. They started out by treating the free electrons as though they were alone in the metal and behaved exactly as gas molecules, moving about with energy due to temperature. Thus we come to speak of the group of free electrons as an electron gas. If an e. m. f. is applied to such an electron gas, it starts of course an average motion of all the electrons in one direction. If there were nothing to interfere with the motion, the electrons would move faster and faster, and the current would continue to increase without limit. The limit is set, however, by the presence of the atoms themselves, or more strictly speaking, of the positive ions, which form the crystal lattice. When an electron collides with an ion which is more or less tightly bound to its position in the crystal, the electron loses the extra energy which it has acquired from the field. On this account, its velocity cannot increase indefinitely. Thus the collisions of the electrons with the fixed ions are observed as a resistance, and the resistance is proportional to the number of collisions per second.

It is perhaps desirable to look at the relative magnitudes of some of the quantities involved in this picture. If we make the very reasonable assumption that there is one free electron for every atom, there will be about $6 \times 10^{22}$ free electrons per cu. cm. When there is no e. m. f. applied, these electrons will be moving with fairly high speeds in all directions, but the average velocity will be zero, so that the electron gas as a whole will not move. This distinction between the velocity of a single electron, and the average velocity of all electrons, which latter is the current, is the same as the distinction between the velocity of the molecules of air and the velocity of the air as a whole. The velocity of the molecules we recognize as heat, while the velocity of the whole we call wind. Now the velocity of a single electron will be of the order of $10^8$ cm. per sec., while if

*Assistant Professor of Physics, California Institute of Technology, Pasadena, California.

1. For references see Bibliography.

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the average velocity of the whole is as great as only one cm. per sec. there will be the tremendous current of about 8000 amperes per sq. cm. or about 50,000 amperes per sq. in. This shows that the applied e. m. f. produces only a *very minute* change in the velocities of the electrons.

All this, of course, has nothing to do with the propagation of the e. m. f. along the wire. That is governed by Maxwell's equations and can be explained as a result of the mutual repulsions of the electrons. This mutual repulsion can be neglected except, perhaps, in the finer details of the theory of conductivity.

Qualitatively, this picture is very satisfactory; but there are very serious difficulties with the quantitative treatment. In the first place, if there is at least one free electron for each atom in the metal, the electron gas should have a specific heat about half as large as that due to the vibration of the ions which make up the crystal. But the observed specific heat is merely that of the ions themselves. This constitutes a very serious objection to the classical theory, since it indicates that not enough energy is put into the metal when the temperature is raised to account for the assumed increased energy of the electrons. In the second place, the number of free electrons which must be assumed to explain the different electrical properties of a metal varies between such wide limits that the theory is evidently inconsistent. Another difficulty is that when the resistance is calculated by means of this theory it is found to be proportional to the square root of the temperature, which is not at all in accord with the observed facts.

On account of these difficulties, many attempts have been made to give other pictures of the behavior of the electrons in a metal. Some of these have been based on the idea that the electrons do not become free from the atoms, but remain attached and under the influence of an applied e. m. f. occasionally pass from one atom to the next. In this case, of course, the electrons need have no specific heat, since they do not move independently of the atom. But it is just this lack of an independent motion which makes it difficult to explain the emission of electrons from hot wires which we use in thermionic vacuum tubes. It is usually thought that this is due to the fact that certain electrons acquire a very high velocity and so are able to pass through the retaining wall of potential which bounds the metal. If there is no motion due to temperature energy, this could not be the case.

Thus, until recently, the theory of the electrical properties of metals contained a number of conflicting hypotheses, and it seemed impossible to form a consistent theory with a few simple assumptions. Within the last few years, two important discoveries have changed the whole aspect of the situation. Perhaps the more important of these discoveries has been the discovery of *the wave nature of the electrons.*

For several centuries there have been two rival explanations of the phenomena of light,—the wave theory and the corpuscular theory. During the nineteenth century, the weight of evidence became almost overwhelmingly in favor of the wave theory, but with the discovery of the photoelectric effect in 1888, it became necessary to use the corpuscular theory, (which has been called the quantum theory), to explain the phenomena of the interaction of light with matter. But although there have been two theories of light, there has been only one theory of the nature of electrons. Since the very early experiments on cathode rays, there has been practically no doubt as to the nature of electrons. They seemed in every way to satisfy the requirements of corpuscles of electricity. No one ever thought of investigating the wave properties of electrons until it was accidentally discovered in 1927 that a stream of electrons produces a diffraction pattern in the same way as a beam of X-rays.[3] Many theoretical considerations had been pointing toward the necessity of treating electrons as waves under some circumstances. Through this experimental confirmation of the theory, *we have now just as good evidence for saying that a stream of electrons is a train of waves as we have for saying the same thing about a beam of light.* The quantum theory, which was so called because it seemed to require that light should be propagated in corpuscles or quanta, has now come to include the requirement that electrons should have the properties of waves. This duality of nature, of both light and electrons, is now a firmly fixed experimental fact. It is one of the discoveries which has made possible a satisfactory theory of electrical conduction.

The other essentially new feature in the present theory is known as Pauli's exclusion principle. Applied to the problem in hand, this states that no two electrons in a wire can be in the same quantum state, *i. e.*, they cannot have exactly the same velocity and direction of motion. At first this seems an outrageous restriction, and yet there is a great deal of experimental evidence in favor of it. It is the basis of the theory of the periodic system of the chemical elements, as well as the very extensive and satisfactory theory of spectra. This principle, combined with the fact of the wave nature of the electrons, makes it necessary to revise the statistics with which we treat the electron gas in a metal.

On account of the large number of electrons with which we have to deal, it is necessary to use the methods of statistical mechanics. There are several different varieties of statistics, each one adapted to dealing with a certain kind of object. It is perhaps easiest to characterize the different types of statistics by giving their distribution functions. These functions give the number of electrons which may be expected to have velocities in a given range.

The classical statistics were developed largely by Maxwell and Boltzmann, and are adapted to the treat-

ment of material particles. The distribution function for these is

$$dn = A\, e^{-mv^2/2kT} \quad d\,\xi\, d\,\eta\, d\,\zeta \qquad (1)$$

This means that $dn$ is the number of electrons, on the average, whose velocity components in the $x$, $y$, and $z$ directions lie between $\xi$ and $\xi + d\,\xi$, $\eta$ and $\eta + d\,\eta$, $\zeta$ and $\zeta + d\,\zeta$. $v$ is the total velocity, $k$ is the molecular gas constant, $m$ the mass of the electron, and $T$ is the absolute temperature. The curve of this function for two different temperatures is shown in Fig. 1. It is evident from Equation (1), as well as from

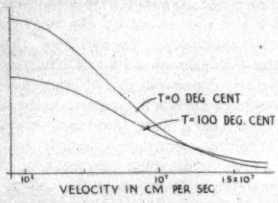


Fig. 1—The Maxwell or Classical Distribution Plotted as a Function of Velocity

Fig. 1 that as the temperature increases, the curve becomes more and more spread out, so that more electrons are found with high velocities.

The theory of quantum statistics with which we are concerned was developed by the Italian Fermi,[4] and independently by the Englishman Dirac. It is based on assumptions which make it applicable to wave motions when the Pauli exclusion principle applies. Thus, according to our latest knowledge concerning the nature of electrons, it should apply to electrons. The distribution function in this case is

$$dn = \frac{2\,m^3}{h^3} \; \frac{1}{\dfrac{1}{A}\, e^{mv^2/2kT} + 1}\; d\,\xi\, d\,\eta\, d\,\zeta \qquad (2)$$

where the letters have the same significance as in Equation (1); $h$ is known as Planck's constant of action and characterizes all equations in the quantum theory. The constant $A$ in both functions is determined so that the integral of $dn$ over all possible values of $v$ gives the total number of electrons present. In the Maxwell distribution function in Equation (1), $A$ is merely a constant by which the exponential function is multiplied, but in the Fermi distribution, the size of $A$ determines the nature of the function. If $A$ is very much smaller than 1, the first term in the denominator is so large that the other may be neglected. The function then becomes the same as the Maxwell function. But in the opposite case, the functions are entirely different. The value of $A$, when $A$ is large, can be determined from the equation

$$\log A = (h^2/2\,m\,k\,T)\,(3\,n/8\,\pi)^{2/3} \qquad (3)$$

where $n$ is the number of electrons per cu. cm. Because of the very large number of free electrons when it is assumed that there is one per atom, $A$ for ordinary metals is about $10^{90}$. Thus, only the case where $A$ is very large need be considered. Fig. 2 shows the curve of the Fermi distribution function for two different temperatures when $A$ is given this value. A gas for which the constant $A$ is greater than unity is called degenerate, and the size of $A$ is a measure of the degeneracy.

It is evident from the curve and from Equation (2) that in the case of the highly degenerate electron gas, the temperature has only a very slight effect on the velocities of most of the electrons. Only the relatively few which have the higher velocities are affected at all. Since the temperature has very little effect upon the motion of the electrons, it follows that the specific heat of the electron gas is very small; in fact it is given by

$$C_v = (\pi^2\, m\, k/h^2)\,(8\,\pi/3\,n)^{2/3}\, R\, T \qquad (4)$$

where $R$ is the gas constant for one gram molecular weight. For room temperature, $C_v$ is less than 1 per cent of the value to be expected with the Maxwell distribution. This is one of the important successes of the present electron theory of metals and was pointed out by Sommerfeld[5] who developed the statistical

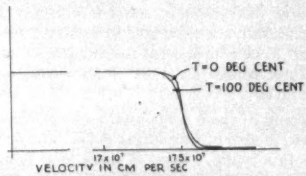


Fig. 2—The Fermi Distribution Function Plotted as a Function of Velocity

The scale of this figure is not at all comparable with that of Fig. 1.

phase of the theory. *Now it can be understood why the electron gas makes practically no contribution to the specific heat of the metal.*

But although the free electrons have a very low specific heat, they do not have a low energy of agitation. It is merely that this energy is not given up when the metal is cooled, but is retained and exists at the absolute zero of temperature. The average velocity of a free electron in a metal is of the order of $10^8$ cm. per sec. This high velocity and the accompanying energy produces a pressure on the surface of the metal which amounts to something like $2 \times 10^6$ atmospheres. Even with this pressure, however, the majority of the electrons are unable to escape from the metal because of the strong electric field which exists at the surface. But there will always be a few with extra large velocities, which can penetrate this surface layer and escape

from the metal, and the number of these increases with the temperature.

In Fig. 3, the Fermi distribution function for the degenerate electron gas is plotted with the energy instead of the velocity, for the horizontal axis. $W_i$ represents the energy at which the function has dropped to ½, while $W_a$ represents the energy which an electron must have to escape from the metal. The electrons which escape are those represented by the part of the curve to the right of $W_a$. By calculating the number of electrons represented by this part of the curve, and taking account of the various directions in which they are traveling, Sommerfeld has shown that the current per sq. cm. coming from a hot wire is given by

$$I = (4\pi e m/h^3) k^2 T^2 e^{-(W_a - W_i)/kT} \quad (5)$$

The equation derived by Dushman and others is:

$$I = B T^2 e^{-b/T} \quad (6)$$

In Equation (5) $(W_a - W_i)/k$ takes the place of $b$ in Equation (6). This shows that the $b$ which is usually measured and called the work function, is not really the energy necessary for an electron to have in order to escape from the metal, but is the difference between

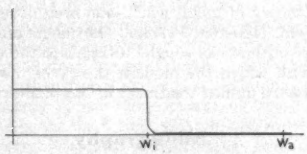


Fig. 3—The Fermi Distribution Function Plotted as a Function of Energy

this energy and an energy which represents the pressure of the electrons inside the metal. In this way, the theory explains completely why we can get emission of electrons from hot wires in spite of the fact that very little energy is put into the electrons by raising the temperature.

The outstanding electrical property of a metal is that of conductivity. It was mentioned above that a current is a relatively slow drift of all the electrons under the influence of an applied e. m. f. This drift would become faster and faster if it were not for the fact that the electrons collide with the metal atoms and so lose the acceleration they have gained from the field. Thus, the average gain in speed and the current is proportional to the time for which an electron can travel without a collision. The average distance which the electron can travel without making a collision is called the mean free path, and this quantity is generally used for calculation instead of the mean time between collisions. Sommerfeld has shown that when the Fermi statistics is used to describe the velocity distribution of the electrons, the specific conductivity in electrostatic units is given by

$$\gamma = (8\pi e^3/3h)(3n/8\pi)^{2/3} l \quad (7)$$

In this equation $e$ is the charge on one electron, $h$ is Planck's constant of action, $n$ is the number of free electrons per cu. cm., and $l$ is the mean free path for those electrons whose energy is equal to the $W_i$ of Equation (6); $l$ is of the order of $5 \times 10^{-4}$ cm. The mean free path is, of course, a function of the velocity, but only the length of the mean free path at this particular velocity is essential in the conductivity.

In Equation (7) all of the quantities except $l$ are independent of the temperature, and so we must explain the fact that resistance increases with temperature by the fact that $l$ decreases with temperature. It is here that the wave nature of the electron becomes directly apparent. The wavelength of an electron wave is determined by the velocity of the electron through the relation

$$\lambda = h/m v \quad (8)$$

This shows that the faster electrons have the shorter waves. From the Fermi statistics, it can be shown that the free electrons in a metal have such velocities that practically all of the wavelengths are greater than about 5 $A$ or $5 \times 10^{-8}$ cm. They are longer than most X-rays. This fact is of importance when we study the effect of a crystal upon these waves.[6] The behavior of an electron in a crystal can be considered from two points of view which correspond to the two natures of the electron. From the corpuscular point of view, the electron makes collisions with the atoms in the crystal and so is deflected from its path. From the wave point of view, the electron wave is diffracted by the crystal in the same way that a light wave is diffracted from an optical grating. In the case of electrons in a metal, the wave point of view is the correct one to use. Hence, the problem of determining the resistance of a metal is the same as the problem of determining the scattering of the electron waves by the atoms which form the lattice of the metallic crystal.

It is possible to calculate this scattering effect by the methods used for calculating the diffraction of X-rays by a crystal, when proper allowance is made for the difference in wavelength. The electron waves are longer than the distances between the atoms of most crystals, so that if the atoms were really stationary and regularly arranged, there would be no scattering at ex- and hence, no resistance whatever. This is not the all, planation, however, of the phenomenon of superconductivity, nor of the fact that the resistance becomes zero when the absolute temperature becomes zero, for there is very good evidence that the atoms in a crystal are not stationary, even at the absolute zero of temperature. There are still other ways in which the resistance may become zero, although if there were no motion of the atoms in the lattice, it would certainly be zero.

The thing that produces the diffraction of the electron waves and consequently the resistance is an irregularity in the arrangement of the metallic atoms. This ir-

regularity may come about either through the presence of impurities which distort the arrangement of the atoms, or through the motion due to the temperature energy. This latter effect produces the resistance in pure metals, while the first effect explains why the resistance of an alloy is always greater than the resistance of at least one of its constituents. It is easy to understand from this the reason for Matthiessen's rule which states that a small amount of impurity causes a small added resistance which is independent of temperature. This is explained by the fact that the irregularity in the crystal due to the impurity is essentially independent of temperature.

It is possible to calculate the resistance due to the heat motion of the metal atoms. This kind of calculation shows that the resistance, in its dependence on temperature, may be closely approximated by

$$R \text{ is proportional to } 1/x_0 \int_0^{x_0} \frac{x^4\,dx}{(e^x-1)\,(x^2+a\,x_0^2)^2} \quad (9)$$

$x_0 = \theta/T$, where $\theta$ is a function of the elastic constants of the metal and $T$ is the absolute temperature; $a$ is a measure of the scattering power of a single atom and so is characteristic of the metal. Equation (9) shows that for ordinary temperatures, the resistance is proportional to the absolute temperature, while for lower temperatures, it falls off more rapidly than would be indicated by the simple proportionality with temperature.

The agreement of Equation (9) with the observations shows that the knowledge of the wave nature of the electron has made it possible *for the first time to give a satisfactory explanation of the way in which the resistance depends on the temperature.*

In addition to the phenomena already mentioned, there are several others which are explained in a satisfactory manner by the present theory. The sudden increase of resistance, which always appears when a pure metal is melted, is due to the destruction of the regularity of the crystal by the metal. The atoms in the solid have a regular arrangement, to a certain extent, while the atoms in the liquid are moving about at random. This loss of regularity causes a large increase in the scattering of the electron waves and a correspondingly large increase of resistance.

The fact that the resistance of a non-cubical metallic crystal is different in different directions can be attributed to the fact that the atoms in the non-cubical crystals can vibrate more easily in one direction than in the others. This causes the diffraction of the electron waves to vary with the direction. The corresponding difference in resistance, calculated on this basis, agrees very well with the observed differences.

A number of other effects, such as the contact potential between different metals, the thermoelectric effect, the Peltier effect, and the change in resistance due to a magnetic field, receive a consistent and satisfactory explanation on the basis of the Fermi statistics and the wave nature of the electron.

The study of atomic structure, which has engaged the attention of physicists for the past 30 years, has now come to the stage where it is possible to treat not only single atoms, but molecules and those very large molecules which we know as solid bodies.

The first extensive application to solids has been the electron theory of metal which has been developed by Sommerfeld, Houston, Frenkel, Nordheim, and Bloch.[7] This brief outline has sought to indicate the degree of success with which the modern theory of the electron has provided a unified treatment of this baffling physical problem.

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# Development of Insulating Oils

BY C. E. SKINNER[1]
Fellow, A. I. E. E.

*Synopsis.—During the last 35 years or more the development of insulating oil for use in transformers, circuit breakers, etc., has paralleled the development of electrical apparatus. Various steps in the development of oils for this purpose are described in the paper. These include the discoveries from time to time of elements which have been responsible for difficulties which arose in the use of such oils. These include such items as the effect of moisture, the importance of flash and fire test values, the question of fluidity for better cooling, the development of oils with non-sludging characteristics, and a statement of the long series of tests and experiments necessary to eliminate these various difficulties. The importance of a universal oil for insulating purposes is stressed and some of the conflicting characteristics for different uses are described. Attention is called to the selection of the proper raw materials from which insulating oil is derived, together with the extreme care which has been found necessary in the handling of containers, in making shipments, and in applying oil to specific purposes. While much has been accomplished in the securing of satisfactory oil, it is intimated that research and development must be more or less continuous so long as the electrical art advances and oil is used for insulating purposes.*

THE integrity of modern transformers and circuit breakers, which are essential features of all transmission systems, is due in no little measure to the insulating oil now universally used in such apparatus. While the oil is a relatively minor part of these devices as a whole, its failure will mean the failure of the apparatus. This is increasingly true as the voltage of the transmission systems is increased. The service rendered by the oil used as an insulating medium in electrical apparatus, is radically different from service rendered by oil in any other class of service and there are rigid requirements for oil for this service which do not exist where oil is used for other purposes. In fact, insulating oil may be considered a material of construction rather than a material of maintenance.

The history of the development of transformer oil begins with the first high-voltage transmission lines in the early '90s, and a continuing and increasing amount of research has been required from that day to this to meet the ever increasing demands for quality and service. The electrical manufacturers' representatives who have been responsible for the quality of the oil used in transformers, have faced many difficulties and have experienced much grief from time to time, due to troubles for which the oil was either directly or indirectly responsible. The fact that such difficulties are rare at the present time does not indicate that further attention to this important material is unnecessary, but on the other hand, it does indicate that a full knowledge of the difficulties which have been so disturbing in the past and a constant watchfulness have mitigated these difficulties to a point where the modern transformer gives perhaps less trouble than any other piece of apparatus in the transmission system.

It may be useful to review some of the history of the development of modern insulating oil and to indicate some of the problems still unsolved, so that a full appreciation by those responsible for the purchase and use of transformer oil may be had. This history may be divided into various chapters, each concerned with the items which seemed to be the cause of the major difficulty prevailing at each particular stage of the development.

When the study was made of oil which might possibly be suitable for the insulating and cooling of the transformers to be used on the Pomona transmission line, this being the first constant high-potential transmission line undertaken in the United States, the study included oils of a very wide variety. Mineral oils, from the heaviest cylinder oil to the equivalent of gasoline and benzine, were carefully studied. Similar tests were made of quite a number of vegetable oils, such as linseed, rosin oil, etc. These early tests were almost entirely on the basis of the determination of dielectric strength. In making these studies, glass containers were used, with the testing electrodes immersed in the oil in a horizontal position. It was observed that any foreign matter visible to the naked eye would line up between the testing electrode and materially reduce the dielectric strength upon the application of the testing voltage, and this at once showed the necessity for extreme care in keeping oil free from foreign matter, such as dirt, fibers, carbonized oil, etc. The necessity for cleanliness has been emphasized again and again with each major increased step in transmission voltages.

In these same tests it was discovered that oil which had been heated in an oven for a considerable period had a much higher dielectric strength than the average oil delivered from the oil manufacturer. There is, of course, the age old tradition that oil and water will not mix, but there seemed no possible explanation for this increased dielectric value of the oil other than that it was due to the elimination of moisture, and that oil was subject to the same difficulties in this regard as most of the other materials of insulation, which at that time had already begun to be studied in considerable detail.

To test the theory, (which from the ancient tradition seemed more or less absurd) that moisture was responsible for the low dielectric value of many oils as delivered, and their changed value on continued heating, the following test was made:

1. Asst. Director of Engineering, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.*



29-123

Extremely small amount of water in increasing quantities was added, each addition being a fraction of a drop per gallon of oil, the oil being very thoroughly agitated after each addition. This gave undoubted evidence that very minute amounts of water in the oil would cause radically decreased dielectric strength. This has been checked again and again during the intervening 35 years and more drastic precautions have been found necessary from time to time as the voltage of transformers has been increased. In fact, it has been found necessary to go to the precaution of treating, not only insulation of the transformer to eliminate moisture, but the whole structure, iron-core frame, etc., and to see that the oil which is introduced, especially in transformers for the higher tension is, as we now say, absolutely dry.

The method of drying oil in the early stages of the transformer oil development was accomplished by giving it an extended heating at moderate temperature; but it was later found that although the temperatures used were relatively low, sufficient oxidation might be started to affect the endurance of the oil against sludging in service. This lead to an investigation of other methods of drying and cleaning the oil, and this is now accomplished by various filtering and centrifuge processes. The requirement is that all suspended matter and all traces of moisture be removed. This is a difficult matter, due to the fact that while the ordinary refining process results in practical elimination of all free water the final moisture to be removed is apparently in solution in the oil.

In the early construction of transformers, the enclosing cases were frequently made of thin material with deep corrugations and with wooden tops, these wooden tops being used for giving added insulation to the outgoing leads. After experience with a number of disastrous fires with constructions of this kind, the underwriters demanded oil having the highest possible flash and fire test, consistent with satisfactory transformer operation. As a result of this requirement, new studies were made and heavier bodied oils adopted. At the same time, attention was given to a better mechanical structure for the transformer cases. The use of this heavier oil resulted in more sluggish circulation and consequently poorer cooling, and apparently little or no decrease in the fire hazard so far as the oil itself was concerned. Soon after this change was made, a new and unexpected phenomenon appeared and this phenomenon is now generally denominated as sludging. This has been perhaps the most difficult matter to deal with that has arisen in connection with transformer oil.

It was soon discovered that a lighter and more fluid oil was in general less subject to sludging than the heavier oils adopted to minimize the fire hazard; but the adoption of these lighter oils merely minimized and did not cure the sludging trouble. As the units became larger and service more difficult, the sludging trouble increased to a point where transformer manufacturers and users found themselves in more or less continual trouble, and very extended studies were made to determine the cause and cure of sludging.

To date, however, no oil has been found which will not deposit sludge if the conditions of its use are sufficiently severe. By very careful selection and by eternal vigilance on the part of the oil refiners and the transformer manufacturers, oil has been produced which under all modern operating conditions is sufficiently free from sludge to give satisfactory service.

Unfortunately, no test has yet been devised which will quickly determine whether or not oil will be free from sludging in service, although an enormous amount of experimental work has been done and many tests have been proposed and used. This question has been considered of sufficient importance to warrant the cooperation of all the nations interested in the production and use of transformer oil to determine, if possible, a satisfactory sludging test. For this purpose, and working through the International Electrotechnical Commission, duplicate samples of oil have been submitted to laboratories of half a dozen or more countries and extensive tests have been entered into for this purpose. At the meeting of the International Electrotechnical Commission in Bellagio, Italy, in October 1927, the report of the various committees and laboratories which have been working on this question for two or three years, was to the effect that the various tests were conflicting in that one test might indicate that a given oil was satisfactory, while another test just as strongly defended, might indicate this oil to be unsatisfactory.

The result of this meeting showed that additional work must be done in order to determine which of the half dozen methods now more or less used would be the satisfactory one to evaluate oil with regard to its sludging characteristics, or whether an entirely new test must be devised. To date, the only safe procedure which has been found has been that of very careful laboratory tests combined with extended service tests, in many cases of several years, to bring the assurance that oil used would show a minimum of sludging troubles.

In the meantime, the oil refiners and transformer manufacturers, and some of the users of transformers, have been making continual studies, both as to the cause and elimination of sludging troubles, and for the securing of oil that would be free from this trouble and would meet all of the other rigid requirements for transformer oil to be used with the highest voltages.

Through a pure accident, discovery was made fairly early in the study of insulating oil to the effect that free sulphur would very greatly impair its insulating value and much study was given at one time to the effect of both free and combined sulphur in minute quantities in insulating oil. In like manner, the residual acids from the refinery treating and other effects of processing the oil, had to be studied with each change in the refining process to bring about the various character-

istics necessary to meet the increasingly exacting requirements on this material.

The manufacturers of apparatus using insulating oils, early found it necessary to establish intimate working relations with the oil refiners and as they were obliged to meet one requirement after another, the refiners developed a special procedure from the selection of crudes in the fields through the final manufacturing process. The characteristics governing selection at the wells include such items as pour point, freedom from wax, amount of sulphur, etc. In some cases special pipe lines are used to transport the crudes selected for the manufacture of insulating oils to the refineries in order that contamination with other crudes shall not occur. During the preparation of the distillate by the vacuum process, rigid inspection for viscosity, flash, and pour point control is maintained and where these oils require treatment with strong sulphuric acid or equivalent, special care is required to see that there is complete neutralization and thorough washing of the oil, and this treatment is sometimes followed by redistillation in order to remove all traces of reaction products remaining after washing.

The advent of outdoor transformer and switching stations imposed an entirely new requirement on transformer and switch oil, namely, the necessity of a very low congealing temperature, or as commonly known, a low-cold test. Transformer oils which were found relatively satisfactory for the old indoor stations had a relatively high-cold test and consequently were not satisfactory for outdoor stations, particularly in cold climates. This requirement for a low congealing temperature is even more rigid in connection with oil switches, which must be free to operate at any temperature which may be reached in the climate where an outdoor switch may be installed.

This requirement for low-cold test oil demanded a whole new series of studies, as the general requirements for indoor apparatus, such as freedom from dirt, moisture, and relative freedom from sludging, etc., had to be maintained. In all such studies it had to be kept in mind that there was a constantly increasing demand for oil and that any oil selected must be available in sufficient quantity to supply this demand. Fortunately, oil has been developed through the cooperation of the oil refiners and transformer manufacturers, which meets the previous requirements, as well or better than any which had been previously used and which has a sufficiently low-cold test to be satisfactory for all ordinary outdoor service.

From almost the beginning of the development of oil for cooling and insulating apparatus, mainly transformer and circuit breakers, the transformer and circuit breaker requirements seemed to be sufficiently divergent so that no single oil would be satisfactory for both services. Certain characteristics of these two services are in opposition to each other, while certain other desirable characteristics coincide. For example, all the early tests and service experience seemed to indicate that the circuit breaker required a relatively heavy and sluggish oil, while the transformer required as light an oil as possible, in order that it might have sufficient fluidity under all conditions to circulate rapidly and transfer the heat from the transformer windings and core to the outer cooling surface. Again, an enormous amount of experimental work was necessary to find an oil which would meet both these services sufficiently well so that utilities would not be required to carry two or three grades of transformer oil and one or more grades of circuit breaker oil. Several years of laboratory and field tests were carried on before there was sufficient confidence on the part of the electrical manufacturers to justify their making a positive assertion that an oil was available in quantity which had all the necessary requirements sufficiently well fulfilled to justify the stand, that this oil could be used as a universal oil for all insulating and cooling work in transformers and circuit breakers.

It has been found that the balance between the two services is very close, and that continued experimental work and the closest possible inspection and testing of oil of this class must be followed in order that the necessary characteristics may be maintained, suitable for all services and for all climates. The advantages of universal oil are so obvious that no arguments are necessary to justify its use.

Throughout the whole history of the development of oil for insulating purposes the question of shipping containers and storage arrangements has been found to be of the utmost importance. In the early days oil was shipped in wooden barrels which were made tight by the use of ordinary glue. This led to interminable trouble from the glue getting into the transformers and other devices, helping to reduce the dielectric strength and to increase the sludging characteristics. Seepage of the oil and the entrance of moisture were common difficulties with such containers.

With the introduction of steel drums, a new kind of trouble developed. Additional dirt and scale were introduced into the oil and it was soon found that the more rigid cleaning and inspection methods did not always eliminate such difficulties. When the use of oil arrived at a point where tank car shipments were necessary, still further difficulties (dirt and water) appeared. It was not at all uncommon in the early days to find a considerable quantity of water in the bottoms of the tank cars containing transformer oil. Condensation of moisture, both on the exposed surfaces of the tank cars and on the surface of the oil itself, were almost inevitable and imperfectly protected openings frequently resulted in additional trouble.

It had been assumed that steel drums with continuous lead washers under the bungs, would be both proof against seepage and proof against entrance of moisture, but this was found not to be the case, and the writer of these notes is familiar with a considerable

number of cases where drums of oil, with bung-up exposed to the weather, were found to contain a considerable quantity of water, when it was absolutely certain that these drums were moisture free on shipment. This was apparently brought about by the heating and cooling of the oil due to the changes in temperatures, between day and night, the resulting pressure and vacuum helping the entrance of water at the bung when this would be covered by rain water.

The oil refiner has accomplished, therefore, only a part of his necessary functions when he has prepared the proper grades of oil. These must be so handled after preparation as to deliver them in the cleanest possible condition to the ultimate consumer. Amounts of contamination which would be inconsequential in lubricating oils will cause no end of trouble in transformer oils, so that an entirely new scheme of preparation of packages and lines of special containers have been found necessary. Every container returned to the refiner must be most carefully inspected and put in such condition that it will not cause any of this contamination. All rust and any traces of foreign materials which may have been stored in the container and every other kind of contamination must be absolutely removed or the container rejected, and many rejections occur in the inspection of such returned containers. The time between the final cleaning and inspection of containers, and the time of filling with the transformer oil and sealing must be an absolute minimum.

Even with all the possible precautions taken, the practise of making individual inspection of oil in drums after allowing a suitable time for foreign matters to collect at the bottom, has been found essential.

There is involved, of course, the shipment of small packages ranging in volume from one to five gallons. Disastrous experiences were run into through the use of ordinary "run of mill" tin cans in the early stages of the business. It later developed that the cause of this was the use of packages, the seams of which had been soldered with acid flux and the latter material had worked into the cans with harmful results to the dielectric strength of the oil which the packages contained. This has resulted in oil refiners installing a special line of machinery for the manufacture of these containers under such control as to insure against the possibility of their becoming contaminated with materials which cause harm to the oil. Not only must these containers be manufactured properly, but they likewise must be tested for leakage and suitably dried before filling, after which they must be immediately capped with the specially designed fittings which have been brought out for this purpose only. Furthermore, it is necessary that inspection be made of a certain portion of the tin containers in order to insure that the quantity of the oil ready for shipment in these packages is running uniformly satisfactory.

During a few months of the year, under carefully controlled conditions, insulating oils of good dielectric strength could be delivered in ordinary tank cars but because of the extreme difficulty of properly drying them before filling, it is unsafe to guarantee deliveries in these tanks at all seasons. As a result of this condition, special cars have been developed with steam coils surrounding the shell, these coils in turn being protected by wooden jackets covered and protected with heat insulating material and thin sheet iron. Only with such equipment as this has it been found possible to properly dry out the cars before filling to such an extent that delivery of dry oil at destination can be assured. With these cars it is possible to not only dry them out before filling is started but during this operation to maintain the temperature of the cars at such a figure as to assure freedom from contamination of moisture in the oil in the cars before the filling is completed and the cars sealed.

A specific example, involving serious difficulty, will be of interest. Serious operating trouble was experienced with some high-voltage circuit breakers, each containing over 3000 gallons of oil. The oil in this particular case was not the standard usually supplied by the manufacturer. As a result of the difficulty the oil had to be completely replaced in an outdoor installation in severe weather, and in the final investigation the trouble was traced to faulty manufacture of the oil and to sloppy methods in its handling.

It was early seen that some sort of cleaning and drying apparatus was essential in connection with the use of oil in some quantity as is required in the average power transmission station. Various schemes of filtering, drying, and cleaning oil have been devised. These included filtering through paper, unslaked lime, and the application of heat and various other schemes. The plan which seems to give the best all-round results and is now quite generally used, is that of the use of a centrifuge type of cleaning device, often combined with a pressure filter. Extensive research work in connection with the universal oil referred to above, has shown that both the transformer and switch oil often may be reconditioned after it has become contaminated, to a point where it is unsatisfactory for use. Apparatus for this purpose is now manufactured and very specific instructions have been worked out for the use of this apparatus in reconditioning and for the testing of reconditioned oil.

Parallel to the research work on the oil itself, many improvements have been made in transformer and circuit breaker designs to aid in eliminating the difficulties encountered in connection with the oil problem. It was early proved through research work that exposure of oil to the air very greatly increased its tendency to sludge and that this increase with a given exposure was more or less a function of the temperature of the oil. This led to transformer case designs, which included the conservator type of case and more recently, the inertair scheme, which automatically provides in service for the elimination of both moisture and oxygen

from contact with the oil in the transformer. While these devices have not changed the tendency of the oil to sludge under a given set of conditions, they have aided very greatly in changing service conditions, thereby inhibiting sludging and maintaining oil in a clean and dry condition.

The final result of all this work, which has extended over a period of more than 35 years, has been to make the modern transformer and circuit breaker with the universal oil, among the most satisfactory devices which goes into the modern equipment for the production, transmission, and utilization of electrical energy. The transformer and circuit breaker manufacturers, together with the oil producers who have brought about these results, realize that only eternal vigilance and continued research will make it possible to maintain and better the conditions which have been arrived at after so much labor and research in the past.

## Discussion

**H. B. Smith:** Last November we had occasion to place 40,000 gallons of transformer oil in an open tank located under a roof. That oil was received from the refinery and when placed in the tank tested at about 36,000 volts on the standard gap. The contents of the tank were given a heat treatment, and with some centrifuging, were brought up to the value of about 42,000, about the first of December. The tank being open, the oil naturally deteriorated in dielectric strength until it had dropped to about 38,000 by the first of April this year.

We then placed in this tank at the bottom on one side, a little electric heater consuming about 3 kw., and that was applied continuously 24 hours a day. This was designed originally to start a column of warmed oil at one side that would rise and flow over the surface to produce a slightly warmer blanket of oil to maintain the surface at a slightly higher temperature than that of the air. The tendency to condense moisture from the air in the oil would then be reduced and the quality of the oil maintained so far as possible. It was found that the temperature of the oil as it reaches the surface is from 5 to 10 deg. above the air temperature.

This process was started about the first of April. Up to the first of July we found that there had been, without other heat treatment or centrifuging, an increase in the dielectric strength. The oil was brought up to about 46,000 on the standard gap. We had expected only to maintain the oil; we had not expected to increase the dielectric strength. On the first of July work had to be discontinued and the top of the tank was covered with canvas. On November 1 the oil tested slightly higher than 46,000 volts.

The only explanation of the increase in dielectric strength that I have had—and I would be glad to have comment on this,—is that this heater raises the oil at the bottom of the tank in contact with the heater elements to a point where we gradually convert any water particles into a vapor which rises with the column of warmed oil and comes to the surface. The vaporization thus creates a continuous slowly dehydrating process at a surface warmer than the air so it does not condense and recombine with the oil. This gives at the heater a temperature which does not produce cracking and a temperature at the surface in contact with the air which does not produce sludging. Whether that proves to be the explanation or not I cannot tell now. It seems a possible explanation.

**J. H. Wilcox:** In regard to cleaning and reconditioning oil that has been in service, Mr. Skinner says "the plan which seems to give the best results is that of the use of a centrifuge type of cleaning device often combined with a pressure filter."

Since under certain conditions this equipment will not satisfactorily recondition oil, perhaps a brief outline of the various general conditions of oil to be handled, will not be amiss here.

The impurities found in transformer oil in normal operation consist almost entirely of water and sludge. These are readily removed by passing through the centrifuge alone.

Transformer oil that has been very badly overheated or burned, as in a transformer breakdown, sometimes is so badly sludged that only chemical-centrifugal treatment will satisfactorily recondition it. The percentage of this type of oil is very small indeed as compared to that from normal operation.

The reconditioning of used circuit-breaker oil is of particular interest at this time, in view of the recent announcement by one of the largest manufacturers of transformers and circuit breakers, authorizing the use of properly reconditioned circuit-breaker oil in transformers. This eliminates the necessity of keeping reconditioned transformer and circuit-breaker oil in separate storage tanks.

The main impurities formed in circuit-breaker oil are carbon, water, and organic acid. The carbon and organic acid are caused by the arc set up in the normal operation of the breaker. Water may be introduced through leakage, condensation, and small amounts from the arcing in which the gases formed may be burned with the resultant products of combustion.

Since the finer particles of carbon are so minute that the centrifuge will not remove them, the combination of a centrifuge and blotter press is widely used for purifying circuit-breaker oil. The centrifuge removes the water and the coarser particles of carbon, and the blotterpress the finer particles of carbon.

The advantage of a combination centrifuge and blotterpress over the blotterpress alone is that by removing the water and coarser particles of carbon, several times as much oil can be put through the blotterpress before cleaning, as if the blotterpress was forced to handle all the impurities in the oil.

Organic acid builds up in the oil to a large extent in direct proportion to the amount of service to which the oil has been subjected. Very often enough moisture and carbon will form in the oil to require purification while the presence of acidity will be hardly detectable.

The combination of the centrifuge and the blotterpress will remove water and carbon satisfactorily from the oil, but will have no effect on the acidity, and oil that has either been in service for a very long time and has had repeated reconditionings with the centrifuge and blotterpress, or been subjected to very severe service, should be tested from time to time for this impurity, as high organic acidity tends to lower the resistance to emulsification and also dielectric strength.

To satisfactorily recondition circuit breaker oil with high acid content or which has been burned or carbonized so badly that it cannot be handled in the combination centrifuge and blotterpress, the following process, which is known as the Sharples chemical centrifugal process, has been developed.

The oil is heated and agitated with water-glass, which agglomerates the fine carbon particles and reduces the acidity; this mixture is then passed through a centrifuge operating as a separator, which separates out the water glass solution carrying most of the impurities.

The separated oil is then mixed with a small amount of fullers earth, which collects any remaining impurities in the oil. The fullers earth is then removed by a second centrifuge operating as a clarifier.

The operation of the process is continuous and the cost of reconditioning oil in this manner is remarkably low.

Oil reconditioned by this process will be the equal of new oil and have the following characteristics: dielectric strength, 22 kv.

or better; precise RE number, 35 seconds; neutralization value, 0.08 mg. of KOH per gram of oil; flash, fire, viscosity, and color, same as new oil.

Only oil having the above characteristics can be considered as properly reconditioned. In some cases used circuit-breaker oil is in such shape that purification by the combination centrifuge and blotterpress will not produce the desired results. Either the Sharples chemical centrifugal process should be used or the oil discarded.

Summing this all up, we have the following main types of oil and the suggested method of purifying each: Transformer oil from normal operation—centrifuge alone; transformer oil, badly sludged or burned—Sharples chemical centrifugal process; circuit-breaker oil from normal operation, satisfactory acidity—combination centrifuge and blotterpress; circuit-breaker oil, badly carbonized or high acidity—Sharples chemical centrifugal process.

This chemical treating process can be operated by the average transformer, or warehouse foreman, without any trouble whatever.

As regards costs, the average cost will run around $11.88 per 1000 gallons treated and a plant of this type will handle approximately 1000 gallons per eight-hour day.

**D. W. Proebstel:** I should like to say a word in regard to the refining of used oils. We had gone over this problem probably along the same lines as Mr. Wilcox and then we decided to make some short cuts.

We first considered the main elements in the refining processes that the oil companies use. In order to be brief I will say that in recovering used oil the process we used was not necessarily dependent upon a centrifuge. We use fullers earth, a tank which has a mixing device in it, steam coils, and a vacuum pump. By mixing fullers earth with the oil, subjecting the oil to heat by the steam pipes, and applying a vacuum we are able to bring the oil that ordinarily would be thrown away back to what appears to be its original condition.

With respect to flash point, fire point, viscosity, low acidity, moisture, and dielectric strength, it is a very easy process to operate and the cost of re-refining oil with us is about 6 cents a gallon.

# Effect of Color of Tank on the Temperature of Self-Cooled Transformers under Service Conditions

BY V. M. MONTSINGER* and L. WETHERILL*

Member, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—The effect of color on the temperature of oil-immersed self-cooled transformers under service conditions has been a mooted question for a great many years. Based upon the relative absorption powers of the various colors often used in painting transformer tanks the lighter colors should give appreciably lower temperatures in hot climate sections. The results of three series of field tests conducted on actual transformers are given in the paper. The results, however, do not show the advantages for the light colors that would be expected, based solely upon the absorption powers of the colors.*

*A method of calculation is used to check the test results, taking into consideration the various factors which apply to a transformer and do not apply to, say, a piece of metal painted and exposed to the sun's rays, such as the ratio of the area of the surface exposed to the sun to the total surface dissipating heat, the difference in thermal capacities, and the condition where in one case the test piece is dissipating heat, as well as receiving heat from the sun, whereas in the other case it only receives heat from the sun. It is shown that when all the factors are taken into consideration the calculated results check very closely the observations. Finally it is shown that the selection of color for repainting transformer tanks exposed to the sunshine should be based primarily on durability and appearance rather than upon color, since the difference in temperature resulting from a tank painted black and aluminum, or even white, will seldom exceed 1 or 2 deg. cent.*

## I. General

THE predetermination of the ultimate temperature rise of a transformer operating in the shade, with constant load and ambient conditions is a comparatively simple problem.

Also, the effect of color on the temperature rise under these conditions can be calculated, knowing the emissivity of the color and the percentage of losses dissipated by radiation and convection for a given color.

In service, however, we have a more complicated set of conditions to deal with, which makes it more difficult to predict the effect of color on the temperature of transformers. For example, only a part of the tank's surface is exposed to the sun's rays. The part exposed is absorbing heat while the part unexposed is not affected by the sun's rays. The tank is exposed only a part of the time—during the day, while at night conditions may be altered; *i. e.*, some surfaces that are advantageous in the sunshine are disadvantageous in the shade. Also the solar intensity varies during the day which still further complicates the problem.

The impression is prevalent that a transformer tank if painted with a light color will operate at an appreciably lower temperature in the sunshine than if painted black. This impression is based either upon the relative absorption powers of the colors or upon tests made on apparatus under conditions not applicable to transformer conditions.

All tests which have been made on transformers under service conditions show, however, that the gain resulting from painting the case a light color is hardly worth considering.

The objects of this paper are (1) to give the results of the available field tests and (2) to reconcile the results of these tests with theoretical results; in other words, to show by a method of calculations, that we should not expect an appreciable gain for the light colors for the conditions under consideration.

## II. Results of Tests Made Under Service Conditions

Three series of tests made under service conditions

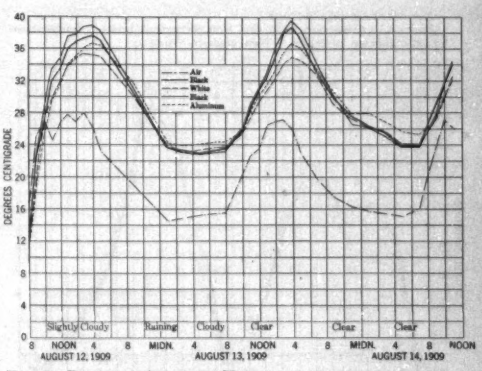


FIG. 1—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—no load

Five kv-a. transformers with plain tanks temperature by thermometer in top oil. Tests made in Pittsfield

(at Pittsfield, Mass., Fresno, Calif., and Dallas, Texas) are given and analyzed.

*Pittsfield Tests.* In 1909 a series of tests was made at Pittsfield, Mass. Some 5- and 50-kv-a. lighting transformers were tested in an exposed location. Tests were made with tanks painted black, white, and aluminum. The transformers were loaded by the

*Both of the General Electric Company, Pittsfield, Mass.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 8-6, 1929.*

"loading back" method which insured equal loads on all pairs.

Figs. 1 and 2 show the results of tests made holding normal excitation only on the units. It will be noticed that the transformer with the black tank averages 1 to 2 deg. cent. hotter than the one with the white tank. The maximum difference which was 4 to 5 deg. cent. occurred about 4 p. m., the black tank being the warmer. During the early morning the white tank was slightly warmer than the black one. The temperature of the aluminum painted tanks was as a rule between those of the black and white tanks.

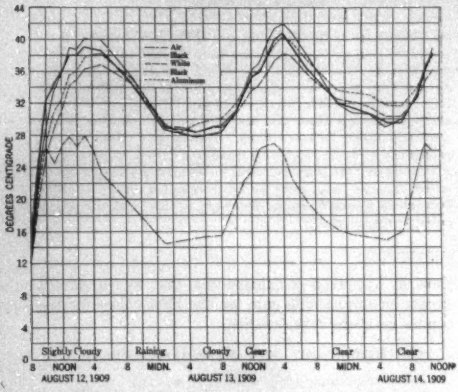


FIG. 2—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—no load
50 kv-a. transformers with cast iron corrugated tanks. Temperature by thermometer in top oil. Tests made in Pittsfield.

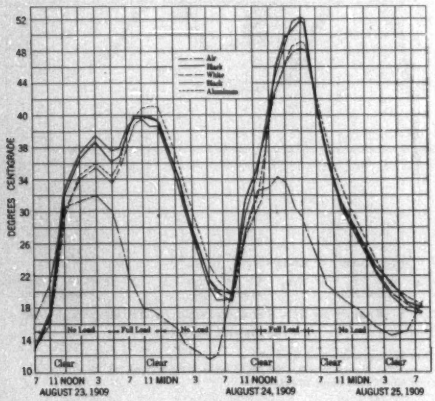


FIG. 3—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—six-hour full-load
5-kv-a. transformers with plain tanks. Temperature by thermometer in top oil. Tests made in Pittsfield

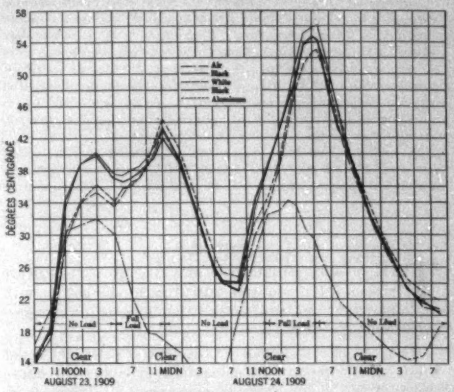


FIG. 4—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—six-hour full-load
50-kv-a. transformers with cast iron corrugated tanks. Temperature by thermometer in top oil. Tests made in Pittsfield

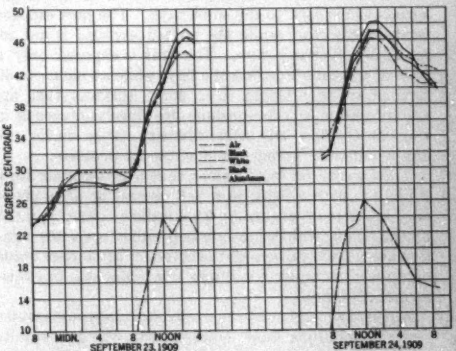


FIG. 5—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Continuous full load
5-kv-a. transformers with plain tanks. Temperature by thermometer in top oil. Tests made in Pittsfield

Figs. 3 and 4 show the results of tests made with six hour full load following normal excitation at 5 p. m. and at 11:30 a. m. The effect of the color is not quite as great in this case as in the excitation run: the maximum

difference occurring at 4 p. m. showing only 3 deg. cent. in favor of white paint over black.

Fig. 5 shows the result of a continuous full load run. The difference in temperature is still less, the maximum difference being about 2 deg. cent. Other tests also indicate that while some colors may seem to make considerable difference on light or intermittent loads, the advantage decreases considerably on continuous full load.

*Fresno Tests.* In 1922 Messrs. Moore and Moulton of the San Joaquin Light and Power Corporation conducted a long series of tests[1] on several 3-kv-a. lighting transformers in the sunshine at Fresno, Calif., where the air reached a maximum temperature of 38.8 deg. cent. (102 deg. fahr.).

Fig. 6 shows curves of the oil temperatures in cases of

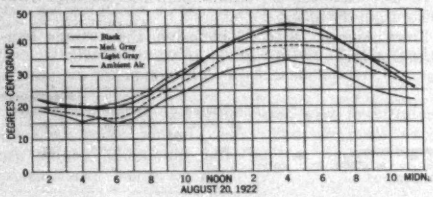


FIG. 6—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

No excitation—no load
Three kv-a. transformers with plain cases. Temperature by thermometer in top oil. Tests made in Fresno, California

various colors without either load or excitation on the transformers. While these data may not be of any particular commercial value as applied to loaded transformers, since the differences in temperature will be less under load conditions, they at least indicate the relative degree to which the different colored idle transformers are affected by the sunshine.

The curves in Fig. 6 show that the average rises over the air temperature covering a 24-hr. period are as follows:

| Color of case | Transformers not excited. Average rise over air | |
|---|---|---|
| | °F | °C |
| Black | 12.4 | 6.9 |
| Medium gray | 12.9 | 7.16 |
| Light gray | 6.6 | 3.67 |

The fact that the medium gray is slightly higher than the black is probably caused by small mechanical differences.

Fig. 7 shows curves of temperature with the transformers excited but without load. The following average temperature rises were formed over a 24-hr. period starting 10 a. m., August 21.

1. See Bibliography for references.

| Color of case | Transformers excited—No load average temperature rise over air | |
|---|---|---|
| | °F | °C |
| Black | 19.8 | 10.8 |
| Medium gray | 21.5 | 12.0 |
| Light gray | 19.0 | 10.55 |

It will be noticed that the differences in temperature rise are less than without excitation.

Fig. 8 shows similar data for full load runs. The fol-

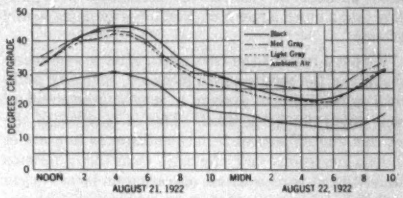


FIG. 7—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—no load
Three kv-a. transformers with plain cases. Temperature by thermometer in top oil. Tests made in Fresno, California

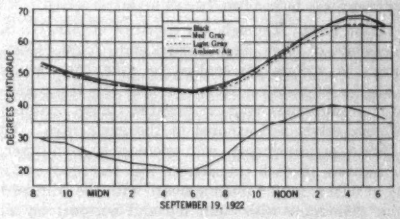


FIG. 8—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—normal load
Three-kv-a. transformers with plain cases. Temperature by thermometer in top oil. Tests made in Fresno, California

lowing average temperatures were observed during a 24-hr. period starting 8 p. m., September 19.

| Color of case | Average ambient | | Transformers with normal load temperature rise over air | | | |
|---|---|---|---|---|---|---|
| | | | Deg. fahr. | | Deg. cent. | |
| | Deg. fahr. | Deg. cent. | Avg. | Max. | Avg. | Max. |
| Black | 85.5 | 29.7 | 43.3 | 53.2 | 24. | 29.5 |
| Medium gray | 85.5 | 29.7 | 42.5 | 52.1 | 23.4 | 29.0 |
| Light gray | 85.5 | 29.7 | 41.0 | 48.6 | 22.8 | 27.0 |

Many more tests were made than shown above. However, the general results were the same.

The following comments are from the report by Moore and Moulton on these tests. They will be of

interest since they were made by operating engineers who have transformers operating in one of the warmest sections of the United States.

"The number of successive days during which tests were made and the consistency of the results leaves little doubt as to the accuracy of the full load tests. The fact that a gray paint will not reduce the oil temperature more than 3 or 4 deg. fahr. or 1 or 2 deg. cent. during the extremely hot weather encountered in the San Joaquin Valley seems established. This was a disappointment in view of the seemingly prevalent belief that a much larger reduction for gray paint would be found.

"We have reached the conclusion, after a very careful study of the results herein recorded, that any additional expenditure to procure a gray case instead of black would not be justified. This is in view of the fact that the differences in temperature do not under full load conditions vary any more than the difference obtained from various makes operating under identical conditions. Assuming that gray or black tanks are available at equal cost and that experience shows that gray paint stands up in service as satisfactorily as the black, we would be inclined to favor the medium gray tank. We feel very strongly however, that any expenditure to repaint black cases now in service would not in any way be justified."

*Dallas Tests.* Through the courtesy of Mr. O. S. Hockaday of the Texas Power and Light Company, the writers are enabled to give the results of a series of tests conducted in 1924 on three 150-kv-a. transformers with corrugated tanks painted different colors and exposed to the sun's rays. To calibrate the transformers with reference to each other, temperature of each transformer was recorded every day at 6:00 p. m. for about a month with the standard paint (aluminum with black top and bottom) on all three tanks. The average reading for each transformer showed that the northeast unit ran 1 deg. cent. cooler than the middle one and the southwest unit ran 0.3 deg. cent. cooler than the middle one.

The northeast unit was then painted all aluminum, the middle unit all black, and the southwest unit left with aluminum with black trimmings. The average results of the readings taken from July 25 to September 17 are given below. As in the calibrating run, one reading was taken at 6 p. m. each day. Fair weather occurred during 80 per cent of the test period.

From July 25 to September 17 inclusive the average temperatures are:

| | Northeast all aluminum | Middle all black | Southwest alum. black trim. |
|---|---|---|---|
| Observed temperature | 47.7 | 49.6 | 49.1 |
| Correction from calibrating run | 1.0 | 0 | 0.3 |
| Corrected temp. (deg. cent.) | 48.7 | 49.6 | 49.4 |

Thus the all-aluminum runs 0.9 deg. cent. cooler than the black.

That the 20 per cent of cloudy or rainy weather has not had any great effect can be seen from the three following sets of figures each based on seven consecutive days of fair weather.

From August 6 to 12 inclusive the average temperatures are:

| | Northeast all aluminum | Middle all black | Southwest alum. black trim |
|---|---|---|---|
| Observed temperature | 49.1 | 50.4 | 50.1 |
| Average correction from calibrating run | 1.0 | 0 | 0.3 |
| Corrected relative temp. | 50.1 | 50.4 | 50.4 |

In this case the all aluminum runs 0.3 deg. cent. cooler than the black.

From August 18 to 25 inclusive, the average temperatures are:

| | Northeast all alum. | Middle all black | Southwest alum. black trim std. |
|---|---|---|---|
| Observed temp. | 50.5 | 52.5 | 52 |
| Average correction from calibrating run | 1.0 | 0 | 0.3 |
| Corrected relative temp. | 51.5 | 52.5 | 52.3 |

In this case, the all aluminum ran 1.0 deg. cent. cooler than the all black whereas the aluminum black trimming ran 0.2 deg. cent. cooler.

From August 28 to September 10 inclusive, the average temperatures are:

| | Northeast all alum. | Middle all black | Southwest alum. black trim |
|---|---|---|---|
| Average observed temp. | 48.3 | 51.7 | 51.0 |
| Correction | 1.0 | 0 | 0.3 |
| Corrected relative temp. | 49.3 | 51.7 | 51.3 |

The all aluminum ran 2.4 deg. cent. cooler and the aluminum black trim ran 0.4 deg. cent. cooler than the all black tank.

Table I gives the results of readings taken every half hour from 10 a. m. to 6 p. m., October 1. Based on the average readings corrected, the all aluminum tank ran 0.7 deg. cent. cooler and the aluminum-black trim ran 0.5 deg. cent. warmer than the all black tank. This last set of readings is perhaps the most reliable since it took account of the entire day and afternoon when the aluminum color shows up to best advantage.

*Pittsfield Tests on Aluminum Tanks.* The preceding tests showed a slight advantage for aluminum but they were made under circumstances favorable to aluminum. Tests made with the tanks shaded from the sun show the disadvantages of aluminum.

Some tests were made in Pittsfield in 1925 to show the

TABLE I

TESTS MADE BY TEXAS POWER AND LIGHT COMPANY

Three Transformers–150 Kv-a., Corrugated Tanks, Bank Capacity 450 Kv-a.

| Time | Kv-a. | Ambient temperature | Transformer temperature | | |
|---|---|---|---|---|---|
| | | | Aluminum | Black | Alum. black trim. |
| 10:00 a. m. | 394 | 23 | 31 | 33 | 32 |
| 10:30 | 394 | 23 | 31 | 34 | 33 |
| 11:00 | 396 | 23 | 32 | 34 | 33 |
| 11:30 | 425 | 24 | 33 | 35 | 34 |
| 12:00 m. | 445 | 25 | 34 | 36 | 35 |
| 1:00 p. m. | 360 | 27 | 36 | 37 | 37 |
| 1:30 | 343 | 28 | 36 | 38 | 37 |
| 2:00 | 373 | 29 | 37 | 38 | 38 |
| 2:30 | 370 | 29 | 37 | 38 | 38 |
| 3:00 | 365 | 29 | 38 | 39 | 38 |
| 3:30 | 357 | 29 | 38 | 39 | 39 |
| 4:00 | 324 | 28 | 39 | 40 | 40 |
| 4:30 | 321 | 27 | 39 | 40 | 40 |
| 5:00 | 376 | 26 | 38 | 40 | 39 |
| 5:30 | 384 | 24 | 38 | 40 | 39 |
| 6:00 | 374 | 22 | 37 | 39 | 39 |

Data furnished through the courtesy of O. S. Hockaday of the Texas Power and Light Company.

effect of aluminum paint on operation in the shade (indoors) on two standard 25-kv-a. transformers having plain cases.

Two units having the same losses were first tested with their tanks painted black. The two tanks were then painted aluminum and the test repeated with results shown below.

| Transf. No. | Room temp. deg. cent. | Top oil rise deg. cent. | | Max. tank surf. rise deg. cent. | |
|---|---|---|---|---|---|
| | | Black | Alum. | Black | Alum. |
| 1 | 26 | 37.2 | 46.3 | 32.5 | 41.0 |
| 2 | 26 | 36.7 | 47.6 | 32.0 | 41.6 |
| Average | 26 | 37. | 47. | 32.3 | 41.3 |

The oil rise of the aluminum tank was 126.5 per cent of the black tank. The maximum tank surface rise of the aluminum tank was 126 per cent of the black tank. This checks very well the estimated percentage of about 130 per cent, assuming a low temperature emissivity of 0.55 for aluminum paint.

The effect of aluminum paint in increasing the temperature indoors is lessened on radiator and tubular tanks, but may still be appreciable. A tank with four rows of tubes will run by calculation about 12 per cent hotter with aluminum paint when operating in the shade. Even on the largest tanks with radiators as close to each other as possible, it is estimated that aluminum paint will increase the temperature rise about 7 per cent when operating in the shade.

## III. Development of Method of Calculating Effect of Color

In considering the effect of the sun's rays on a transformer it must be remembered that the radiant heat received is only that passing through the projection of the transformer on a plane perpendicular to the sun's rays. In order to predict the effect of the sun it would be necessary not only to know the strength of the sun's rays as a function of the time of day, but also to know the projection of the tank on a plane perpendicular to the sun's rays as a function of the time of day. It would be possible to do this, but this laborious process can be avoided.

Instead of taking readings of the sun's intensity on a plane perpendicular to its rays and correcting for the

*TABLE II

LOW TEMPERATURE TOTAL EMISSIVITIES

| | |
|---|---|
| Silver, highly polished | 0.02 |
| Platinum " " | 0.05 |
| Zinc " " | 0.05 |
| Aluminum " " | 0.08 |
| †Monel metal, polished | 0.09 |
| Nickel " | 0.12 |
| Copper " | 0.15 |
| Stellite " | 0.18 |
| Cast iron " | 0.25 |
| Monel metal, oxidized | 0.43 |
| Aluminum paint | 0.55 |
| Brass, polished | 0.60 |
| Oxidized copper | 0.60 |
| Oxidized steel | 0.70 |
| Bronze paint | 0.80 |
| Black gloss paint | 0.90 |
| White lacquer | 0.95 |
| White vitreous enamel | 0.95 |
| Asbestos paper | 0.95 |
| Green paint | 0.95 |
| Gray paint | 0.95 |
| Lamp black | 0.95 |

*These data are the result of investigations made by the Bureau of Standards, the British National Physical Laboratory, General Electric Research Laboratories, and several eastern universities, and were collected by W. J. King of the General Electric Co.

†Questionable because of scant or inconsistent data.

variation in projected area of the transformer in order to correlate the sun's intensity with the behavior of a transformer with a special finish, it is possible to use a similar transformer with a standard black paint for an instrument to measure the effect of the sun. This effect as determined, will be automatically corrected for

*TABLE III

COEFFICIENT OF ABSORPTION OF SOLAR RADIATION

| | |
|---|---|
| Silver, highly polished | 0.07 |
| Platinum " " | 0.10 |
| Nickel " " | 0.15 |
| †Aluminum " | 0.15 |
| Magnesium carbonate | 0.15 |
| Zinc oxide | 0.15 |
| †Steel | 0.20 |
| Copper | 0.25 |
| White lead paint | 0.25 |
| Zinc oxide paint | 0.30 |
| Stellite, polished | 0.30 |
| Light cream paint | 0.35 |
| Monel metal, polished | 0.40 |
| Light yellow paint | 0.45 |
| Light green paint | 0.50 |
| Aluminum paint | 0.55 |
| Zinc, polished metal | 0.55 |
| Gray paint | 0.75 |
| Black matte | 0.97 |

*These data are the result of investigations made by the Bureau of Standards, the British National Physical Laboratory, General Electric Research Laboratories, and several eastern universities, and were collected by W. J. King of the General Electric Co.

†Questionable because of scant or inconsistent data.

variation in the projected surface and its relation to the total surface effective in dissipating heat. The effect will be expressed as, $r$, the average solar intensity in watts

per sq. cm. of effective tank surface. The same curve will hold for any transformers having similar tanks and similar locations close by. The behavior of any such similar transformers can be calculated if their losses, thermal characteristics, and initial temperature are known, as well as the manner of variation of ambient temperature.

The following symbols will be used:

$C$ = Thermal capacity in joules per sq. cm. per degree centigrade divided by 3600.
$E$ = Coefficient of total emissivity at low temperature.
$F$ = Ratio of average tank surface temperature rise over ambient to top oil rise over ambient.
$L$ = Transformer loss in watts per sq. cm.
$P$ = Pressure in atmospheres.
$r$ = Effective intensity of solar radiation in watts per sq. cm. of effective surface.
$r_a$ = Average value of $r$ over one hour period.
$S$ = Coefficient of solar absorption. See Table III.
$T_o$ = Top oil temperature in degrees Kelvin.
$T_{oa}$ = Average value of $T_o$ over one hour period.
$T_{oi}$ = Value of $T_o$ at beginning of one hour period.
$\Delta T_o$ = Change in $T_o$ in one hour.
$T_1$ = Temperature in degrees Kelvin of surface absorbing heat radiation.
$T_{1a}$ = Average value of $T_1$ over one hour period.
$T_2$ = Temperature in degrees Kelvin of surface radiating heat.
$t$ = Time in hours.
$W_C$ = Watts per sq. cm. dissipated by convection.
$W_R$ = Watts per sq. cm. dissipated by radiation.
$W_T$ = Watts per sq. cm. dissipated by radiation and convection.

It is shown in Appendix A that the following empirical expression can be used for the total loss by convection and radiation from a vertical plane in watts per sq. cm.

$$W_T = 6.50 \times 10^{-4} (T_2 - T_1)^{1.19} \quad (1)$$

Equation (2) is the general differential equation for the thermal behavior of a self-cooled transformer, subjected to the rays of the sun.

$$S r + L = 6.50 \times 10^{-4} (T_2 - T_1)^{1.19} + C \frac{d T_o}{d t} \quad (2)$$

The approximate expression for the total heat dissipated given in Equation (1) is used. In the term containing the thermal capacity, $C$, the top oil temperature, $T_o$, is used as the thermal capacity has been worked out on that basis,[2] although not all of the oil and tank is actually that hot. In the expression for heat dissipation the tank surface temperature $T_2$ is used. In the cases analyzed the tank surface temperature is not available, so the tank surface rise is assumed to be proportional to the top oil rise.

Thus:

$$T_2 - T_1 = F(T_o - T_1) \quad (3)$$

$$T_2 = F (T_o - T_1) + T_1 \quad (4)$$

Substituting this expression for $T_2$ in Equation (2) gives Equation (5).

$$S r + L = 6.50 \times 10^{-4} F^{1.19} (T_o - T_1)^{1.19} + C \frac{d T_o}{d t} \quad (5)$$

As the data consist of hourly readings we assume that the differential equation holds for average values over a one-hour period. Any errors caused by this assumption are too small to have any effect.

In what follows intervals of one hour will be considered; $T_{oa}$, $T_{1a}$, and $r_a$ will be used to represent average values over a period of one hour and the average value of $\frac{d T_o}{d t}$ will be represented by $\Delta T_o$, the change in $T_o$ on one hour.

Rewriting Equation (5) to use average values gives

$$S r_a + L = 6.50 \times 10^{-4} F^{1.19} (T_{oa} - T_{1a})^{1.19} + C \Delta T_o \quad (6)$$

This is not in a convenient form because both $T_{oa}$ and $\Delta T_o$ are unknown. For $T_{oa}$ substitute $T_{oi}$, the initial value, plus $\Delta T_o/2$; which gives the average value, assuming linear variation.

$$S r + L = 6.50 \times 10^{-4} F^{1.19} \left( T_{oi} + \frac{\Delta T_o}{2} - T_{1a} \right)^{1.19} + C \Delta T_o \quad (7)$$

This can be simplified by expanding $[(T_{oi} - T_{1a}) + \Delta T_o/2]^{1.19}$ by the binomial theorem and dropping the third and subsequent terms.

$$S r_a + L = 6.50 \times 10^{-4} F^{1.19} (T_{oi} - T_{1a})^{1.19} + \frac{1}{2} 6.50 \times 10^{-4} \times 1.19 F^{1.19} (T_{oi} - T_{1a})^{0.19} \Delta T_o + C \Delta T_o \quad (8)$$

Solving Equation (6) for $F$ and $r_a$, and Equation (8) for $\Delta T_o$ gives Equations (9) (10), and (11).

$$F = \left( \frac{S r_a + L - C \Delta T_o}{6.50 \times 10^{-4} (T_{oa} - T_{1a})^{1.19}} \right)^{.84} \quad (9)$$

$$r_a = \frac{6.50 \times 10^{-4} F^{1.19} (T_{oa} - T_{1a})^{1.19} + C \Delta T_o - L}{S} \quad (10)$$

$$\Delta T_o = \frac{S r_a + L - 6.50 \times 10^{-4} F^{1.19} (T_{oi} - T_{1a})^{1.19}}{C + 3.88 \times 10^{-4} F^{1.19} (T_{oi} - T_{1a})^{0.19}} \quad (11)$$

Equations (9), (10), and (11) are sufficient to handle cases where hourly readings are available.

In order to calculate the top oil temperature of a transformer with a special coat of paint operating in the sunshine, it is necessary to have the following information.

(a) Hourly readings of the ambient temperature during the period of the test.

(b) The initial temperature of the test transformer.

(c) Hourly readings of the top oil temperature of an indicating transformer with a tank and location similar to the test transformer. The indicating transformer

probably does not need to be identical with the test transformer or to carry the same load, although in the tests referred to later this was done for convenience.

(d) Effective surface, losses, and thermal capacity of the two transformers. Strictly speaking, the effective surface is not required as a study of the equations will show that any surface area may be assumed and the constant $F$ will come out of such a value as to correct the results. In this paper the actual effective surface

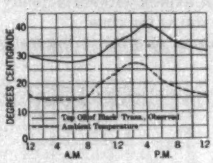


FIG. 9—NO-LOAD HEAT RUN

Made on 50 kv-a. transformers exposed to sun at Pittsfield. A black corrugated tank was used

is used to show more clearly the physical significance of the mathematical steps.

Having these data the process of solution may be summarized in the following steps.

(a) Apply Equation (9) to the identical transformer with standard paint for a period of one hour during which the transformer receives no solar radiation. This may be taken from operation at night, indoors or in the shade. From Equation (9) calculate $F$. It is well to take several hours and use the average value of $F$.

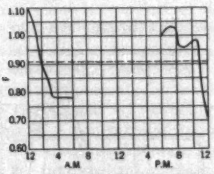


FIG. 10—VALUES OF CONSTANT $F$

Ratio of tank rise to top oil rise, for 50 kv-a. transformers during period in which solar intensity is zero. Dotted line gives average value

(b) Apply Equation (10) to a transformer with a coat of standard paint having a low temperature emissivity, $E$, of 0.95 and a known co-efficient of solar absorption, $S$. This transformer must be similar to the one with the paint under test in the construction of the tank and in location. They must both have the same situation with respect to the sun. Equation (10) should be applied to the tank with the standard finish during the portion of the test in which the tanks are receiving solar radiation, about 6 a. m. to 6 p. m. From Equation (10) $r_a$ is determined for each one-hour period.

(c) Apply Equation (11) to the transformer with the paint undergoing test, the behavior of which is to be determined. $F$ was determined as given in paragraph (a). During the hours in which the tank received sunlight $r_a$ was determined as given in paragraph (b). At other times $r_a$ is zero, as the tank is receiving no solar

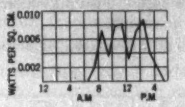


FIG. 11—WATTS PER SQ. CM. INTENSITY OF SUN

As determined from data on 50 kv-a. transformer with black tank. Average intensity over effective surface is used

heat. Start with the initial top oil temperature $T_{oi}$ and calculate the change $\Delta T_o$ by Equation (11). Then $T_{oi} + \Delta T_o$ gives the final temperature at the end of the hour, which becomes the initial temperature for the following hour. The process is repeated, each time giving a new value of $T_o$ one hour after the last, until the end of the test period is reached.

## IV. CALCULATION OF EFFECT OF COLOR

The first example selected for calculation is the data for August 13, shown in Fig. 2. Two 50-kv-a. transformers with corrugated tanks operated at normal excitation and no load. The curve for the black tank is shown on a larger scale in Fig. 9.

The calculation of $F$, the ratio of tank surface rise to top oil rise, for the hours before sunrise and after sunset is plotted in Fig. 10. The average value is 0.92. Cooney[2] gives the average value of this constant as 0.85 for all self-cooled transformers.

Fig. 11 gives the calculation of $r_a$, the effective intensity of solar radiation, during the daylight hours. The points are not all accurate as the data were taken only to the nearest half degree, and two- or three-tenths

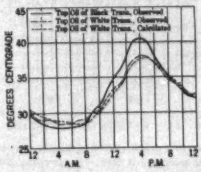


FIG. 12—COMPARISON OF TOP OIL TEMPERATURE OF 50-KV-A. TRANSFORMERS OPERATING IN SUN

of a degree is enough to cause considerable variation in $r_a$. Such an error is not serious as an equal error in the other direction will occur in the next hour and counteract the effect of the first one.

The calculation of the top oil temperature of the second transformer which is painted white ($S = 0.30$) is plotted in Fig. 12 and compared with the observed values. The top oil temperature of the black transformer is also plotted, to show that the calculated

curve has really taken care of the effect of the color and come decidedly closer to the observed curve of the white transformer than that of the black one.

The second example selected for calculation is the data shown in Fig. 8 for September 19. Black and light gray cases were used. Two 3-kv-a. transformers were run at full load in the sun.

Figs. 13 to 16 give the data, calculations, and results.

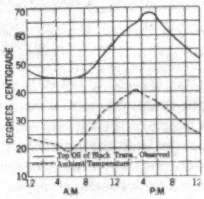


Fig. 13—Full Load Heat Runs

Made on three-kv-a. transformers exposed to sun, by San Joaquin Light and Power Corporation at the Fresno O. Street Substation, September 19, 1922. A black smooth tank was used

The agreement shown in Fig. 16 between calculated and observed top oil temperature is as close as can be expected.

In this case the transformers were carrying full load and $L$, the loss per sq. cm. of effective tank surface, varies with the temperature. As the variation in loss is not very great it is sufficient to use the loss corresponding to the coil rise over oil (15 deg. cent. in this case) plus the top oil temperature at the beginning of the one-hour period.

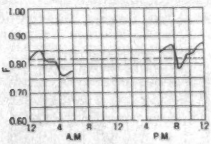


Fig. 14—Values of Constant $F$

Ratio of tank rise to top oil rise, for three kv-a. transformers during period in which solar intensity is zero. Dotted line gives average value

It is possible to show that the maximum values of $r_a$ are about the right order of magnitude to agree with the intensity of solar radiation. The ratio of the sun's intensity to $r_a$ should be approximately the ratio of the effective surface to the projected area of the tank on a plane perpendicular to the sun's rays.

The maximum intensity of the sun's rays on a clear day at sea level[3] is about 0.094 watt per sq. cm. Corrugated tanks were used at Pittsfield, so we would expect the effective surface to be on the order of ten imes the projected surface, which would mean that $r_a$ would be one-tenth of the solar intensity. Actually the maximum value of $r_a$ is 0.0089 watt per sq. cm. while one-tenth of the maximum solar intensity is 0.0094 watt per sq. cm.

In the California tests smooth tanks were used and we would expect that the maximum value of $r_a$ would be about one-sixth of the maximum solar intensity. The maximum value of $r_a$ is 0.0091 while one-sixth of the solar intensity is 0.0157. These figures give as close a check as we can expect without actually recording the intensity of the sun at the time.

The chief sources of error in the method used is the

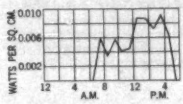


Fig. 15—Watts Per Sq. Cm. Intensity of Sun

As determined from data on three-kv-a. transformer with black paint. Average intensity over effective surface is used

possibility of small mechanical differences in the two transformers used giving them slightly different thermal characteristics, and the effect of wind. Mechanical differences will not often cause more than one or two degrees error and usually less than one degree. If there should be a discrepancy the possibility of error due to mechanical differences could be investigated by making heat runs on the two transformers. In the cases investigated very little discrepancy was found so we must conclude that the pairs of transformers were very nearly identical.

The wind may affect the results a great deal as a small

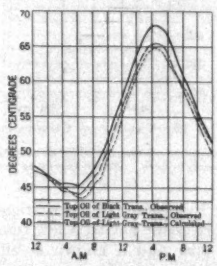


Fig. 16—Comparison of Top Oil Temperature of Three Kv-a. Transformers Operating in Sun

amount of wind will greatly increase the convection loss by disturbing the air film adhering to the tank surface. Errors due to wind, if it is present, appear as errors in the curve of $r$ shown in Fig. 12. When the resulting incorrect curve of $r$ is used to calculate the behavior of the second transformer the error is partly compensated

for. However, this method of calculating could not be expected to give good results on a windy day.

One reason why it is possible to consider average values over a period of an hour is that the method automatically corrects the resulting errors. If the first step results in an error making the transformer too hot, the transformer will dissipate too much heat later and counteract the effect. An error caused in any way will gradually die out.

## V. Conclusions

*A. In Shade.*

1. The temperature rise of a transformer in a tank

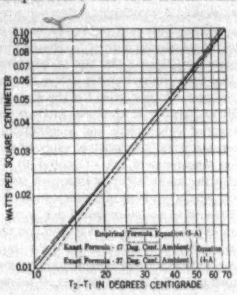


Fig. 17—Comparison of Empirical and Exact Formulas for Total Heat Dissipated

painted with a non-metallic paint is practically independent of the color.

2. Metallic paints radiate less heat than non-metallic paints and may cause a transformer to over-heat.

3. A plain aluminum painted tank will run approximately 30 per cent higher temperature rise* than if painted with a non-metallic paint.

4. Thirty per cent represents the maximum increase of temperature rise caused by painting a tank with aluminum instead of a non-metallic paint. If a plain tank is finished with a surface having a lower emissivity than aluminum the temperature increase naturally will be more than 30 per cent, increasing to about 75 per cent* where the emissivity is very low such as for polished silver, nickel, etc.

5. As the surface of a tank becomes more and more convoluted (with tubes and externally connected radiators) the effect of a metallic paint in increasing the temperature rise becomes less and less, in extreme cases getting as low as 7 per cent.*

*B. In Sunshine.*

1. The improvement resulting from using special paint on self-cooled transformer tanks either plain or with convoluted surfaces is in service very small, hardly enough to be worth considering. Even under the most favorable conditions (white lead paint, smooth tank surface, and a hot sunny day) the gain is not more than 2 deg. cent. average during a 24-hr. period and in some cases less than 2 deg. cent.

2. The repainting of transformer tanks in the field for operation in the warmer sections of the country should be based upon the consideration of durability and appearance rather than upon color.

*Refers to oil rise. The winding rise over room will be increased the same number of degrees as the oil rise is increased.

## Appendix A

Heat energy is dissipated from a surface exposed to the air in two ways, convection and radiation. The losses of heat energy by these two methods are independent and may be calculated separately.

It has been shown that the convection[4] loss from transformer tanks can be expressed with fair accuracy by the equation:

$$W = 2.17 \times 10^{-4} P^{1/2} (T_2 - T_1)^{1.25} \qquad \textbf{(1a)}$$

This equation gives the loss from a vertical surface and its application must be limited to vertical surfaces of reasonable heights.

The heat energy dissipated by radiation[5] is given by the Stefan-Boltzman law:

$$W_R = 5.7 \times 10^{-12} E (T_2^4 - T_1^4) \qquad \textbf{(2a)}$$

In this equation $E$ is the coefficient of total emissivity. For most non-metallic paints the value is 0.95 approximately.

The total heat dissipated from a plain surface $W_T$ is the sum of the two.

$$W_T = 2.17 \times 10^{-4} P^{1/2} (T_2 - T_1)^{1.25} + 5.7 \times 10^{-12} E (T_2^4 - T_1^4) \qquad \textbf{(3a)}$$

If $P$ is one atmosphere and $E$ is 0.95 Equation (4a) results:

$$W_T = 2.17 \times 10^{-4} (T_2 - T_1)^{1.25} + 5.4 \times 10^{-12} (T_2^4 - T_1^4) \qquad \textbf{(4a)}$$

Equation (5a) is a much simpler approximate expression for $W_T$.

$$W_T = 6.50 \times 10^{-4} (T_2 - T_1)^{1.19} \qquad \textbf{(5a)}$$

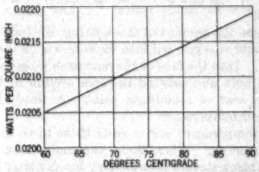


Fig. 18—Watts Loss Per Sq. Cm. of Tank Surface at Full Load *vs.* Winding Temperatures—for Three-Ky-a. Transformers

The close agreement existing between the exact and empirical expressions is best shown graphically. In Fig. 17 the dotted and dashed lines represent the amount of heat dissipated from a vertical surface for ambient temperature of 27 deg. cent. and 37 deg. cent. respectively, according to Equation (4a). The solid

line is obtained by using Equation (**5a**). It is seen that over the operating range the empirical expression gives satisfactory results.

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2. *Predetermination of Self-Cooled Oil-Immersed Transformer Temperatures before Conditions are Constant*, by W. H. Cooney, A. I. E. E. TRANS., Vol. 44, p. 611.

3. "Effect of Solar Radiation upon Balloons," Bureau of Standards No. 128.

4. *Temperature Rise of Sationary Electrical Apparatus as Influenced by Radiation, Convection, and Altitude*, by V. M. Montsinger and W. H. Cooney, A. I. E. E. TRANS., Vol. 43, p. 13.

5. *Free Convection of Heat in Gases and Liquids—II*, by Chester W. Rice, A. I. E. E. TRANS., Vol. 43, p. 131.

## Discussion

**W. C. Smith:** It is evident, from data submitted in the paper, that the operators who are using aluminum paint, and who have standardized it over their entire system, should immediately change over all indoor self-cooled transformers, or those shaded from the sun, to some other color such as gray.

The thought has occurred to me, and I believe there are some data existing on the point, that the use of sunshades in the desert localities in this part of the country would be very beneficial.

If anyone has that information at hand, I should appreciate a word on the matter, as I know from actual test that the effect of the sun beating down on a transformer tank will raise its temperature at least 20 to 30 deg. over the ambient shade temperature.

In conditions such as exist in the Imperial Valley, it would seem desirable perhaps to bring out the high-tension connections horizontally to a sufficient distance to allow of a sunshade, protecting the transformers from the hotter day temperatures, and then paint the tank a non-metallic dark color.

**C. H. Holladay:** We have had a few experiments on the effect of the color, not on the transformer tanks, as shown in this paper, but on our Florence Lake Dam at Big Creek. To prevent entrance of water the surface of the dam, about 400,000 sq. ft., was painted with black bituminous paint. After it had been on several years it was noticed that the paint had deteriorated in a number of places and had come off in small flakes. It seemed that possibly it was due to the heating effect of the sun on the black surface.

To determine the amount of this heating, the bulb of a recording thermometer was grouted into the concrete on the face of one of the arches. Into the face of the next arch we grouted another thermometer bulb and painted the area around it, 10 ft. by 10 ft., with one coat of aluminum paint. A third thermometer recorded the air temperature.

The daily temperature curves from these three thermometers are very interesting. When there was sunlight on the face of the dam, the black surface became very much hotter than the air or the aluminum surface. On a typical clear day in November, the three temperatures are the same at 8 a. m. The peak is reached at about 1 p. m. with a black-surface temperature of 107 deg. fahr., aluminum 64 deg., and air 50 deg. After 3 p. m. the temperatures drop very rapidly though there is enough heat stored in the concrete to keep it about 10 deg. above the air. Even on a cloudy day there is as much as 6 deg. difference between the aluminum and black.

We made still another series of tests to determine the difference in temperature on the interior of cottages when the roofs are painted with aluminum and with dark paint. Two identical cottages having the same exposure were chosen. The roof of one was painted with our standard dark brown paint, while the other roof was painted with aluminum. We then took daily temperature charts in both houses.

In the day the temperature of the house with the dark roof was 3 to 6 deg. fahr. above that with the aluminum roof. During the summer both houses would come to a peak at about five in the afternoon. At night the house with the dark roof cooled off faster and reached a temperature of three deg. fahr. below the house with the aluminum roof.

**J. F. Dunn:** We should like to call attention to the statement that the results of the tests show such a slight difference between light and dark paints as effecting final temperature that it is "hardly worth considering." In the results of the Pittsfield tests the statement is made that the transformer with the black tank averages 1 deg. to 2 deg. cent. hotter than the one with the white tank. A maximum difference which was 4 deg. to 5 deg. cent. occurred about 4 p. m., the black tank being the warmer. Most of us are familiar with the emphasis placed by transformer manufacturers on the rise of temperature and also with the fact that for a slight decrease in rise of temperature for a given output we pay a higher price for the apparatus. In view of this, the offhand manner in which the authors deem the saving of an average say of 2 deg. cent. and a maximum of say 4 deg. cent. in temperature rise is surprising, especially in view of the fact that when transformers are subjected to the acceptance temperature run the manufacturers insist on correcting the rise for the viscosity of the cooling oil, which under the worst conditions would amount to not more than 1 deg. cent.

This average difference of say 2 deg. cent. in the relation between oil temperature and output rating of the transformers may amount to 5 per cent or more in the maximum percentage of safe load on the transformer for a given hottest oil temperature. This fact is brought out in a very interesting way in the recent paper by E. T. Norris entitled *Safe Loading of Oil Immersed Transformers*, (A. I. E. E. Quarterly TRANS., Vol. 48, October 1929, p. 1206). The slope of the curve developed by Mr. Norris as shown in Fig. 4, giving the relation between hottest oil temperature and maximum percentage safe load for a given case shows up as one-half, or for a given maximum temperature rise an increase of percentage of safe load in the ratio of 1 to 2.

It should be further noted that the experiments showing this average of 2 deg. cent. were conducted at Pittsfield, Mass. and that for southern and tropical countries where the intensity of the sun's rays is considerably greater, we should have a corresponding increase in the average temperature between light-colored and dark-colored transformers. The experiment made in Texas should not be considered seriously because of the fact that one reading per day was taken at 6 p. m., when the minimum difference was to be expected between light and dark colors and the transformers were not properly calibrated. The difference noted in the calibrating run might possibly be caused by mechanical and electrical differences in the transformers and not be due to position or radiation. The difference between the light and dark colors obtained in California as shown in Fig. 6 may be noted as 6 deg. cent. at 4 p. m. as against 4 deg. cent. at 4 p. m. in Fig. 2 and 4½ deg. cent. at 4 p. m. in Fig. 1. Figs. 1 and 2 were taken at Pittsfield and Fig. 6 was taken in California some 500 miles nearer the equator. This illustrates the point made above as to the results to be expected in the warmer territory. We are much interested in aluminum paint for transformers in very warm climates and hope that some further experiments will be conducted either to prove or disprove its desirability for use in these localities. Unfortunately, the experiments in California did not include aluminum paint.

There seems to be a discrepancy between the conclusions of the authors as given on the ninth page under "A: In shade," paragraph 5 which is quoted as follows: "As the service of the tank becomes more and more convoluted (with tubes and externally connected radiators) the effect of a metallic paint in increasing

oil temperature becomes less and less, in extreme cases getting as low as 7 per cent," and the results and conclusions reached by the late John R. Allen, a noted heating and ventilating engineer. These results and experiments are recorded in Vols. 24 and 26 of the *Journal* of the American Society of Heating and Ventilating Engineers, pp. 274 and 109 respectively. He states that "In radiators having a large proportion of rating surface such as pipe coils or wall coils, the effect of paint will be more marked than in 4-column radiators having a comparatively small radiating surface in proportion to the convecting surface."

All finely ground materials have about the same radiation constant; therefore all paints made from finely ground pigments will have the same effect. Metals have a poor radiating effect so that any paint involving a flake metal such as bronze will have a low radiating constant.

**J. S. Moulton:** This paper supplements the field data previously available with calculations confirming the several field tests referred to. It is gratifying to have such calculations confirm the tests made by Mr. L. J. Moore and me during 1922. At that time, we concluded that the repainting of transformers when received from the manufacturers, or when taken down from service, was not justified by any improvement in temperature characteristics secured by the use of a light colored paint.

The data of Messrs. Wetherill and Montsinger show that paint may be selected for its durability in service, or to conform with a distinctive color scheme, if one is in effect, without consideration of resulting effect upon the temperature.

**V. M. Montsinger:** The discussion of Mr. Dunn criticizes the Dallas tests because of the fact that readings were taken at 6 p. m. instead of at the hottest part of the day. While the latter would have been preferable, it will be noted from Table I that the conclusions would not be altered to any essential degree.

I note that he has compared the black and white tank with normal excitation only on the transformers at Pittsfield. Comparing these tanks with continuous full load, Fig. 5, the maximum difference is 2 deg. cent. instead of 4 to 5 deg. cent. All the tests show that the difference decreases as the temperature increases. This is pointed out in the paper. Furthermore, the difference between the black and aluminum is about one-half the difference between that of black and white, meaning that the maximum difference is about 1 deg. cent. under full-load conditions. The average difference is probably less than 1 deg. cent. Factory tests are made under full load conditions rather than under no-load conditions.

Mr. Dunn has taken the curve in Fig. 4 of Mr. E. T. Norris' paper to prove that for a difference of 2 deg. cent. in oil the load may vary 5 per cent. This curve does not attempt to show how the load varies with temperature rise but rather the difference in temperature between the oil and hot spot as the load increases. For the purpose of illustration, Mr. Norris assumes that at 100 per cent load the hot spot rise over the oil is 20 deg. cent., and that the hot spot should not exceed 105 deg. cent. For 100 per cent load the oil then should not exceed (105 — 20) = 85 deg. cent. For 140 per cent load the hot spot rise is $20 \times \left(\frac{140}{100}\right)^2 = 39.2$ deg. and the oil, therefore, should not exceed (100 — 39.2) = 65.8 deg. cent. In other words, when the oil reaches the value shown on this curve for any given load the load should either be reduced or removed. This is quite different from the way in which Mr. Dunn has used it.

Answering the point in question, namely, the variation in per cent load with temperature rise, calculations made by the proper formula will show that the load can be increased about 1 per cent or slightly more for each 1 deg. cent. increase in hot-spot temperature. This question will be discussed in detail by the writer in a paper entitled *Loading Transformers by Temperature* to be presented at the Winter Convention, 1930.

With reference to our conclusions and the late John R. Allen's conclusions on the effect of color in the shade on tanks with varying ratios of radiating and convecting surfaces, if he quotes Mr. Allen correctly there is no disagreement. Both say the same thing, but in a different way. I should like to point out that our data do not show that the light colors cause as large an increase in the temperature in the shade as is shown by Mr. Allen's data. We are unable to explain how Mr. Allen obtained such large differences. The most reliable emissivity factors do not check these results. In fact, recent tests reported by C. H. Fessenden and Axel Marin in an article entitled "New Data on Heating Effect of Painting Tubular Radiators" in *Heating and Ventilation Magazine*, February 1929, show much smaller differences than those claimed by Mr. Allen.

The following is quoted from p. 64 of this report:

"Prof. John R. Allen presented a paper about 18 years ago in which it was reported that paints having a flake-metal base when applied to a cast-iron rectangle reduced the heat emission of the radiator as much as 25 per cent. Although the statement frequently has been made that the form and distribution of the surface of the radiator would influence such quantitative data, the erroneous impression seems to be rather widespread that aluminum paint reduces the effectiveness of *any* radiator by about 25 per cent."

These invesitgators found that the difference between an unpainted radiator and one painted with aluminum was in the order of 7 to 8 per cent. The largest difference they found was between aluminum and flat brown paint, this being around 10 or 11 per cent.

# Population as an Index to Electrical Development

BY N. B. HINSON[1]
Member, A. I. E. E.

IN making plans for the future in the electrical utility business it is necessary to make estimates of future growth. Various methods have been used. The usual method is to plot growth of one kind or another against time. This gives an upward curve which is difficult to project mathematically and usually is misleading if projected ahead more than two or three years in a rapidly growing territory. In the electrical utility field various values have been plotted against the number of consumers or meters. This is all right for past data but for the future the number of meters or consumers would have to be estimated and this would depend upon the increase in population, especially if all the present population now had service.

This led to the use of population as the abscissa rather than time or consumers with any of the values desired as ordinates. This gives a straight line for practically all present values and the future is a straight line projection with a simple formula. The lower end of the line does not usually cross both zero points and this fact gives the changing values per unit of population.

The various values at the very beginning of the industry do not give the correct trend as only a small number of people had service, but the business is now and has been for the last ten or fifteen years developing very uniformly and consistently and these later values give the correct past trend.

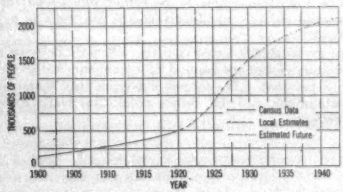


FIG. 1—POPULATION SERVED DIRECT BY SOUTHERN CALIFORNIA EDISON CO.

Population for the past, at least up to the last census date for any city, town, or county, is easy to obtain and in many locations accurate estimates up to 1928 are available. However, when it comes to projecting these values for ten or fifteen years into the future quite a problem arises, particularly in rapidly growing territory such as is found in numerous locations in the United States.

Raymond Pearl in his book, "Studies in Human Biology" has developed a theory of population growth which gives a curve of population for various cities and countries that describes past growth with great precision and fidelity, and predicts future growth in a more satisfactory manner than the usual method of projecting ahead with the same percentage increase as the place under consideration has had for a number

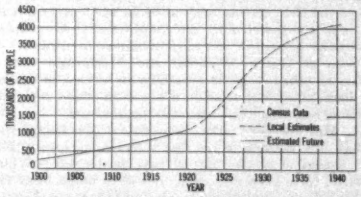


FIG. 2—TOTAL POPULATION SERVED BY SOUTHERN CALIFORNIA EDISON CO.—INCLUDING WHOLESALE

of years back. This type of curve Mr. Pearl calls the "Logistic" type curve though it has come to be known in our territory as the "Fly Curve" from one of the experiments he performed and describes in an article entitled the "Biology of Population Increase."

The population curves used for the territory which will be described were compiled from the census data for 1900, 1910, and 1920, and from estimated values of various Chambers of Commerce, Local and State Officials, Statistical Bureaus, etc., for the years 1921 to 1928. These curves were then projected ahead from the known data, the rate of growth, according to Mr. Pearl's conclusions, decreasing as the saturation point is approached. See Figs. 1 and 2.

The system on which these studies have been made is that of the Southern California Edison Company serving in Central and Southern California. Southern California, in which most of the small towns and cities are located, is one of the fastest growing communities in America. More than 99 per cent of all the houses in the territory covered have electric service and this value has been more than 90 per cent for ten years. Also the Southern California Edison Company supplies 62 per cent of the total kilowatt-hours direct to their own retail consumers, and 38 per cent wholesale to other companies and cities for redistribution and to the railways.

1. Southern California Edison Co., Los Angeles, Calif.

*Presented at Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., September 3-6, 1929.*



29-124

In considering gross revenue, kilowatt-hours generated, and kilowatt peak, the total population in the territory served direct and indirect were used, and for horsepower connected, number of meters, and system betterment budget, the population served direct was used. These are illustrated in Figs. 3 and 4.

As will be seen, the population served is plotted uniformly and the date at which so many people were in the territory, or it is estimated from the population curve will be in the territory, is set opposite that number of people. The values of kilowatt-hours or horsepower or whatever is being plotted are set opposite the year in which they occurred. These points lie in such a position that in all cases a straight line can be drawn through the group, and this line projected ahead gives values for the future.

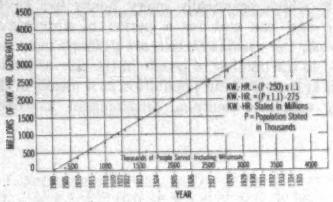


Fig. 3—Total Kw-Hr. Generated Yearly—Uniform Population

Since the values for the future are dependent on population which is an estimation, such future values for more than five years are liable to be in considerable error, but it supplies a means of getting values which can be calculated and is much better than projecting curves which are changing their shape from year to year. Figs. 5 and 6 illustrate the same data plotted against time. This will illustrate the difference in the two methods. Also as additional data are available such as the census for 1930, the population curve may change but it is only necessary to move the date to its correct position on the various studies. In other words, the straight line values are such that they show the value when there is a given number of people, irrespective of the date on which it occurs.

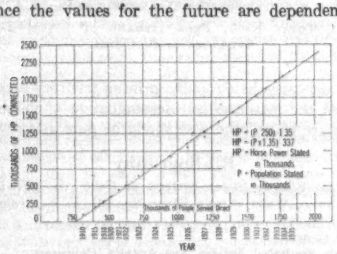


Fig. 4—Total Retail Hp. Connected—Uniform Population

The foregoing are all with regard to the system in general and assist in forecasting so far as generation and transmission are concerned. A study was made of the load on small stations supplying cities and towns so as to be able to forecast the transformer capacity necessary in the future, particularly when new stations are contemplated so as to install transformers that will not have to be changed within a year or two.

These studies were started on a load density basis of kv-a. per square mile. These studies were made on ninety cities and towns in Southern California, ranging from 1500 to 150,000 in population, the average being 10,000. The original study was made in 1925. This same study was made for the year 1928, using seventy cities which are incorporated, and on which it is possible to get a fairly accurate estimate at this time of population.

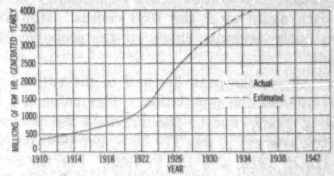


Fig. 5—Total Kw-Hr. Generated Yearly—Uniform Time

The maximum kv-a. demand for the year 1928 was used and the area in square miles of the developed territory, that is the territory actually built up including all vacant lots. This gave a value of kv-a. demand per square mile which varied from 270 to 2700. There seemed no logical relation between areas so the population for each city was taken and the cities grouped according to size, that is average values for all cities 1000 to 5000, 6000 to 10,000, 11,000 to 21,000, 21,000 to 30,000, 31,000 to 40,000, and 41,000 to 150,000, the last group including only five cities.

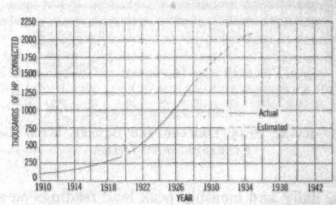


Fig. 6—Total Retail Hp. Connected—Uniform Time

The values of kv-a. per square mile for each group plotted against the average population for each group gave practically a straight line as shown on Fig. 7. Spotting all seventy of the cities shows how close they follow the average. This gives a simple formula for kv-a. per square mile for various sized cities and this

times the developed area in square miles gives the peak demand. This has been applied to several cities for which the data are available for five or ten years in the past and they check very satisfactorily. These apply only to a unit city; if two cities have combined and each had its own business district the combined city will give values of kv-a. per square mile that are too high, that is a city of 25,000 people developed as a unit has a greater load density per square mile than two cities each of 12,500 combined as one city. This system of future peak load projection has been used to set up the probable demand for all cities five years in the future. There has been some increase in the kv-a. demand per square mile during the last three years for any sized city so that it will be necessary to check these data again after the 1930 census. However, it gives a fairly accurate check on the probable future demands.

Fig. 8 shows the peak demand of the various cities plotted against the population. This value has been increasing yearly due to the increased use per capita of electric energy; it was 110 kv-a. per 1000 people in 1920, 125 in 1925, and 150 in 1928. For the smaller cities the peak demand is higher due to less diversity of load. This is also seen in the kv-a. per square mile being lower for the smaller cities as the development is not as uniform as the larger cities.

For making forecasts for the future no hard and fast rules will apply and all these means are used to check from as many angles as possible the future value. The

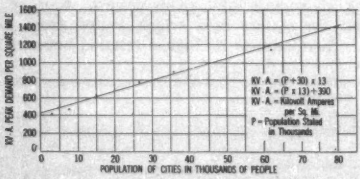


Fig. 7—Kv-A. Peak Demand per Square Mile—Group Averages of 70 Cities

regular daily and monthly peak load readings on each station which have been kept for a number of years can be projected ahead as a check on future loads.

The distribution system is divided into thirty-two districts with an average of 13,000 customers, the minimum being 3000 and the maximum 50,000. Each of these districts has separate records and is set up similar to a small company. Any data that check up satisfactorily for all the districts may be used for the system. From these data yearly, average values of people per meter, per distribution transformer, per distribution transformer kv-a. rating, per pole, per mile of line, per substation, kv-a. capacity, per substation peak kv-a., per kw-hr. per year consumed can be determined. These values change from year to year but only slightly and these changes can be determined.

These data would not be the same in various parts of the country as the saturation is different and the character of the territory is different. Such values worked out for a particular territory enable fairly accurate estimates to be made of many of the factors entering into its electric utility business. In a territory in which practically every house has electrical service and has had for a period of approximately ten years, the various factors are perhaps more nearly related to the number of people in the city or territory.

This system of using population as a means of determining values of electrical development has been of

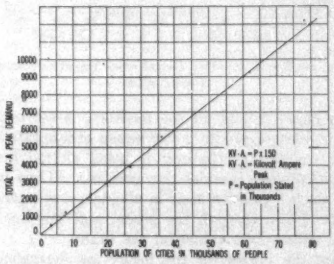


Fig. 8—Total Kv-A. Peak Demand of Cities—Group Averages of 70 Cities

great assistance in a rapidly growing territory and has enabled the mathematical determination of values in the future which otherwise would be pure guess work.

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## Discussion

**C. I. Anissimoff:** I think Mr. Hinson has given an excellent paper; I object, however, to one expression he used, namely, "mathematical determination." I think, it is fortunate, it is not mathematical; it is determination "by sight," I should say, from the graphs. It could have been mathematical only if the complex phenomena involved were "idealized," which in our case means distorted, and the results would have little practical value, if any. The results of Mr. Hinson's method, however, can be used to advantage.

Also I want to ask a question. Ordinarily estimated future load is plotted against time; Mr. Hinson plots against population. I want to ask what is the advantage of changing the coordinates as Mr. Hinson did?

**M. A. Lissman:** Forecasters of population have made use of that branch of mathematics dealing with probability and statistics. While uninitiated people may hold the opinion that this branch of science is rather crude, I can assure them that the mathematical equipment desirable to deal with problems of population forecasting is of the highest order. At first glance, it appears paradoxical that in probability problems, provided the effect investigated is the result of numerous small independent causes, then the less we know about these causes the more satisfactory the treatment of the problem. In fact, if very large trends are apparent, then the effect of such known tendencies must be considered separately, because large known tendencies cannot be included in the statistical treatment.

**N. B. Hinson:** I might have gone into more detail regarding some of the methods of determining population. First of all, if you try to guess at the total population of a section of the state, and say there are so many people in Southern California without any further study, you are likely to be far from the real facts, but if you break the territory up into counties, cities, towns, rural communities, and analyze each of them, and then add them all together, you get a resulting population which is much more accurate than if you are guessing at the large section.

If we plot time against population, or time against any electrical values, we get a curve which is fairly flat in the early years but rises rapidly toward the end. In Southern California where we have had a rapid increase in population this upward trend is very pronounced. If you attempt to guess where it is going in the future you have quite a problem. Of course, you can say it is going to grow at the same rate of increase as during a certain period in the past. If you did this for this territory, using the last eight years as the index, in a very few years you would have an infinite increase in one year. From observing these you know that such an assumption is wrong, except for a short time in the future.

When you plot the same data against uniform population, with the date opposite the number of people in the territory at that time, you get practically a straight line. If you project this line ahead it is still correct for the particular number of people, though it may not be correct for the date which appears there. In other words, if you are talking about 3,000,000 people, and you have a certain value for 3,000,000 people, and a date, we will say 1930, if this number of people doesn't happen to arrive until 1932 all that is wrong is the date, so we just change the date. By that I mean, if you are making one of these projections, the thing you have to change, after you discover your population trend is different, is the date and you still have the value, stating that there will be so many kilowatt-hours for so many people.

The census data for 1910, and 1920, were used in these studies and we are looking forward to the 1930 census as another definite point on our population curve. We have also used the number of customers which we have connected year by year as a check on population growth. The yearly school attendance records give another check. There are numerous local bodies which have data on population and these are all used as checks on information obtained from other sources.

These various values are plotted together and if they all show the same trend, we have a good reason for assuming that the population curve is nearly correct. When they start to bend over you have a good idea that the population is not growing at the same rate as it did in the earlier period.

With regard to Mr. Anissimoff's question of the term "mathematically"—I meant only that if the data are correct, it is easy to determine the ratio between the two sets of data and to project it mathematically into the future.

# Flames from Electric Arcs

BY J. SLEPIAN[1]
Fellow, A. I. E. E.

*Synopsis.—The origin of flames from arcs is considered. Their low dielectric strength is attributed to ionization, and their rate of recovery of normal dielectric strength is computed. The large influence of temperature is brought out. Computations are given and experiments described which show how flames can be reduced by passing the arc gases through narrow channels.*

## Flames from Electric Arcs

It is well known that heavy current arcs in air such as occur in switches of usual construction give off large volumes of luminous gases or flames. These flames have a large volume in comparison to the arc itself which forms a core of comparatively small section, and it is quite certain that they have a much lower temperature and much lower electrical conductivity than the arc core itself.[2] Nevertheless these flames constitute one of the most troublesome features of switching in air in circuits of more than a few hundred volts, because they have a very small dielectric strength and will cause breakdown if they bridge live parts. This low dielectric strength persists for a relatively long time, and because of their large volume, considerable clear space must be provided in which these flames may dissipate themselves.

### I. Origin of Flames

In general, these flames consist of gases which have passed through the arc core itself. The temperature of the arc core is more than 2500 deg. cent.[3] and hence the density of the air or gas there is one-ninth or less of the density of the air originally occupying the arc core space. The air displaced by the formation of the arc core will thus make up some of the flame, and if the flame temperature is more than 1000 deg. cent., will occupy a volume more than four times the volume of the arc core. This, however, will account for only a small portion of the arc flame.

The motion of the air in the neighborhood of the arc while it is playing, probably accounts for a great deal more of the flame. When the motion of the air is regular, (stream line motion) and such as does not tend to change the cross-sectional area of the core, the arc will merely move with the air, and little air will pass through the arc core itself. When, however, the motion of the air is such as to tend to increase the cross-sectional area of the core, and particularly when the air motion is turbulent, then a considerable volume of air will pass through the arc core. Such turbulent motion is to be expected from the magnetic reactions in a heavy current arc and when an arc is moved laterally very rapidly as in a magnetic blowout switch.

The gases and vapors given off by the electrodes will also contribute very largely to the flame. When the end products of the combustion of the electrode materials are gases, as in the case of carbon for example, the contribution of large volumes to the flame will be apparent; but also when the electrode vapors may be expected to condense to finely divided solids or liquids in the relatively cool flame, as in the case of copper and other metals, the projection of large volumes of vapor from the electrodes longitudinally into the arc will cause a turbulent motion which will bring large volumes of air through the arc core.

Flames will also result from gases which do not pass through the arc core, if the arc passes near a material which is decomposed by heat into an easily combustible gas. Thus if the inner faces of the arc chute of a switch are lined with fiber, paper, or similar material, a great increase in the volume of flame will result. In fuses of the expulsion type where the arc plays in a fiber tube, a large part of the flame is probably due to burning decomposition products of the fiber.

### II. Low Dielectric Strength of Flames due to Ionization

The dielectric strength of the flames from arcs is astonishingly low. Many instances are known where the flames from arcs caused breakdown between parts having potential differences of less than one thousand volts, and separated by inches through the air. The normal breakdown between such electrodes would be 50,000 volts or more.

This very low dielectric strength indicates that the flames are in a state of considerable ionization, a conclusion which would be reached from their luminosity also. If the flames were only very slightly ionized, like ordinary air, we should expect a dielectric strength approximately proportional to their density, that is reduced from normal only three or four fold. The presence of ions in large numbers causes the field produced by an applied potential to be considerably distorted, so that the breakdown voltage is lowered very considerably, and made approximately independent of electrode separation. This is explained in the author's paper, *Extinction of an A-C. Arc*, (A. I. E. E. Quarterly Trans., Vol. 47, October 1928, p. 1398).

The flame gases which have passed through the arc

1. Consulting Research Engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

2. Hagenbach, "Der Elektrische Lichtbogen," *Leipzig*, 1924, p. 257.

3. *Ibid.*, p. 216.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.*



29-130

core are of course intensely ionized at the moment they leave the core. Recombination reduces the density of ionization very rapidly at first, but later the rate of recombination becomes much smaller so that ionization may persist for some little time.

The temperature of the flame gases very shortly after they leave the core is far too low to account for any ionization on a purely thermal basis, as may be seen by calculating from Saha's equation.[4] The only other obvious source of ionization is chemical effects such as arise in combustion flames.[5] Where there are combustible materials in the flame this ionization may persist for a long time, since the rate of combustion is limited by the rate of diffusion of oxygen into the flame which is a relatively slow process.

## III. Dielectric Strength of an Ionized Gas

In the paper, *Extinction of an A-C. Arc*, referred to above, the following formula is derived for the breakdown voltage of ionized air.

$$V = 2.42 \times 10^{13} \times \left(\frac{273}{T + 273}\right)^2 \times \frac{1}{n} \qquad (1)$$

Here $V$ is the breakdown voltage, $T$ is the absolute temperature, and $n$ is the number of ion pairs per cm.$^3$ of the gas. It will be noticed that the distance between the electrodes does not appear in the equation.

This equation, which must be regarded as only very approximate, was derived by considering conditions in the layer of air immediately adjacent to the cathode. On the application of voltage, this layer becomes at once denuded of electrons, and until breakdown occurs, bears practically the whole impressed voltage.[6] The thickness of this layer for a given impressed voltage was calculated on the hypothesis that the positive ions were relatively immovable in space, and breakdown was assumed to occur when the maximum gradient in this layer reached $30{,}000 \times \frac{273}{273 + T}$ volts per cm.

Actually, the positive ions do move, and their motion will cause the gradient in the cathode gas layer to be considerably less than calculated. Also the gradient for breakdown at lower voltages is much greater than $30{,}000 \times \frac{273}{273 + T}$ volts per cm. Equation (1) then can only be used to give very rough orders of magnitude. It can be very useful, however, in bringing out the strong influence of the temperature of the gas, and the value of any means for reducing the density of ionization of the gas.

4. *Phil. Mag.*, 40, 1920, p. 972.

5. *Handb. d. Physik*, Geiger & Scheel, Berlin, 1927, Vol. XIV, p. 190.

6. For detailed quantitative treatment of the physics of these deionized sheaths around electrodes in ionized gases see Langmuir & Mott Smith, *General Elec. Rev.*, Vol. XXVII, 1924, pp. 449, 538, 616, 762, 810.

## IV. The Decay of Ionization in a Gas

Immediately after leaving the arc core, if the gases are not exposed to deionizing surfaces of solids, the density of ionization is practically entirely determined by the rate of recombination of the ions. This rate of recombination is proportional to the density of positive ions and also to the density of negative ions, so that we have[7]

$$-\frac{dn}{dt} = \alpha n^2 \qquad (2)$$

If $\alpha$, the recombination constant, was really constant in time Equation (2) could be readily integrated giving

$$\frac{1}{n} - \frac{1}{n_0} = \alpha t \qquad (3)$$

$n_0$ being the initial density of ionization, and if $n_0$ is very large, as it is in the arc core itself, $\frac{1}{n_0}$ is negligible and Equation (3) becomes

$$n = \frac{1}{\alpha t} \qquad (4)$$

Plimpton[8] has found that $\alpha$ for ions generated by X-rays shows an aging effect, being considerably smaller for older ions than for newly formed ones. This result may, however, be due to the non-uniform distribution of ions formed by X-rays. For air at normal pressure and temperature several investigators have found $\alpha = 1.6 \times 10^{-6}$ for "aged" ions. $\alpha$ is found to be greatly affected by the temperature, increasing very rapidly as the flame cools. Meager experimental data show that $\alpha$ varies inversely as the cube of the temperature. Equation (2) might then be better written

$$-\frac{dn}{dt} = \alpha (t, T)\, n^2 \qquad (5)$$

showing explicitly the dependence of $\alpha$ upon the time $t$, and absolute temperature $T$.

However, since it is not the purpose of this paper to determine actual numerical values of the dielectric strength of arc flames, but merely to get orders of magnitude and to show the great influence of temperature, we shall work with the following assumptions:

1. We shall take the value of $\alpha$ for air at normal pressure and temperature to be $7.6 \times 10^{-6}$.

2. We shall assume that the flame gases, immediately upon leaving the arc core, take on the absolute temperature $T$, and keep that value of temperature thereafter. We shall assume that $\alpha$ varies inversely as the cube of the absolute temperature. Thus

$$\alpha = 7.6 \times 10^{-6} \times \left(\frac{273}{T + 273}\right)^3 \qquad (6)$$

7. Townsend, "Electricity in Gases," *Oxford*, 1913, Chap. VI.

8. *Phil. Mag.*, (6), 25, 1913, p. 63.

## V. The Dielectric Strength of Flames from Arcs

From the standpoint of the designer of switches, it is the dielectric strength of flames from arcs which is important, rather than their luminosity, temperature, or other properties. Where the ionization of the flames is almost entirely residual, or that is, where there is little combustible material in the flames, Equations (1), (4), and (6) above serve to determine the dielectric strength of the arc flame as a function of the flame temperature $T$ and the time $t$, in the resultant equation

$$V = 1.84 \times 10^9 \left( \frac{273}{T + 273} \right)^5 t \qquad (7)$$

A few numerical values will best bring out the significance of Equation (7) and particularly the great influence of the temperature. Consider the dielectric strength of the flame 0.01 sec. after it has left the core of the arc, during which time it may have traveled several feet.

DIELECTRIC STRENGTH OF FLAME
0.01 Seconds after leaving arc

| Temperature of gas | Density of ionization ion pairs/cm.³ | Dielectric strength volts |
|---|---|---|
| 2000°C | $7.6 \times 10^9$ | 450 |
| 1500°C | $3.6 \times 10^9$ | 1,610 |
| 1000°C | $1.3 \times 10^9$ | 8,300 |
| 500°C | $3.0 \times 10^8$ | 98,500 |
| 0°C | $1.3 \times 10^7$ | 1,840,000 |

The advantage gained by cooling the flame gases, which is considered desirable instinctively by switch

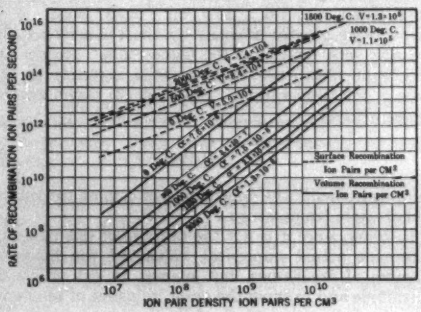


Fig. 1

designers, is forcibly brought out in the table. However, the direct instantaneous effect of lowering the flame temperature is only slight. The great increase in dielectric strength follows the lowered temperature shortly in time as a result of the large increase in the recombination rate of the ions in the cooler gas.

## VI. Recombination of Ions at Surfaces of Solids

When an ionized gas is exposed to the surface of a solid, ions are lost by diffusing to the surface and being caught and recombining there. Under proper circumstances this loss of ions to surfaces of solids may far exceed the loss by recombination in the volume of the gas.

The rate of loss of ions to a surface will be given by

$$N = \frac{1}{4} n \nu \qquad (8)$$

where $n$ is the density of ions in the gas adjacent to the surface, $\nu$ is the mean velocity of agitation of the ions, and $N$ is the number of ions reaching the surface per

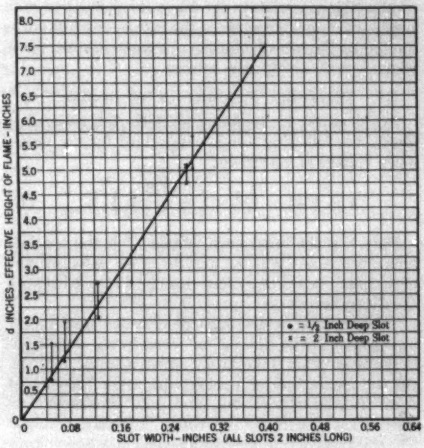


Fig. 2

cm.² per sec.[9] When the velocity of agitation of the ions of one sign exceeds that of the ions of the other sign, an electric field sets itself up at the surface which retards the faster ion, so it is the velocity of the slower ion which must be used in Equation (8).

The curves of Fig. 1 give a comparison of the recombination rates of ions at a surface with the recombination rates of ions in the volume of the gas for conditions which are of practical importance in the flames from switch arcs. We see that the recombination rate per cm.² of surface is 100 to 1,000,000 times as great as the recombination rate per cm.³ of the gas immediately adjoining.

If the gas is at rest relative to the surface, the layer of gas immediately adjacent to the surface becomes very quickly denuded of ions, and then ions which further reach the surface must diffuse through this layer of deionized gas. The surface then loses most of its deionizing efficacy. If, however, the gas is in rapid turbulent motion past the surface, fresh portions of the

9. Langmuir & Mott-Smith, *General Elec. Rev.*, XXVII, 1924, p. 450.

ionized gas are constantly exposed to the surface, and its deionizing activity is maintained.

## VII. Experiments of C. L. Denault on Reduction of Flames from Arcs

The considerations given above of the influence of temperature and the deionizing effect of surfaces would lead one to expect that the flames from arcs would be greatly reduced in volume if the gases from the arcs were compelled to pass through narrow channels between solid walls. This is beautifully confirmed by

Fig. 3

experiments of C. L. Denault (which have not yet been published).

In these experiments an arc was formed by blowing a fuse in a soapstone chamber with an open top, 9/16 in. by 2-1/8 in. and 1-9/32 in. high. Covers were then placed over the chamber which compelled the escaping flame to pass through slots of various widths. A spark gap consisting of ½-in. diameter brass roads

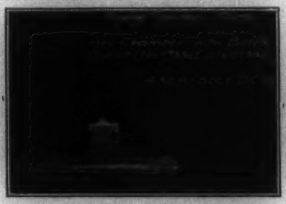

Fig. 4

with rounded ends, separated 0.9 in., and with 2200 volts 60 cycles impressed upon it, was used to determine the effective height of the flame, by determining what was the shortest distance above the vent at which the spark gap could be placed without breaking down. The breakdown voltage of the spark gap in normal air was 30,000 volts.

The curve of Fig. 2 and the photographs in Figs. 3 and 4, show the remarkable reduction in flame obtained by exposing the arc gases to deionizing surfaces.

## VIII. The Deion Contactor

Recently contactor switches have been developed which use a weak blowout magnetic field and which extinguish the arc by means of a column of deionizing metal plates. These switches show an enormous reduction of flame in comparison with previous types of switches.

In the Deion contactor by the use of the deionizing

Fig. 5

plates the arc length has been considerably shortened, which in itself would cause a reduction in the total volume of arc flame. The arc is in a weaker magnetic field, which reduces the amount of air carried turbulently through the arc core, and therefore also the volume

Fig. 6

of flame. Lastly, before escaping from the switch the flame gases pass through 1/16-in. channels between the deionizing plates where they are effectively cooled and deionized.

Figs. 5 and 6 show a comparison of the amount of flame emitted by a magnetic blowout contactor of the usual type, and a Deion contactor. The size of arc box is the same for the two switches, and the arc current is of the same magnitude. The absence of flame from the Deion contactor is quite remarkable.

# Design Features that Make Large Turbine Generators Possible

BY W. J. FOSTER[1] and M. A. SAVAGE[2]
Fellow, A. I. E. E. Associate, A. I. E. E.

DEVELOPMENT in turbine generators has been so rapid during the past four or five years that any attempt to go into a detailed description of such development would involve too voluminous a work. The purpose of this paper, therefore, is to pick a few facts from a large experience of one manufacturer with the hope that these might be of interest to the profession in general.

In discussing the design features that may be incorporated in a turbine generator to give it high rating, the authors wish it to be understood that they do not subscribe to the carrying to an extreme of certain of the features. In fact, it is their idea that conservatism should be used in order to obtain the machine that will prove most satisfactory in service.

The electrical and the mechanical are so combined and interwoven that it is hardly possible to discuss each by itself but it may assist in understanding this subject to mention, first, the mechanical factors, and second, the electrical factors.

In 1924, the authors described some features in the building of a 62,500-kv-a., 1200-rev. per min. generator. Owing largely to economic consideration, the years since that date have seen the interest in machines of 1200 rev. per min. decline and the interest in machines of 1800 and 3600 rev. per min. increase at such a rate as to make it difficult for manufacturers to keep up with the ever increasing demand for larger and larger units.

## 62,500-Kv-a. Generator

During the year 1925, the company with which the authors are associated built and installed a 62,500-kv-a. generator, operating at 1800 rev. per min. As this generator constitutes a milestone in the progress of turbine generator development, it will be in order to give some of the factors which made possible the building of such a machine. The largest previous machines at this speed had a rating of 37,500 kv-a. These machines were ventilated by carrying part of the air to a chamber at the longitudinal center of the machine, from whence it flowed inwardly to the air gap where it joined the main body of air which had entered the air gap at the two ends, from whence it flowed outward through the remaining sections of punchings. This division of the air was adequate for 30,000-kw. machines. With machines requiring a length necessary for 50,000 or 60,000 kw., it was apparent that to force enough air through them, even though two paths were employed, would require pressures far beyond what would constitute good practise. The natural development, therefore, was to employ a larger number of multiple paths. The employment of a greater number of multiple paths removes the restriction from the air gap and places it in the air ducts themselves. Naturally if each alternate air duct were used as an inlet duct the air velocity through the ducts would be just twice as great as if all the ducts were outlet ducts. With higher velocities in these air ducts it became apparent that a real gain in efficiency could be made by improving the entrance conditions to these air ducts. The air as it enters the air gap has a direction parallel with the shaft. As soon as it passes within the restraining walls, formed by the armature and rotor surfaces, it is immediately acted upon by the rotating surface of the rotor and its direction quickly changed from an axial to a tangential flow. By means of specially designed vanes, which were inserted from the back of the punchings directly into the air gap, a complete study was made of the direction and velocities of the air in the air gap on actual machines under a wide varying ventilating arrangement. These experiments showed some rather surprising results as regards the resistance imposed on the air in passing from a tangential to a radial direction in entering the air ducts.

In order to obtain data, as regards the above feature, model sections of armature punchings were made up. These were tested in an air tunnel at pressures and velocities corresponding with those in the actual machine. A vast amount of data was collected on a large number of entrance ducts of many shapes. Some of these data showed that variations as great as 300 per cent were possible in the amount of air put through a given shape of air duct, and in a few cases it was even found that the air actually flowed into the air gap instead of outward as would be expected.

Fig. 1 shows a photograph of one of these models. It will be seen that the air duct which it is supposed to represent can be turned through an angle of 90 deg. By this means, it was possible to study the entrance condition to the various air ducts throughout the length of the machine and to determine their resistance to the flow of air over a wide variation of angular flow. In other words, the direction of flow of air in the air gap having been determined by measurement on an actual machine, it is possible by rotating the model into the correct angle to carefully measure the duct resistance to the flow of air from this angle.

1. Consulting Engineer, General Electric Company, Schenectady, N. Y.

2. Turbo Generator Design Engineer, General Electric Company, Schenectady, N. Y.

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Fig. 2 shows the variations in the volume of air from one duct. The length of radial lines represents the volume of air passing through the duct at a fixed pressure for different angles.

Figs. 3 and 4 show the variations which exist in

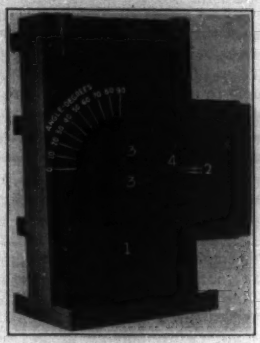

Fig. 1—Stator Ventilation Model

1. Air tunnel
2. One-half of adjustable block shown in position corresponding to peripheral air flow
3. Duct wedges of "air-slide" type
4. Stator inside space blocks

different designs of ducts. They represent the maximum and minimum flow under this study. These charts were made by putting a piece of paper over the ducts and marking out the outline and then recording

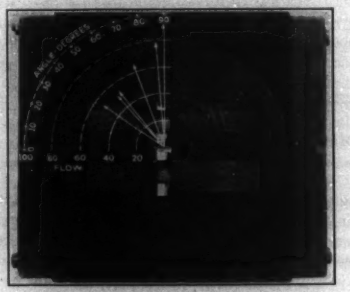

Fig. 2—Stator Ventilation Model

Showing wedge combination No. 17 completely assembled and ready for test. The radial arrows give the relative flow in the several positions

the impact pressures at various points across the face of the ducts.

Armed with these data, the ventilating passages of the 62,500 kv-a. were laid out and it is gratifying to report that subsequent tests on the machine verified the earlier experimental results.

Fig. 5 shows results of test on this machine.

The net result of all this information when applied in the design of the 62,500-kv-a. generator was that this generator employing external blowers required practically the same amount of power to ventilate it as the 30,000 kw. previously built. When it is considered

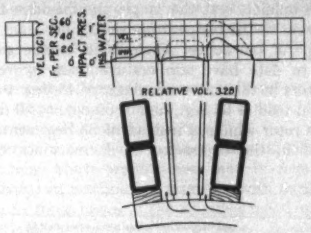


Fig. 3—Air-Flow Curves

Minimum flow obtained—the best shaped retaining wedge; heavy lines—impact; dotted lines—velocity in the three passage ways between slots

that 40 per cent of the loss on a turbine generator was formerly chargeable to windage, it will be seen that this saving in loss constituted a real step forward in the matter of efficiency. The outstanding facts which these experiments indicated, and which subsequent

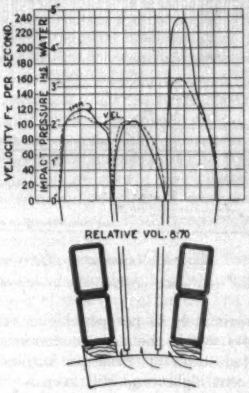


Fig. 4—Air-Flow Curves

Maximum flow obtained—no retaining wedge across air duct; heavy lines—impact; dotted lines—velocity in the three passage ways between slots

tests on the machine substantiated, was that as far as ventilation was concerned machines of any length could be built and if properly designed they could be as well ventilated as the shorter machines. This conclusion was of the greatest importance as it removed one of the factors which up to this time had more than any other impeded the progress in the size of generating units.

### Temperatures and Their Relation to the Size of Units

A few years ago it was thought by some designers, as well as users, that low temperatures were incompatible with large machines. The authors have never shared this view, and after a long experience are more strongly of the opinion that the larger the machine the more conservative the temperature should be.

Some of the largest single-shaft turbine generators built to date have temperature rises, by embedded detectors in the stator windings, of 45 deg. to 50 deg. cent. instead of 60 deg., and of 60 deg. to 70 deg. cent. in the rotor windings instead of 85 deg. cent. as permitted in the contracts. Such machines could be rated approximately 15 per cent higher and still have temperatures within the usual commercial guarantee in the United States for the largest turbine generators, or 25 per cent higher and still keep within the limit that is recognized as good practise for Class B insulation by the Standards of the A. I. E. E.

Most of the armature failures with which the authors are familiar, and which have occurred in recent years, have been the result of mechanical rather than electrical causes. A majority of such cases occurred before the general adoption of the closed ventilating systems of the present day, and were largely brought about by the stoppage of the ventilating passages by foreign substances. This in many cases caused the generation of gases in windings due to the temperatures getting beyond the boiling point of the constituents of the binding varnishes. These gases usually forced themselves along the length of the coil until the restraining influence of the slot walls allowed their escape. Once free of this restraint, they ruptured the insulation wall causing a failure. Still other failures were caused principally in the rotors by purely mechanical movements between the copper and iron, which movements cause an abrasion of the insulation to the point of failure. Either of these effects is greatly multipled when we come to core lengths such as are necessary in machines of 100,000 or 160,000 kw.

It has seemed best, therefore, to feel our way along in the matter of proper temperature rises for the extremely large turbo generators, at the same time putting forth every effort to minimize the serious consequences of expansions and contractions by introducing certain constructions in the windings themselves that will permit of expansions that will not be wholly longitudinal, and at the same time continue the improvements that have already been made in the quality of the varnishes or other cementing materials employed, in the hope of eventually obtaining insulations for high voltages that will be able to withstand much higher temperatures.

It can readily be seen that the quantity of insulating material is a factor in the temperature rises and that insulations should not be any thicker than what is required to give the dielectric strength needed for the

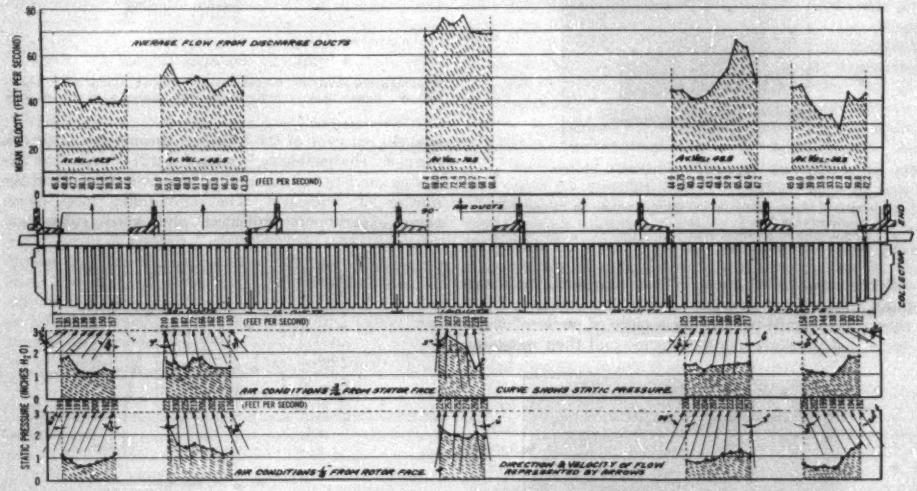


Fig. 5—Ventilation Tests on 62,500-Kv-A., 1800-Rev. per Min., 13,800-Volt Generator

Longitudinal cross section of stator core showing ingoing and outgoing sections: static pressures and relative directions and velocities of flow

highest potentials generated in service. The practise is now well established in the United States, as also abroad, of requiring insulations that will stand a high potential test for one minute of twice the rated potential plus 1000 volts. It is a question in the authors' minds as to whether such test is not too high and yet some designing engineers advocate higher tests, and a few engineers in the public utilities are inclined to call for still higher tests, apparently on the theory that the higher the test that insulation will stand the better the generator.

This attitude may be the result of the experience on earlier machines, where low potentials were the rule. Such machines if given sufficiently thick insulation to supply the proper space between copper and iron may have continued in service even when the dielectric value of the insulation was impaired to the point equivalent to that of air.

A one-minute high potential test should not be used as the sole criterion of a good insulation. The authors have witnessed tests on armature coils insulated for 13,200 volts which successfully withstood a one-minute high potential test of 100,000 volts. Such coils when subjected to potential of some 30,000 volts continuously failed after a short period.

The fact should not be lost sight of that the insulation surrounding a conductor serves a dual purpose. It restrains the voltage induced in the copper, and also acts as a conveyor of heat from the copper to iron. Its thickness, therefore, should be no greater than what will insure a resistance for years to such potentials as the windings are subjected.

### Losses and Their Relation to Output

It is a much mooted question as to the relation that should exist in any given instance between the armature and the field magnetizations. High armature reaction becomes overpowering unless the designer by increasing the air gap maintains a ratio within such limits as he thinks will prove satisfactory in operation. The relation of field ampere turns at no load, normal voltage, to field ampere turns on short circuit with normal current is known as the short circuit ratio. Hence, a low short circuit ratio tends to a high rating for the speed under consideration and the physical dimensions of the machine. A few years ago it was the practise of the authors to design large turbo generators with a short circuit ratio of approximately unity but, in view of the designs of many of the European engineers where short circuit ratios not more than one-half as great exist, the tendency with us at present is to lower somewhat our former figure.

Machines of greater rating are possible when magnetic materials of the best quality are employed. It is important that careful studies be made of the magnetic densities that are permitted in order to obtain the lowest losses under load conditions. Any reduction in the fixed losses in the generator is of a two-fold benefit, for less air is required to provide the proper ventilation with lower power loss chargeable to the ventilation. For each kilowatt saved in these losses, approximately 0.25 kw. less power is required to ventilate such a machine.

Higher armature reactions or lower short circuit ratios result in an increase in the so-called load losses; at the same time they reduce other losses and result in cheaper machines. A proper balance then must be maintained between these factors so as to obtain machines of great reliability and long life.

With enormous amounts of power built into a single unit the desirability of building machines of great reliability cannot be overemphasized.

In a previous paper the authors made reference to investigations which were carried out in regard to losses existing in machines of this type with particular reference to those losses in the so-called inactive magnetic materials at the heads of machines. As a result of these and subsequent investigations the practise of using magnetic steels for such parts as the clamping fingers and flanges has been discontinued on all of these large machines, and non-magnetic materials substituted for them. The employment of these non-magnetic steels has resulted in a gratifying reduction in the losses. As a result of these and other improvements the efficiencies of these large units are of the order of 98 per cent instead of the 96.5 to 97 per cent which were the rule a few years ago.

One of the contributing factors in the trend toward larger units is the increased efficiency which such a unit brings. High efficiency, therefore, assumes an importance in these large units far beyond what it did in the units of years ago. The design factors for which the modern designer must strive in the order of their importance should be reliability, efficiency, and cost. If these factors are followed through to a logical conclusion, the size of units for a given output becomes greater than what would obtain if machines were designed to get the greatest output compatible with their temperature guarantees.

Due to their high rotational speed the frictional loss, commonly called windage loss, becomes a serious factor in the efficiency of this type of unit. The problem of operating this class of apparatus in a medium of low density has claimed the attention of engineers for years. With the advent of the closed system of ventilation and surface coolers for extracting the heat from the cooling medium, the problem of the utilization of a gas lighter than air received a marked impetus. Hydrogen cooling is a perfectly practical thing and its adoption will mark the next big step forward in the increase in efficiency of these large units. By employing $H_2$ cooling we may expect an increase in efficiency of some 0.6 per cent and some 25 per cent larger outputs from the same physical size of units.

### High-Voltage Generators

Within the past few years interest has developed both in this country and abroad in generators built for volt-

ages higher than those which had been standard, namely 13,200–14,000 volts. This trend has been for entirely different reasons. In England voltages as high as 33,000 have been advocated and one machine has been built at this voltage. The justification for such a voltage lies solely in the elimination of the step-up transformers. In this country the trend toward higher voltages has been brought about largely by the increase in generator capacities, and in an effort to minimize switching difficulties.

The distribution areas being so widely scattered in this country, most of the power from the large stations to-day is sent out at potentials much higher than it would be possible with our present knowledge to build generators for. No attempt, therefore, has been made to adapt the generator voltage to the transmission potential. In those cases where power is distributed at various potentials, say 33,000, 66,000, and 132,000 volts, it usually works out cheaper to use step-up transformers for all three voltages than to wind the generator for 33 kv. and use step-up transformers for the two remaining voltages.

Still another difficulty in the design of generators for transmission potentials lies in the hazard involved in surge potentials to which such transmission lines, especially those of moderate potentials, are subjected. The class of insulation which it is desirable to use in the generator is not as well suited for resisting surge potentials as other classes which are totally unsuited mechanically to large generators.

All of these considerations have worked together to confine the building of large generators to the potentials which are most economical in station switching and bus bar equipment.

The introduction of the so-called double winding in large generators has retarded to some extent the trend to higher voltages in these machines. This double winding consists, briefly, in dividing the coils, which make up the three phases, into two circuits and arranging them in the correct slot relationship in such a manner that they will be in phase and voltage agreement with high self induction with respect to each other.

Each winding, therefore, will carry half the output of the machine. If these independent windings are tied to separate buses, the switching problem is greatly minimized as the current to be handled is just half of what would be the case in an ordinary generator or it would be the same as if the generator were wound for 27,600 instead of 13,800 volts.

## Rotor

No description of generator development would be complete without some reference to the rotor as no part of these large generators has come in for such careful analysis and painstaking study as the revolving element. It is this element which must withstand all of the centrifugal strains, bending strains, and temperature strains due to heating and cooling and still maintain its alinement and balance so as to provide smooth operation.

There are three distinct types of rotors built by the leading manufacturers of to-day. The first is the solid rotor type in which the rotor is made up of one or more forgings. The second is the plate rotor type in which a series of plates or disks is bolted together to form the rotor body structure. The third is the through-shaft dovetail punching type, in which the shaft is a solid forging which has been slotted and dovetailed to receive the punchings which carry the rotor coils.

Each of these types has its advocates, and each type has some inherent advantages which the others do not possess. From time to time articles appear in the technical press of the world in which some author attempts to point out the superiority of one type over another. Such articles are distinctly all right as they tend to stimulate thought which leads to progress. The authors have no intention of joining in such a controversy. Their first-hand knowledge would allow them to speak with some authority on only two of the three types.

Suffice it to say that the manufacturing company with which the authors are associated has brought its steel forged type of rotor to its present state of perfection only after the most careful and painstaking research and that over one thousand of these rotors have been built and put into service and not one of them has failed due to imperfections in the rotor forging. This is an enviable record and is a most convincing argument that this type of rotor is thoroughly reliable if properly built.

In the design of the 62,500-kv-a. generator, described earlier in this article, the rotor diameter was the same as those of the 30,000 previously built. The centrifugal stresses, therefore, were no greater than had been previously encountered. With further increases in capacity of the units the diameters have been increased. Many of the stresses, however, on these rotors of greater diameter have not increased due to the fact that the copper space has not been increased in proportion to the increased diameter. The body stresses have increased somewhat but, to offset this, alloy steels are being employed which give a higher factor of safety than many of the smaller units enjoyed.

In the largest sizes the rotors are made of three pieces, a center cylinder and two stub ends, which carry the journals. There is a number of reasons for this construction; it reduces the size of the individual piece, and therefore the cost of such piece. It allows the main cylinder to be worked on its inner bore as well as its outside diameter, insuring better material, and it allows a more thorough inspection to be made of the forgings.

## 100,000-Kv-A., 16,500-Volt, 1500-Rev. per Min. Generator

Fig. 6 shows the 100,000-kv-a., 16,500-volt, 1500-rev. per min. generator installed in the Long Beach

Station of the Southern California Edison Co. This is the largest single turbine generator in operation in America. Its design brought up a number of problems largely mechanical, which are typical of the trend in modern design. When the order for this unit was placed, it was contemplated that the machine would be assembled at destination. The difficulty of transporting all of the component parts of a machine of this

FIG. 6—100,000-KV-A., 1500-REV. PER MIN., 16,500-VOLT, 50-CYCLE GENERATOR

With 4000-kw auxiliary generator and 94,000-kw. tandem compound turbine. Long Beach Station of So. California Edison Co.

size 3000 miles across the country, and assembling them under conditions which are anything but ideal, made it seem desirable to design the machine so that it could be

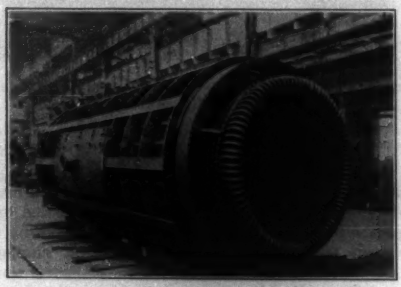

FIG. 7—100,000-KV-A., 1500-REV. PER MIN., 16,500-VOLT, 50-CYCLE GENERATOR

View of inside stator structure complete with winding and supports. Turbine end

shipped completely assembled and wound. Weights were carefully scrutinized and it was finally decided that if the frame weight could be kept to 25,000 lb. the problem could be solved. Such a weight was out of the question on the basis of any past design. A design was finally worked out whereby both the weight and dimensional requirements for shipment could be met. The frame was divided into two parts, an inner member or cage (see Fig. 7) and an outer structure (see Fig. 8). The inner member consists of annular plates held on the outside by narrow steel slats, and on the inside by the core dovetail ribs which were let into the plate. This structure is intended largely as an assembling jig for the punchings. After the punchings were assembled and clamped the ribs and outside slats were welded in place. The whole structure thus became a rigid member which could be handled.

The outer structure consists of a number of foot plates spaced so as to coincide with the circular plates of the inner structure to which they are securely bolted when assembled on the base. These foot plates are welded to side plates which form an enclosure and add stiffness horizontally. Over this structure when assembled is placed a steel cover. This cover plate also carries radial supporting plates which form the various air chambers.

The strength of any structure is the strength of its

FIG. 8—100,000-KV-A., 1500-REV. PER MIN., 16,500-VOLT, 50-CYCLE GENERATOR

View of outer stator frame shipped separately and bolted to inside structure at destination

weakest member. In the design it became apparent that the inner cage would be subjected to certain unusual stresses. It was found that no formula existed for calculating these stresses and a formula had to be developed. The calculations showed conservative stresses in this member. However, as there were available no data by which the correctness of the formula could be verified it was decided to test out the strength of the structure by means of a photo-elastic method. A celluloid model of one of the inner rings was made and loaded to simulate the body of the actual plates in the machine and the stresses determined. The stresses as determined by this method checked very closely with the calculated values.

### 160,000-KW., 1500-REV. PER MIN., 25-CYCLE GENERATOR

The use of 25-cycle power has practically given way to 60 cycles in this country except in certain districts, notably around Niagara Falls and the metropolitan

area of New York. While these latter places are considering the problem of changing over to 60 cycles, they still require large blocks of 25-cycle power.

Fig. 9 shows the frame with the ventilating housing and cooling casing for the 160,000-kw., 25-cycle,

FIG. 9—160,000-KW., 1500-REV. PER MIN., 11,400-VOLT, 25-CYCLE GENERATOR

Ventilation housing containing the coolers

1500-rev. per min. generator for the New York Edison Company and installed in their 14th Street station. The building of a generator of this enormous capacity involved a number of new problems. The frame (see Fig. 10) is made entirely of steel plate welded and repre-

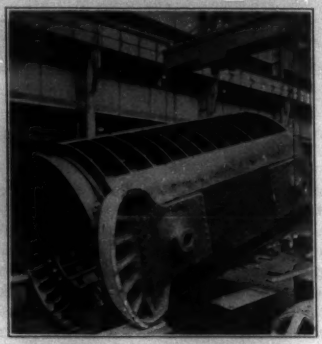

FIG. 10—160,000-KW., 1500-REV. PER MIN., 11,400-VOLT, 25-CYCLE GENERATOR

Showing stator frame and the special trunnion for changing after stacking core from vertical to horizontal position

sents the most approved practise in this construction. The non-magnetic steel clamping flanges at the two ends of the stator and the cast iron end shields are the only castings in the generator proper. The employment of steel plate and the application of the art of welding has resulted in marked reduction in weight and at the same time resulted in a much stronger structure than was possible with fabricated cast iron structure formerly built. As an example of this weight reduction, a recent design of frame on a 75,000-kv-a. generator showed practically the same weight as the frame of a 37,500-kv-a. generator of an earlier design in which castings were employed. Owing to the physical dimensions of the 160,000-kw. generator and enormous weight, the stator of this unit was built at destination. Specially designed trunnions were necessary in order that the frame, after it had received its load of half a million pounds of laminations, could be turned from a vertical to a horizontal position on its base. See Fig. 10.

The winding of this generator is of the transposed bar type with two bars assembled in each slot. This is the first machine to make use of the two circuit or so-called double winding. Each winding is connected delta and, to eliminate the objectionable harmonic

FIG. 11—160,000-KW., 1500-REV. PER MIN., 11,400-VOLT, 25-CYCLE GENERATOR

Wound rotor without end retaining rings showing aluminum saddles and blocking-in windings, length over-all 39 ft. 7 in., weight complete 290,000 lb.

currents in the delta, the pitch of the coils was made 66⅔ per cent. Each winding will be connected to a separate bus section and these buses will have no tie between them other than the generator windings. In case of a short circuit on one bus the generator windings act as a limiting reactor in reducing the flow of current along the bus.

Fig. 11 shows a view of rotor for the 160,000-kw. unit. The retaining rings are not assembled. The end construction of the rotor can be seen. The rotor forgings were made in three pieces, a body and two stub ends. The body portion alone weighed 228,000 lb. and is the largest single forging ever turned out by the steel mills. This forging involved the use of billet weighing 465,000 lb.

There is not contemplated at the present time, as far as the authors know, a turbo generator larger in capacity

than this unity power factor 160,000 kw. It may not be generally known to engineers other than designers that it is more difficult to design a 25-cycle machine of great capacity than it is to design a 50-cycle at the same speed, namely 1500 rev. per min. The amount of magnetic material is much greater for the lower periodicity and the extensions of the end windings of both stator and rotor beyond the magnetic cores are much greater. Hence, the authors have confidence that by the introduction of certain features discussed in this paper, such as hydrogen cooling, a 50-cycle generator conservative in its temperatures and other important characteristics could be designed and built at the present time for a rating of 200,000 kw. at 90 per cent power factor, or 222,222 kv-a.

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## Discussion

**L. J. Neuman:** I should like to ask the question as to how the possibilities of ignition of the hydrogen are taken care of in this problem.

**E. S. Henningsen:** Designing a large turbine generator and making the outer structure explosion-proof seems to be impractical. That is, it is perfectly possible, but entirely uneconomic. Therefore, with such a machine there might be a possibility of an explosion.

With the synchronous condensers which we have built to date, because of their being much smaller machines, it has been possible to utilize the frame as an explosion-proof steel case. However, I believe the dangers of explosion from hydrogen are practically nil. The control of the gas in the frame of the machine can easily be arranged so that there will always be some positive pressure. Any leakage will be outward and there will be very, very little danger of air getting inside the machine to form an explosive mixture.

The second thing that makes me think the danger isn't very great is that there isn't much energy involved in the hydrogen inside of one of these machines and the explosive force is over so very quickly that even if it did explode, my opinion is it would simply open up a seam and it wouldn't blow off a piece of the machine.

One thing of interest in considering the dangers of an explosion, is that a great many manufacturing plants have hydrogen-filled furnaces for various kinds of work. At Schenectady, we have some large furnaces that are used for brazing pieces of steel together in an atmosphere of hydrogen. Those furnaces have been in constant use for many years right in the shop building with employees all around and we have never had an accident.

# Effect of Surges on Transformer Windings

BY J. K. HODNETTE[1]
Associate, A. I. E. E.

***Synopsis:***—*A study has been made of the reaction of transformer windings in grounded neutral systems when subjected to transient voltage surges such as exist on normally insulated lines. Measurements of the voltage distribution throughout the windings between various elements and to ground were effected by means of a cold cathode type cathode ray oscillograph and sphere spark-gaps.*

*An estimate of the stresses occurring in transformers due to the voltages occurring on transmission systems is made, basing them on the most recent data obtainable. The data indicate that the worst stresses, both within the winding and to ground, are in the vicinity of the line coil.*

* * * * *

## I. Introduction

WITH the rapid growth of transmission systems and their interconnection into larger systems, continuity of service is becoming increasingly more important. This has prompted a great amount of study on the subject of increased reliability of all component parts making up the system. Such studies have been conducted on transmission lines and connected apparatus. The power transformer constitutes a vital link in such systems. These transformers have shown an excellent record, undoubtedly due to the unceasing research and study conducted during their rapid growth in size and voltage in the past few years.

Transient voltage surges have long been recognized as one of the chief sources of trouble. During the past five years the klydonograph has yielded much information on the magnitude and frequency of occurrence of these surges on transmission systems under service conditions. More recently the cathode ray oscillograph has been perfected, making it possible to record accurately voltage-time relationships occurring in a small fraction of a second. By means of this instrument it has been possible to obtain actual photographs of surges.

The voltage surges occurring on transmission systems, and of necessity those with which we are concerned as affecting transformers, can be divided into three general classes according to their origin, namely, arcing grounds, switching surges, and electrostatic or lightning surges. It is the purpose of this paper to analyze various types of these surges and afford a common basis of studying their effects, particularly on grounded neutral systems.

*Relative Importance of Arcing Grounds, Switching Surges, and Lightning Surges.* Arcing grounds are discharges to ground usually from one phase or line of a transmission system. In case the neutral of the system is grounded the maximum voltage developed would be approximately 2½ times the normal voltage to neutral. For an isolated neutral system the maximum voltage may be as great as six times normal.

When a switch is opened or closed, energizing or deenergizing a circuit, a transient condition of voltage and current exists. The voltage during this process may reach values above normal as determined by the circuit conditions.

Reviewing the literature[2] on this subject we find the data obtained on a number of systems covering the whole operating range of transmission line voltages indicates that approximately 50 per cent of switching operations cause no appreciable voltage surge. Of the remainder 81 per cent are less than twice normal, 93 per cent less than three times normal, and 99.2 per cent less than 4.5 times normal. That is, only one switching operation in 250 causes voltages in excess of 4.5 times normal. The maximum voltage recorded on any system was six times normal and that was caused by deenergizing a line.

As a rule switching surges do not cause flashover of the line insulation. They must of necessity be short in duration in order to obtain excessive values and may rise to a maximum in the order of a few microseconds. Lightning surges on the other hand attain values of many times normal line voltages. In many of the cases recorded by the klydonograph, flashover of the line insulation is known to have occurred. The magnitude of the voltage, by virtue of the fact that the line insulation was flashed over, is much greater than for arcing grounds or switching surges. In Fig. 1 is shown a comparison of the voltages to be expected from the several sources together with the normal voltages of the system, the transformer test voltages, and the 60-cycle dry flashovers of normally insulated lines. It may be seen from this that surges produced by lightning are of most serious consequence and may be as great as 14 times normal for very short surges with lower values for surges of longer duration.

This does not mean that arcing grounds and switching surges are of no importance. Operating experience, however, indicates that they are not a common source of trouble with modern designs of transformers.

*Shape of Lightning Surges.* Much information has been contributed on the formation of lightning surges on transmission lines by Peek, Fortescue, Simpson, Cox, and others. It is generally accepted that induced voltages from lightning discharges are relatively low in magnitude and steepness, whereas surges produced by direct strokes may have abrupt fronts and be high in magnitude.

*Factors Limiting Lightning Surge Voltages.* The

1. Engineer, Westinghouse Electric & Mfg. Co., Sharon, Pa.
2. See Bibliography.

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principal factor limiting the voltage on a transmission line is the spark-over of the line insulation. The flashover of a string of insulators depends both upon the magnitude and the shape of the impressed surge and in the case of lightning surges is always greater than the 60-cycle flashover voltage. We may assume that failure commences as the 60-cycle spark-over voltage is approached and that spark-over is a function of time and the voltage above this value. The tail of the surge

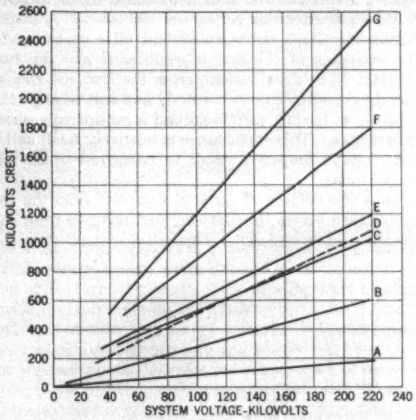


Fig. 1—Comparison of Surge Voltages and Transformer and Transmission Line Insulation Voltages (Estimated)

*A.* Normal voltage of transformer (line to neutral)
*B.* Transformer test voltage
*C.* 60-cycle dry flashover of normally insulated transmission line
*D.* Probable maximum switching surges
*E.* Probable maximum voltage for 60-microsecond surge not causing flashover
*F.* Probable maximum voltage for 5-microsecond surge not causing flashover
*G.* Probable maximum lightning voltage possible (flashover on rise)

as well as the front affects spark-over and the more abrupt each is, the higher the voltage necessary to produce arc-over will be.

A rate of rise of 4000 to 5000 kv. per microsecond is probably about as rapid as would be expected for natural lightning surges. From experimental data for the flashover of line insulators, it is estimated that the maximum voltage which could exist on a line as a result of a direct stroke would be in the neighborhood of 2.5 to 2.7 times the 60-cycle crest sparkover. The curve for the probable maximum voltage, curve *G*, Fig. 1, is based on this computation. Points of this curve agree approximately with the maximum voltages recorded by the klydonograph.

Similarly, curves *E* and *F* for surges rising to maximum in less than a microsecond and decreasing to half-value in five and 60 microseconds respectively are drawn. These curves represent the approximate maximum voltages which can be propagated without causing sparkover.

In this connection reduced line insulation, ground wires, protective gaps, and lightning arresters should be mentioned. Each tends to limit the voltage on the system, particularly lightning arresters.

The second factor limiting the potential surges on apparatus is attenuation. It has been shown that where the voltage of the surge is very high the attenuation is very great. An example of this is in the attenuation of a surge of 1740 kv. to about half-value in a space of four miles. To this property of traveling waves much protection to connected apparatus is due.

## II. General Considerations

When a steep wave traveling along a transmission line strikes a transformer it proceeds along the conductor of the first turn or turns in much the same manner as along the line.

As soon as a potential is established on the first turn of the entrance coil it sets up an electrostatic field enveloping the total space between it and ground. Each element of the winding thereby will acquire a potential depending upon its position in the field. As the wave penetrates further into the coil the electrostatic field changes every instant and with it the potential of the various elements.

Thus, a transformer reacts to an abrupt front wave during the time in which the wave is restricted to the first element much the same as a chain of condensers,

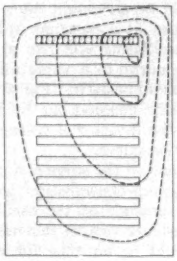

Fig. 2—Sketch Showing Electrostatic Distribution of Voltage within a Winding Due to a Steep Impulse on the First Turn

Fig. 3A. *Cc* represents the capacitance between elements of the winding and *Cg* the capacitance to ground. The distribution of voltage to ground through the capacitances can be expressed as follows:

$$E = E_0 \frac{\sinh n \sqrt{\dfrac{Cg}{Cc}}}{\sinh N \sqrt{\dfrac{Cg}{Cc}}}$$

Where $E$ is the voltage above ground of any elements $n$, $Eo$ is the voltage above ground of the first element, and $N$ is the total number of elements involved.

A typical curve for the initial or electrostatic distribution in a transformer winding is shown in Fig. 4A. Each element of the winding includes an elementary portion

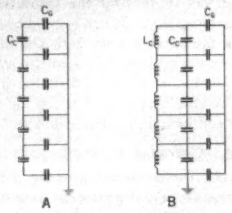


FIG. 3—EQUIVALENT CIRCUIT OF A TRANSFORMER

*A.* Equivalent circuit at instant of impact of steep wave
*B.* Complete equivalent circuit

of the total inductance of the winding. In order to completely represent the transformer winding schematically these inductances should be connected in parallel with the coil capacitance $Cc$, as shown in Fig. 3B. As time progresses a current will be established through the inductance and there will be a redistribution of the electrostatic energy between each of the elements and throughout the winding as a whole. This redistribution of energy will take place in the form of oscillations about the final steady-state distribution, which in the case of a transformer would be a straight line. If the incoming wave is maintained at a constant value long enough, the voltage in oscillating will rise above the steady-state distribution curve to a value almost as large as its initial displacement below it. (Fig. 4C.) These oscillations will be rapidly damped out by the losses in the transformer and the division of voltage reduced to the uniform distribution curve.

On the other hand, if the surge is not maintained but decays rapidly the axis of oscillation decays correspondingly and the magnitude of the oscillation is greatly reduced. To illustrate this, if the rate of decay were infinite there would be no time for the fundamental oscillation about any axis above the zero axis, and the original electrostatic distribution would generally represent the maximum voltages to ground. As the rate of decay decreases the magnitude of the oscillation would increase and a wave maintaining a constant value for one-half cycle of the natural period of the transformer would represent the other extreme.

Considering again the electrostatic distribution of voltage, the elements of the winding may either refer to the successive turns of a coil or to the various coils which make up the winding. In the case of the former, the several turns are insulated with a mass of insulation having a relatively high permittivity and are coupled closely together compared to their disposition to ground or other coils. Therefore the ratio $\sqrt{\frac{Cg}{Cc}}$ is low and the voltage gradient is correspondingly low. Extending the condenser chain beyond the first coil, assuming the first two coils connected together at the starts, introduces a voltage distortion from that represented by the equation (see Fig. 2). Since the end turns of the second coil are in close proximity to the line turn they receive a voltage from it as determined by the capacitance chain extending across the coil stack. A distribution of voltage across the second coil in opposition to the extension of the first is established and the two overlap. The distribution across the first coil should then be considered more correctly as a unit wherein the capacity of the last turn to ground is considered a series capacitance. This capacitance is relatively small and a high-voltage drop will result as compared to the adjacent turns.

Thus the voltage to ground decreases from the entrance turn across the first coil and increases from the start of the second coil. This effect extends into the

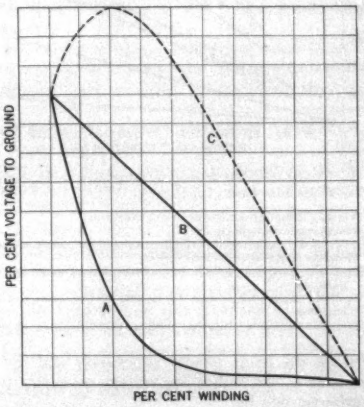


FIG. 4—INITIAL VOLTAGE DISTRIBUTION AND MAXIMUM POSSIBLE OSCILLATION PRODUCED BY A TRAVELING WAVE (ESTIMATED)

*A.* Initial or static voltage distribution
*B.* Final or 60-cycle distribution
*C.* Maximum possible voltage to ground by oscillation

winding but with less difference in potential across the coils the further they are removed from the entrance coil.

The distribution of voltage across the coil stacks follows in the same manner except that a compensation is necessary wherever the ends of two adjacent coils are connected together. If the coil stack is broken up by the interposition of other windings or reentries having a relation to earth much lower than the winding

considered, the effect will be the same as connecting a large capacitance to ground at that point in the capacitance chain. This means that in the electrostatic distribution, almost all of the voltage will be present in the line group. On the other hand, during the time of oscillation the increased capacitance requires a larger charging current which tends to retard the oscillation or increase its period.

From the above consideration it may be concluded that by properly proportioning the constants of the transformer it is possible to alter the static distribution

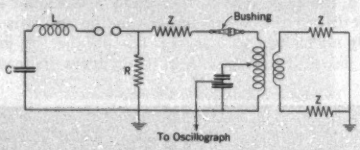


Fig. 5—Schematic Diagram of Testing Circuit

of voltage in the windings. For a given output capacity, the mass of the windings of a transformer is a constant within certain limits. Thus, if the coils are made narrow and of few turns the length of the winding must be long, and if the coils are wide and of many turns the coils will be few in number and the stack short. In the first case, the capacitance between coils will be relatively less than for the larger coils, whereas the capacitance of each to ground will not be greatly altered except near the ends of the winding or groups. As may be seen from this, the static distribution curve will be displaced much more from the uniform axis with a large number of narrow coils than with a few wide ones.

In proportioning the design of a transformer, consideration must be given to the space distribution as well as the turn-to-turn distribution of the voltage. In so doing the relative strength of the insulation to lightning voltage in the space should be given due weight. The amount of solid insulation used, its characteristics and the characteristics of the surrounding media, and the length of the path are factors in determining the lightning breakdown strength of insulation.

## III. Experimental Results

The circuit used in conducting these tests is shown in Fig. 5. The capacitance $C$ was charged from an alternating source by means of kenotron rectifiers and discharged through an inductance $L$ and resistance $R$. The potential drop across the resistance was impressed upon the transformer terminal. A lumped impedance $Z_s$ of approximately 500 ohms was connected between the transformer terminal and the source of voltage supply. The terminals of the secondary winding were connected to ground through similar impedances.

Waves rising to a maximum in less than a microsecond and decaying to one-half value in 5 and 60 microseconds were considered representative of fairly short and long lightning surges and these together with waves chopped while rising were used principally in this investigation. Waves of approximately 5- and 30-microsecond fronts were also used.

When the capacitance was charged to the required amount the surge was initiated by means of a three-way gap interconnected with the supply for the cathode of the cathode ray oscillograph. This provided the means for synchronizing the surge and the oscillograph. The voltage plates of the oscillograph were connected to various points in the winding through an electrostatic potentiometer. The maximum potential of these points was checked by a sphere spark-gap.

The effect of surges on the windings of the following transformers was studied in the course of this investigation.

3000-kv-a., 140,000- to 5000-volt single-phase, shell type transformer with the high-voltage winding divided into three groups.

667-kv-a., 66,000- to 7200-volt core type transformer with cylindrical low-voltage coils and circular pancake high-voltage coils. The winding was arranged on two legs with a reentry in the middle of each leg.

Both transformers were equipped with condenser type bushings.

*The Effect of Varying Steepness of Wave Fronts on the*

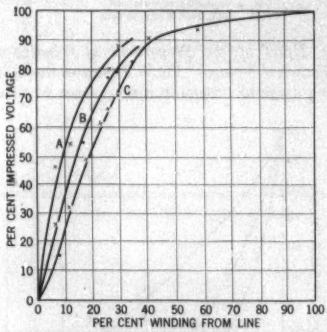


Fig. 6—Distribution of Voltage in Winding as Measured from Line End (3000-Kv-A. Transformer)

*A.* Surge with one-quarter-microsecond front
*B.* Surge with five-microsecond front
*C.* Surge with 30-microsecond front

*Initial Distribution of Voltage in Windings.* The curves in Fig. 6 show the distribution of voltage in the winding for waves of different fronts. In obtaining these curves the voltage was measured from the entrance terminal to various points within the winding. In the portion of the winding near the entrance, this approaches the initial or electrostatic distribution, since subsequent changes tend to make the voltage divide uniformly or the difference in voltage less. The fronts of the waves then are effective in establishing this relation and the longer the fronts the nearer uniform the voltage will divide.

This process was not carried to the limit but a uniform division would be expected after the front was of the order of a period of the fundamental.

The length of the tail of the waves has little effect on this curve as confirmed by measurements made with surges decaying to half value in 5 and 60 microseconds.

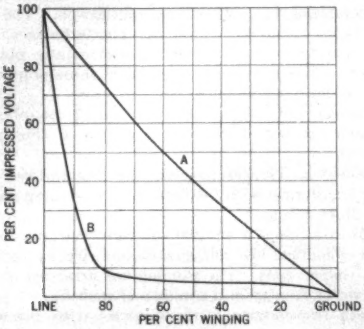


FIG. 7—COMPARISON OF VOLTAGE DISTRIBUTION IN LONG AND SHORT STACKS OF COILS

*A.* Short stack of wide coils
*B.* Long stack of narrow coils

*The Effect of the Proportions of Winding on the Distribution of Voltage.* Fig. 7 illustrates the difference in the voltage to ground in a short stack of wide coils

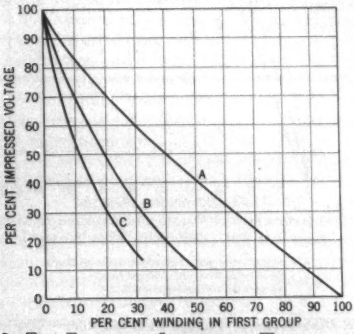


FIG. 8—THE EFFECT OF INTERLEAVED WINDINGS ON THE VOLTAGE DISTRIBUTION

*A.* Voltage distribution with one group
*B.* Voltage distribution with two groups
*C.* Voltage distribution with three groups

and a long stack of narrow coils when subjected to a five-microsecond surge. These values, as will be shown later, represent approximately the initial voltage distribution and are indicative of the worst stresses occurring in the stacks. Curve *A* represents what occurs in the line group of a well proportioned wide stack of coils and Curve *B* represents what occurs in a narrow stack of coils when short steep waves are impressed upon them.

When the windings are interleaved or broken up into groups the line group absorbs most of the surge voltage. Data were taken on the 3000-kv-a. transformer first by impressing a surge across the total winding, then across two groups, and finally across a single group of the winding. A five-microsecond surge was used and measurements of voltage were made to ground. Referring to Fig. 8, the three curves are seen to be of similar shape, or the distribution of voltage in the line group is practically unchanged by varying the number of groups. The discontinuous points in the curves indicate the

FIG. 9—OSCILLOGRAMS SHOWING VARIATION IN INTERNAL OSCILLATIONS OF 3000-KV-A. TRANSFORMER WITH DIFFERENT LENGTH SURGES

1. Very long surge, 250 microseconds to half value
2. Long surge, 60 microseconds to half value
3. Short surge, 5 microseconds to half value
4. Chopped surge

division of voltage across the group. The decrease in this value with the number of groups is not rapid. As shown, approximately 91 per cent of the voltage drop will occur in the first group where two groups are used and 85 per cent where three groups are used.

*Internal Oscillations and Voltage to Ground.* When a steep front surge strikes a transformer, oscillations are set up in the winding. The values attained by these oscillations depend largely upon the shape of the surge. Referring to the oscillograms, Fig. 9, the oscillations are seen to be higher for the longer tail waves. A point in the winding 29.7 per cent above ground reaches a maximum value of approximately 75 per cent of the total applied voltage for the extremely long wave, approximately 47 per cent for the long or 60-microsecond wave, 10 per cent for the short or 5-microsecond wave, and 5 per cent for the chopped wave. These

measurements were checked with the sphere-gap within reasonable accuracy.

Thus it may be seen that if the surge is sufficiently short, the voltage by oscillation does not rise above the initial voltage acquired from the front of the wave. This

FIG. 10—VOLTAGE AT MID-POINT OF WINDING OF 667-KV-A. CORE TYPE TRANSFORMER PRODUCED BY A 60-MICROSECOND SURGE

condition is seen to be fulfilled by the five-microsecond surge in the case of the 3000-kv-a. transformer and a measurement of the maximum voltage to ground would also be approximately a measure of the initial voltage. On the other hand a measurement of the voltage above ground for longer waves would indicate the maximum values reached by oscillation. This is confirmed by

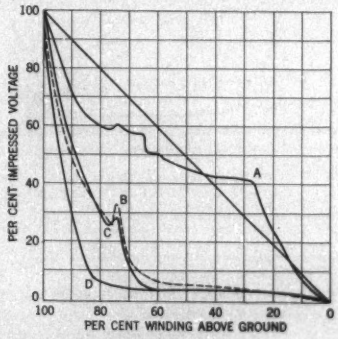


FIG. 11—MAXIMUM VOLTAGES TO GROUND FOR DIFFERENT TYPES OF SURGES

*A.* Voltage distribution in 3000-kv-a. transformer with 60-microsecond surge
*B.* Same with chopped surge
*C.* Same with five-microsecond surge
*D.* Voltage distribution in 667-kv-a. transformer with five-microsecond surge

the agreement between the curves (Fig. 11), and the oscillograms.

The internal oscillations in general are composed of a fundamental corresponding to the natural period of the transformer with many superimposed harmonic frequencies. It should be noted that the length of the wave affects the composition of the resulting oscillation to the extent of determining the proportions of fundamental and harmonic. For the long wave the fundamental is very large, comparatively, except for the parts of the winding near the line. With the five-microsecond wave the fundamental is reduced and the proportions of the harmonics increased, and, in the case of the chopped waves, the fundamental is entirely absent and only the harmonics exist.

The natural frequency of the shell type transformer investigated was approximately 5000 cycles and that of the core 6700 cycles. It is believed that the order of these fundamental frequencies is representative of that of power transformers in general.

Referring again to Fig. 11, a very close agreement

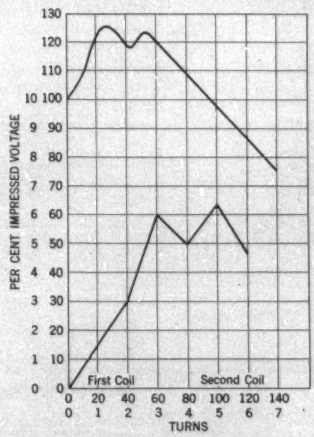


FIG. 12—VOLTAGE DISTRIBUTION IN LINE COILS (FIVE-MICROSECOND SURGE)

*A.* Voltage across first six turns
*B.* Voltage to ground in line coils

between the voltage to ground for the five-microsecond and chopped waves is observed. This follows the explanation just given that the initial distribution and not the oscillatory portion of the transient was the factor determining the voltage to ground. This is further substantiated by the agreement between these curves and the curve (Fig. 6) for the initial distribution of a ¼-microsecond front surge.

The breaks or departures from continuous smooth curves were caused by taps in the winding.

The voltage to ground for the 667-kv-a. transformer subjected to a five-microsecond surge is also given. A basis for comparing the two transformers is not simple. However, the curves show for the same surges that 86 per cent of the voltage drop occurs across 15 per cent of

the winding of the 667-kv-a. transformer as against 57 per cent of the voltage for the same percentage of the 3000-kv-a. winding.

*Distribution of Voltage in the Line Coils.* The division of voltage across the first few turns of the line end of the shell type transformer is given in Fig. 12. This indicates that approximately six per cent of the voltage drop occurs across the first three turns. Data of this nature are very hard to obtain accurately but it is believed that the curve is a fair representation of existing conditions.

When the applied surge is chopped near the transformer, oscillations of a high magnitude exist in the line coils. Such a condition is illustrated in Fig. 13, I and II. The first rise in voltage is due to the initial distribution; following this the terminal voltage is reduced to zero and the oscillations take place about the zero axis. The predominant period is of the order of three microseconds and as the damping factor increases with the frequency, the oscillations are quickly damped out.

The oscillograms III and IV show the oscillations produced in the same coil by the five-microsecond surge

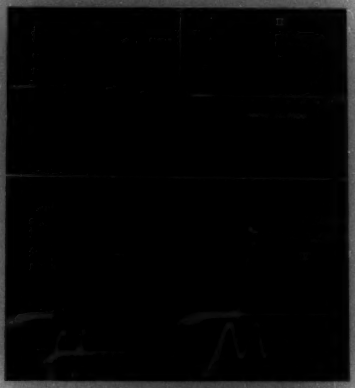

Fig. 13—Voltages in Line Coil of 3000-Kv-A. Transformer

1. and 2. Voltage resulting from surge chopped near transformer
3. Voltage resulting from 5-microsecond surge
4. Voltage resulting from surge rising to maximum and decaying to half value each in 5 microseconds

and a surge with both a five-microsecond front and tail. In the case of the former they are greatly reduced in magnitude and in the latter almost absent. Thus, both the rate of rise and the rate of decay affect the magnitude of these oscillations.

The voltage to ground at the end of the first coil rises to a value in excess of the impressed voltage. This is the result of an oscillation, the energy for which is supplied through both the first and second coils due to the initial distortion of gradient through the first two coils, since the outer layers of these coils are more closely coupled electrostatically than the inner and outer layers of the first coil. Spark-gap data indicate higher than applied voltages to ground throughout the first coil (see Fig. 12B). As points in the second coil were inaccessible only the end points were measured and the curve extended through them.

## IV. Magnitude of Stresses in Transformers as Determined by the Line Conditions

*Stresses within the Windings.* Referring to Figs. 6 and 11 from which the stress along the length of the winding can be estimated and to the probable maximum

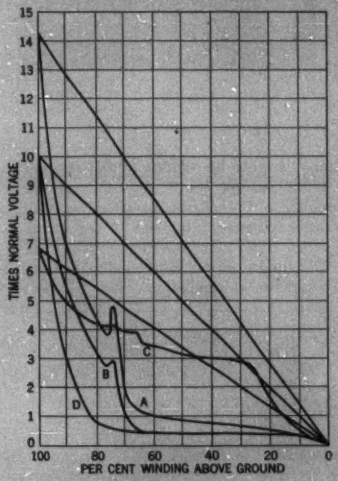


Fig. 14—Probable Magnitude of Internal Voltages above Ground

*A.* Chopped surge, 3000-kv-a. transformer
*B.* Five-microsecond surge, 3000-kv-a. transformer
*C.* 60-microsecond surge, 3000-kv-a. transformer
*D.* Five-microsecond surge, 667-kv-a. transformer

potentials on transmission line as given in Fig. 1, the following may be deduced.

The highest stresses are evidently those caused by surges with very steep fronts as these give the worst initial distribution of voltage and attain the highest values which, in the case of surges limited by flashover of the line insulation, may be of the order of 14 to 15 times normal. Surges of this character cause no fundamental oscillations on transformers having periods of the order of those investigated herein; therefore, the initial distribution is the only factor necessary to consider. This distribution is largely a function of the physical properties of the winding. It may be seen by reference to the above curves that the greatest stresses occur near the line end where the winding is

made of the simplest possible form of construction, free from taps, which lends itself for providing adequate insulation.

*Stresses to Ground.* The voltages to ground as expressed in the curves of Fig. 11 have been multiplied by the ratios of the probable maximum surge voltages of Fig. 1 and are plotted with respect to their relative values in Fig. 14. On this basis, the latter curves represent the maximum voltage stresses to ground obtained in the various parts of the transformer winding, either through internal oscillation or by the initial electrostatic induction. In recording these values, measurements by oscillograph and sphere-gap are in agreement within experimental accuracy. Obviously these stresses are placed upon the major insulation of transformers and for uninterrupted service must be withstood. Since in this case, as in the previous case, the highest stresses are produced by the very short surges, the transformer major insulation may be subjected to 14 to 15 times normal voltage in the vicinity of the line end. In the mid-section of the transformer the highest voltages are produced by the long surges and are 3 to 5 times normal. Their value is fixed by the amplitude of oscillation. The amplitude of oscillation is a function of the initial distribution which in turn is a function of the physical proportions of the winding. Transformers insulated sufficiently to withstand the maximum stresses at the line end should without difficulty withstand the stresses imposed at any internal portion, even though the insulation there is reduced.

The above conditions refer to the maximum surges expected in service. For longer surges such as represented by curves *E* and *F*, Fig. 1, or for surges removed a considerable distance from the transformer, the stresses would be diminished.

ACKNOWLEDGMENTS

The author is pleased to acknowledge the valuable assistance rendered by Messrs. F. J. Vogel, J. F. Peters, J. M. Blackhall, and others of his associates in the Engineering Department of the Westinghouse Electric and Manufacturing Company in obtaining the experimental data and preparing this paper.

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## Discussion

**K. K. Palueff:** (communicated after adjournment) Mr. Hodnette's contribution consists of an effort in five directions:

First, he gives us a new impulse ratio for transmission-line insulation.

Second, he attempts to show that the initial voltage distribution produced by a traveling wave of steep front can be made more uniform by increasing the width of the coil and shortening the length of the winding stack.

Third, he shows by test (Fig. 6) that in shell-type transformers the initial voltage concentration on the line end is as high as in the core-type transformer tested by him.

Fourth, he expresses his conviction that the natural period of oscillation of all shell-type power transformers is of the order of 5000 cycles.

Fifth, he tells of his belief, that in practise the relation between the length of the traveling wave and the natural period of internal oscillation, of all shell-type transformers, is such that no dangerous oscillation can be created inside of the transformer winding designed for solidly grounded neutral, and having insulation between high-voltage winding and ground and between high-voltage winding and low-voltage winding, graded in the order of operating-frequency voltage stress between the respective parts.

All of the above points were brought up by Mr. Peters, one of the associates of Mr. Hodnette, in his discussions of a paper by F. F. Brand and myself presented at Dallas last May, and have been briefly answered by me in the closing discussion.[1]

*Impulse Ratio.* The only numerical data so far published on the impulse ratio of line insulators, have been obtained by F. W. Peek. Mr. Hodnette's values of arc-over of line insulators

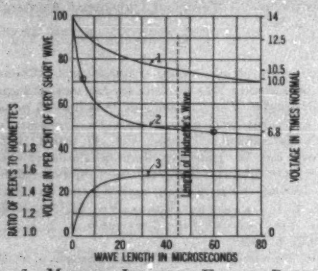


Fig. 1—Maximum Lightning Voltage Possible

No. 1—Peek's test
No. 2—Hodnette's hypothesis
No. 3—Ratio of Peek's to Hodnette's

by traveling waves of different shapes differ radically from Mr. Peek's. Refer to Fig. 1 of Mr. Hodnette's paper and to Fig. 1 of this discussion. For example, line *E* of Fig. 1 shows that the amplitude of a wave 60 microseconds long cannot be more than 6.4 times normal, as the normal line insulation would arc-over at that value, provided it would take 14 times normal voltage to arc-over the same insulator string with a wave of a few microseconds. Mr. Peek's data (see Fig. 1 herewith) show that in such a case a wave 60 microseconds long must reach a value 10.3

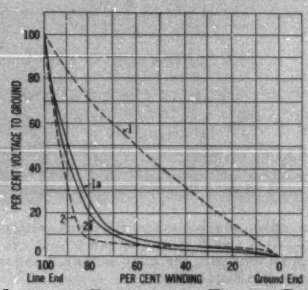


Fig. 2—Initial or Electrostatic Voltage Distribution in Transformer Windings

No. 1 —Hodnette's hypothesis, shell type
No. 1A—Hodnette's test, shell type
No. 2 —Hodnette's hypothesis, core type
No. 2A—Palueff's test, core type (without static plate)

times normal before it arcs over the insulators. This fact alone makes all values of internal voltages of shell-type transformers 55 per cent higher than they are shown in the paper (Curve *C* of Fig. 14).

I should like to know what experimental data were used as a base for Fig. 1.

1. A. I. E. E. Quarterly Trans., July 1929, p. 989.

*Initial or Electrostatic Voltage Distribution.* Mr. Hodnette found it helpful to employ methods used in my paper of last January,[2] and confirmed by his test, that initial voltage concentrates at the line end of the winding of a complete shell-type transformer to the same degree as in the core type. (See Fig. 6 of Mr. Hodnette's paper and Fig. 2 of this discussion.) It is therefore rather a surprise to me that the author overlooked an

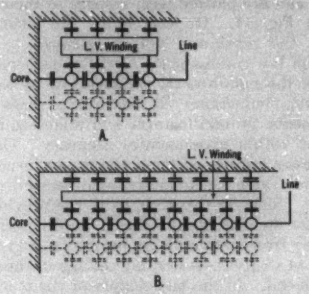


Fig. 3—Comparison of Distributed Capacitance in Narrow and Wide Coils

A. Narrow coils
B. Wide coils

exceedingly important fact in his theoretical discussion of the phenomena. Fig. 2 of his paper corresponds to Fig. 19 of my January paper, except that it does not give numerical values of the equi-potential surfaces. Among other things, it shows that considerable voltage drop takes place across the first coil from outside turn toward the inside. This happens because the first coil (as well as all others) at the instant of impact of the traveling wave acts as a chain of condensers composed of the capacitance

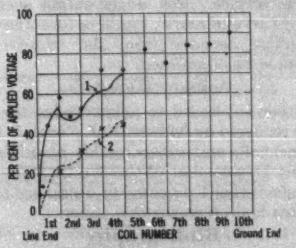


Fig. 4—Effect of Coil Width on Voltage Concentration near Line End

No. 1—Coils 10 in. wide. No. 2—Coils 2 in. wide. The curves are calculated, and the points tested values

between turns as shown in Fig. 3. Mr. Hodnette seems to appreciate this fact, judging by the middle paragraph of p. 70, but in spite of it he tells us that the initial voltage distribution throughout the winding can be determined by the equation given at the bottom of p. 69. This equation would be applicable were individual coils acting as solid metal plates (of width and thickness corresponding to the coil build). Since each coil does not act as a plate, but as a chain of series condensers, the equation is inapplicable. This may be illustrated by the fact that the equation

2. A. I. E. E. Quarterly Trans., July 1929, p. 681.

shows that the wider the plates the more uniform the initial distribution. This of course is incorrect, as it is obvious that the wider the coils the longer the chains of condensers to which the coils are equivalent, and the greater the drop in voltage across them.

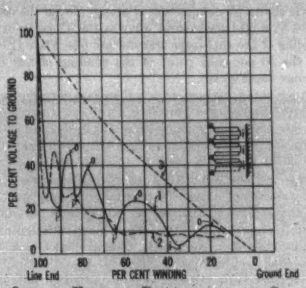


FIG. 5—INITIAL VOLTAGE DISTRIBUTION IN SHELL TYPE TRANSFORMERS

No. 1—Palueff's test, one group
No. 2—Palueff's test, three groups
No. 3—Hodnette's hypothesis

To confirm this theoretically, a detailed equivalent circuit, including capacitance between turns, and from turns of one coil to turns of next coil, as shown on Fig. 3 herewith, was computed for coils of different widths, and calculations made which show very close agreement with results of test (see Fig. 4 herewith).

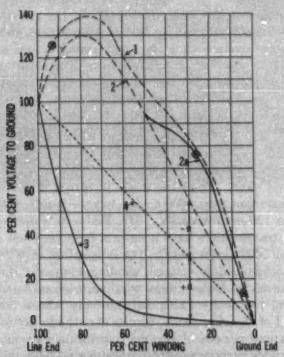


FIG. 6—VOLTAGE PRODUCED BY A SINGLE TRAVELING WAVE

No. 1 —Maximum voltage to ground, Palueff's calculation
No. 2 —Maximum voltage to ground, Hodnette's calculation
No. 2A—Curve 2 corrected according to results of Hodnette's test
No. 3 —Initial or electrostatic distribution
No. 4 —Final distribution, or line of equilibrium. Points shown are from Hodnette's tests

Fig. 5 shows an initial voltage distribution in a 5000-kv-a. shell-type transformer. The saw-tooth shape of the curve for one and three groups must be noted, as this is characteristic of initial distribution of short windings of wide coils. The lowest points of the curve were obtained by measuring voltage of the inside turns (next to the core leg). The peaks of the curve were obtained by measuring the voltage on the outside of the winding. If a curve is drawn through the outside points only, it obviously gives an impression of more uniform distribution than is actually the case. Mr. Hodnette states that the inside points next to the core leg were not accessible in his test. This probably accounts for the smoothness of the initial voltage distribution in shell-type transformers, as shown in his Fig. 6.

The title of Fig. 7 of his paper misled me for the moment, as I took curve *A* for the result of Mr. Hodnette's test of initial voltage distribution in one group of his three-group shell-type transformer, and curve *B* for the same of his core-type transformer. In the body of the paper, however, it is stated that it is a curve of the voltage to ground produced by a 5-microsecond wave. In other words, it is the maximum voltage to ground that occurs in the transformer from the time it is struck with the 5-microsecond wave up to the time when the oscillation completely dies out, and as the initial voltage distribution precedes the oscillation and gives the minimum voltage to ground, the only conclusion that can be derived from his Fig. 7 is that in the particular core-type transformer, which Mr. Hodnette tested, much

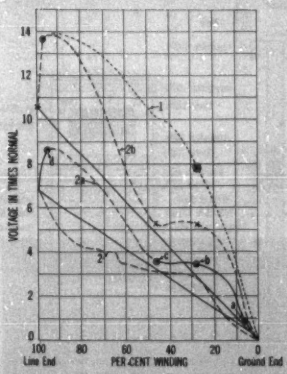


FIG. 7—MAXIMUM VOLTAGE TO GROUND DUE TO A WAVE OF MODERATE LENGTH (SHELL TYPE TRANSFORMERS)

No. 1 —Maximum voltage possible, Palueff's calculation
No. 2 —Hodnette's hypothesis
No. 2A—Hodnette's test
No. 2B—Hodnette's test corrected for applied wave of voltage 10.5 times normal

lower voltages to ground were produced by the 5-microsecond wave than in the shell-type transformer used by him, which means that the natural frequency of the shell-type transformer was many times that of the core-type transformer.

I would suggest that Mr. Hodnette check our test and calculations, as shown on Figs. 4 and 5 herewith, by using the winding of a transformer that he considers to be "well proportioned." However, it would be quite necessary to measure voltage between line end and all inside and outside turns of the coils.

The calculation and the test will show immediately that the initial distribution grows worse as the width of the coils increases and on account of the fact that the stack becomes shorter as coils increase in width, the voltage per unit length of the stack increases. The comparison of these stresses in the short and long stack is shown in Fig. 8 herewith, where a cross section of core and shell-type transformers, having approximately the same bulk of winding, is drawn to the same scale, and the insulation distribution and voltage stresses, due to initial distribution and subsequent oscillation, are given.

Fig. 6 of the paper shows that at the initial moment 46 per cent of the applied voltage of a steep wave appears across 6.7 per cent of the winding in the so-called "well proportioned" shell-type transformers. Curve *B* of his Fig. 7, which Mr. Hodnette considers to give very nearly the initial distribution in the core-type transformer, gives 50 per cent of applied voltage across the same percentage of the winding. Does not the author think that this is good evidence, since the initial voltage distribution is so nearly alike, in two windings so radically different that our opinion is correct, that in practical transformers it is quite impossible to appreciably modify the initial voltage distribution by a mere change in the width and the length of the stack?

In the light of the above, I should very much appreciate it if the author would explain to us the reason for classifying as well proportioned the shell-type transformer that he tested? The reason becomes particularly obscure, since the author himself emphasizes that in shell-type transformers about 85 per cent of the applied voltage appears across the line group, that is, across ⅓ or ¼ of the entire winding, depending on the number of

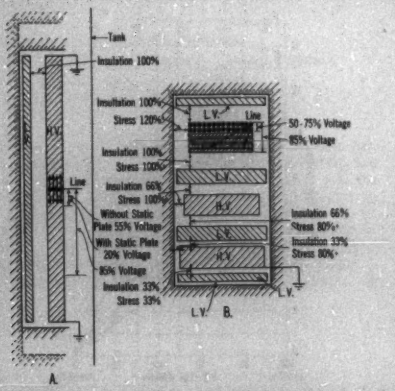


Fig. 8—Comparison of Voltage Stresses and Insulation in Grounded Neutral Transformers

A. Concentric type, not graded
B. Shell type, graded insulation

groups. In my opinion the goal of a designer should be to get a uniform initial distribution, and not that of his Fig. 6.

*Internal Oscillation and Voltage to Ground.* In my paper presented last January, I stated that both core and shell-type transformers undergo a violent internal oscillation when struck by a single traveling wave.

It appears from the discussion that the tests of some of Mr. Hodnette's associates showed such oscillations in shell-type transformers. I am, therefore, particularly glad to see that further study, as revealed by his oscillograms Figs. 9 and 13, confirm in all respects our conviction that the oscillation of shell-type transformers is of the same magnitude as that of the core-type. The shell-type transformer, as theory shows, has also certain additional oscillations peculiar to that type, but lack of space here does not allow going into the phenomena at length.

On Fig. 6 herewith, Curve 1 is an envelope of maximum voltage to ground possible in a long stack of narrow coils. This curve is copied from Fig. 4 of *Lightning Study of Transformers by Cathode Ray Oscillograph.*[1] Encircled crosses correspond to the values obtained from Mr. Hodnette's oscillogram No. 1 of Fig. 9 and Curve *A* of Fig. 12. Incidentally, these points of Mr. Hodnette's test exceed materially his theoretical curve of maximum voltage to ground (Curve *C* of Fig. 4), as should be expected since the method employed by him for constructing Curve *C* is in radical conflict with requirements of the theory, described in detail in both of our above mentioned papers.

Further similarity of oscillations in the two types of transformers is shown by comparison of amplitudes of the oscillations produced by a 60-microsecond wave at the 47 per cent point of the winding of the shell-type transformer (see Plate II of Fig. 9) and at the 50 per cent point of the winding of the core type transformer (see Fig. 10).

As shown in my January paper, there is a very simple relation between the length of a traveling wave and the amplitude of maximum voltage to ground created by it in a transformer winding. This relation is a function of the ratio of duration of half of a period of the first few natural frequencies of a transformer and the duration of the applied wave. Mr. Hodnette's test shows that in his shell-type transformer the natural frequency happened to be 5000 cycles, and that of the core-type transformer to be 6700, and by assuming that the longest dangerous lightning wave is not more than 60 microseconds, he arrives at Curve *A* of Fig. 11 (by scaling oscillograms of Plate II, Fig. 9) as an envelope of maximum possible voltage to be expected in service in any power transformer of shell type. There are several objections to this conclusion.

1. Referring to Fig. 7 of this discussion, encircled crosses *a*, *b*, and *c* were obtained by measuring more accurately oscillograms of Plate II, Fig. 9. Point *d* is taken from Curve *B*, Fig. 12. Comparison of these points with the Curve *C* of Fig. 14 shows that the curve is from 10 to 50 per cent below the true values, as shown by the oscillograms.

2. Since the voltage to ground increases with an increase in the length of the applied wave, it is very essential to know accurately the length of the wave that produced the voltage indicated by points *a*, *b*, and *c*. Mr. Hodnette considers this wave 60 microseconds long, but observing the fact that neither time nor voltage scale of Plate II, Fig. 9 is uniform, and exercising all necessary care in scaling the oscillograms, it appears that the wave is not 60 but 47 microseconds long. The theory shows that were the wave really 60 microseconds long, it would produce voltages in excess of even those shown by *a*, *b*, and *c*.

3. If the natural frequency of the transformer were not 5000 cycles but, say, 10,000 cycles, then as theory shows, half of the winding next to the neutral end will practically reach Curve 1 of Fig. 7 of this discussion when the transformer is struck by a 60-microsecond wave. The same would happen if the natural period of the transformer were 5000 cycles, but the length of the applied wave were 120 microseconds. Mr. Hodnette's opinion that all shell-type transformers have a natural frequency not materially higher than 5000 cycles rests on the supposition that the presence of an interleaved low-voltage winding increases the effective capacitance of the high-voltage winding to ground and prevents the natural frequency rising substantially above 5000 cycles. On Table I of this discussion, results of cathode ray oscillograph tests of natural periods of various transformers are given, which show very wide variation in the natural period in accordance with theoretical conclusions published in my January paper. They also show that the minimum and maximum natural frequencies of shell-type and core-type transformers tested covered about the same range.

The fact that the 5-microsecond wave produced voltage to ground in the short stack of wide coils as shown by Curve *A* of Fig. 7, indicates that the natural frequency of that particular stack was very much higher than 5000 cycles, and substantially higher than that of the core-type transformer that gave the voltage distribution shown by Curve *B* of the same figure.

On the strength of all of the above, we can revise Mr. Hodnette's Curve *C* of Fig. 14. The results are shown on Fig. 7 of this discussion. Curve 2 is a copy of Mr. Hodnette's curve *C* of

Fig. 14, which is supposed to be an envelope of maximum voltage to ground produced by a 60-microsecond wave of the maximum amplitude possible in service.

Curve 2a is the revision of this curve in accordance with Mr. Hodnette's own oscillograms, as mentioned before. Curve 2b is the revision of curve 2a, with the amplitude of the applied wave increased from 6.8 times normal to 10½ times normal on account of the difference in impulse ratio given by Mr. Peek and Mr. Hodnette for the 47-microsecond wave. (See Fig. 1 of this discussion).

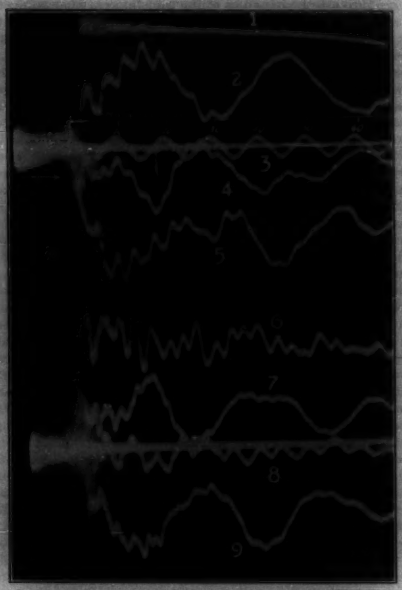

Fig. 9—Internal Voltages in One-Group Shell Type Transformer

No. 1—Applied wave. No. 2—Voltage 50 per cent from ground end. No. 3—Timing wave. No. 4—26 per cent from ground. No. 5—78 per cent from ground end. No. 6—91 per cent from ground end. No. 7—32 per cent from ground end. No. 8—6 per cent from ground end. No. 9—50 per cent from ground end. Nos. 4, 5, 8, and 9 were obtained with reversed polarity

Dotted Curve 1 represents the maximum possible voltage to ground calculated for a long stack of narrow coils. The encircled point on it was taken from Plate 1 of Fig. 9 of Mr. Hodnette's paper. This proves that the voltage that would appear in shell-type transformers, at least at that particular point of the winding, rises far in excess of the strength of graded insulation at that point, and reaches the same value as in a long stack of narrow coils. That the necessary relation of the natural period of shell-type transformers and the length of the applied wave is possible, is substantiated by Table I of this discussion, and Curve *A* of Fig. 7, as well as by theoretical considerations.

I did not find in the paper either test data or theoretical estimates of voltage stresses that may be produced in a shell-type transformer by a damped switching transient. Since the shell-type transformer has a number of natural frequencies, it may get in resonance with the transmission line. This will produce very high internal voltages. I should like to know just what are the author's findings in this branch of the phenomena.

On account of all of the above, I feel that we must remain of the opinion that grading of major insulation in the order of low-frequency stresses is not a safe practise. This is substantiated by service experienced with some modern transformers built with graded insulation, which have failed during a lightning storm at a point on the winding far removed from the line end.

TABLE I

NATURAL FREQUENCY OF POWER TRANSFORMERS

| Type | Capacitance kv-a. | Fundamental natural frequency in kilocycles | Duration of natural period in micro-seconds | Second natural frequency in kilocycles | Duration of second natural period in micro-seconds |
|---|---|---|---|---|---|
| Shell | 2,000 | 40. | 25. | | |
| Shell | 2,500 | 33.4 | 30. | | |
| Core | 3,300 | 33.2 | 30. | 100. | 10. |
| Shell | 1,000 | 11.0 | 90. | 40. | 25. |
| Core | 22,000 | 10.5 | 95. | 37.0 | 27. |
| Core | 23,300 | 16.7 | 60. | 80.0 | 12.5 |
| Core | 12,000 | 12.9 | 77.4 | 65.0 | 15.0 |
| Core | 6,670 | 9.0 | 111. | 31.0 | 32. |
| Shell | 5,000 | 6.25 | 160. | 25. | 40. |
| Core | 8,000 | 6.40 | 157. | 28.8 | 35. |

| | Shell type | Core type |
|---|---|---|
| Lowest fundamental frequency (kilocycles) | 6.25 | 6.40 |
| Highest fundamental frequency (kilocycles) | 40.0 | 33.0 |

Fig. 10—Cathode Ray Oscillogram of the Surge Flashover of a Line Insulator

**F. W. Peek, Jr.:** I find Mr. Hodnette's paper of great interest because the subject has been a hobby of mine for a long time.

The first test of this nature was made about 1913. There were some very peculiar failures far in the interior of a transformer winding and the only apparent cause was some high-voltage phenomenon due to arcing grounds or lightning. However, it did not, at that time, seem possible that very high frequency or lightning voltages could penetrate the very high inductance of a transformer. An investigation was started by applying high-frequency currents to transformer terminals. High voltages were built up even at the ground end. This was surprising. However, the mystery was soon solved when it was realized that, while a transformer was an inductance at operating frequencies, it was largely a capacitance at high frequencies.

At 60 cycles or for direct current or any low frequency, the applied voltage divides along a transformer stack in proportion to the inductance or the resistance. The voltage distribution is caused by these factors and is thus very good. When a high-frequency or steepfront voltage is applied to a transformer the voltage distribution at the first instant is controlled entirely by the capacitance. This capacitance distribution is always such that the voltage becomes practically all concentrated on a few turns of the winding near the line end. After a short interval of time has elapsed, the inductance must become the controlling factor. In passing from the transient distribution stage to the final or inductance distribution stage, the voltage over-shoots and oscillations occur. In this manner extremely high local voltages may be caused in any part of the winding.

The above characteristics apply to either a shell-type or to a core-type transformer. In fact the original failure and the original investigations were on shell-type transformers. The first step in improving this transient condition was a change from the shell-type to the core-type transformer. While this was an improvement it was the ambition of the engineers interested in this investigation to produce a transformer that would not resonate, or, in fact, that would have the same voltage distribution under all conditions of frequency or impulse. This has been accomplished in the shielded winding, or non-resonating transformer recently discussed before the Institute.[1,2] The means employed are quite simple. A shield is added to the transformer in such a way that the capacitance distribution corresponds to the inductance distribution. In other words, in the shielded winding, whether the distribution is caused by the capacitance at high frequency or by inductance at low frequency, the voltage gradient is uniform throughout the winding. Since the initial and steady-state distribution are thus the same, there can be no oscillation. By this arrangement local stresses are reduced as much as 80 to 1. Besides the enormous strength of such a transformer under the voltage transients incidental to operation, it has an additional advantage in that the 60-cycle acceptance test is the equivalent of a lightning test. This follows because of the uniform voltage distribution at any frequency.

There may be some question as to whether or not a transformer is subjected to the same frequencies or impulses in practise as were used in making tests in the laboratory. The original test covered a very wide range of transients and impulses. Cathode ray oscillograms of lightning which have been obtained this year and last show quite conclusively that the worst laboratory effects would occur on practical lines. The highest voltages to which transmission lines are subjected are caused by lightning. As a general rule, the maximum voltages caused by switching or arcing grounds are approximately half the lightning voltages. Accordingly, switching surges have practically no influence on line insulation. It so happens, however, that surges of the type caused by switching, because they are oscillatory, build up about twice the voltages that are built up by single impulses for the same applied voltage. The effects are thus, on many lines, equal.

It is my opinion that the non-resonating transformer is one of the greatest advances made in the art in the last 20 years.

**F. E. Terman:** After we have been working with transformers for a while we get accustomed to think that the voltage between two points of a coil will be proportionate to the number of turns within those two points. I want to point out that there are some types of coils in which that is not the case.

In an air-core coil the linkages per turn are less at the ends of the coil than at the center. As a consequence, with air-core coils such as used for radio we get a coil with a higher voltage rating by spreading out the center turns and bunching them together at the end.

**Mabel Macferran:** I should like to inquire what effect a reactor in the neutral of a Y-connected bank would have on the resonance phenomena under discussion.

**Alexander Nyman:** The subject of Mr. Hodnette's paper has long ago been recognized by designers of transformers. It has been usual to take account of these phenomena by proper insulation of the end turns of transformers, but in spite of that, occasional disturbances of great magnitude have caused breakdowns.

The value of this paper lies therefore in summarizing the results of the recent studies on lightning disturbances and other surges and applying these results to the study of transformer operation so as to give a clear picture of the phenomena that take place.

It appears that the main reason for the unequal distribution of voltage through the windings of the transformer, when subjected to a surge, is the fact that the distribution of capacity between the coils and from coils to ground throws an excessive burden of initial surge voltage on the turns closest to the line. It is evident, of course, that if the capacity to ground of these coils is reduced relatively to the capacity between coils, the distribution of surge voltage would be more even. In a limiting case, if all of the distributed capacity to ground were eliminated and the capacity between the individual coils were the same throughout, the distribution of surge voltage would be exactly the same as the distribution of 60-cycle voltage. Of course, such a condition is impossible to reach in practise, but it is possible, and entirely feasible, to work in the opposite direction and to increase the capacity between the coils, as compared to the capacity to ground. The easiest way to achieve this is to introduce static condensers external to the transformer coils but connected to them at intermediate points.

Condensers to withstand high voltages and to pass surge currents of considerable magnitude have been developed and can be built in such small physical dimensions for the required capacity that they can be easily installed within the transformer tank and constitute a part of the final assembly of the transformer structure before immersion into a tank. For example, a condenser to withstand a 60-cycle voltage of 10,000 would occupy a physical dimension of 4 by 6 by 10 inches for a capacity of about 0.01 microfarads. Thus, if a number of units of this size be built up into a structure, with taps brought out corresponding to the voltages on the individual coils, it is quite evident that the resulting capacity will be far in excess of any capacity to ground that may exist from the corresponding coils, and therefore voltage distribution due to surges will be practically equalized. The condensers of this nature have been subjected experimentally to surge tests and are known to withstand a surge voltage of at least ten times the operating 60-cycle voltage. Since the author states, as a result of his investigation, that the voltage seldom exceeds double the line voltage and never exceeds five times the line voltage, it is evident that such a condenser would be quite safe, and moreover, on account of its large capacity, it will have a tendency to take over the peak of the surge, due to its steep wave front.

**J. K. Hodnette:** Apparently Mr. Palueff has incorrectly interpreted the object of my paper. The intention was not to prove that Mr. Palueff was wrong in any respect or to present the real merits and demerits of shell- and core-type transformers, but the object was to present additional data on the general subject and coordinate previous data.

In Mr. Palueff's discussion he stressed the idea that the voltage distribution was substantially the same in all non-shielded transformers. I strongly disagree with this. In the paper of Blume and Boyajian published in February 1919, which Mr. Palueff correctly refers to as a classic, you will find that the value $\alpha$ which corresponds to the term $\sqrt{\frac{C_g}{C_c}}$ in my paper, $C_g$ being the capacitance to ground and $C_c$ the capacitance between coils. They further state that $\alpha$ is found to vary between 5 and 30 for disk-type windings. It was not my intention to point out the relative values of the constants of shell- and core-type

transformers. But it is easily seen that this ratio is much smaller for the usual proportions of shell-type transformers than for the usual proportions of core-type transformers. Therefore, generally, the initial voltage distribution would be better for wide-coil transformers than for narrow-coil transformers.

With reference to the discussion on the initial or electrostatic voltage distribution, it is conceded that the problem becomes very complicated to predetermine the voltage at some particular point in a winding unless the elements of the winding are considered as being solid plates. This is the very assumption made in both Mr. Palueff's and Mr. Peek's work in connection with the shielded transformer. Otherwise they could not apply shields, effective on the edges of the coils only, and obtain a uniform distribution of voltage throughout the windings of the transformer.

It is necessary to define a wave with respect to time when determining its effects. This has been carefully done in the body of this paper. The wave shown in Fig. 10 of this discussion was used as a basis for computing Curve *E*, Fig. 1 of the paper. This wave would have decreased to one-half value in approximately 50 microseconds had the insulators not flashed over and reduced it to zero at 19 microseconds. In this oscillogram the dotted line represents the 60-cycle flashover voltage, and with this wave the impulse is 6.4 times normal instead of 10.3 as stated by Mr. Palueff. Therefore, in comparing the voltage stresses they should not be increased by the ratio of 10.3 to 6.4 but are correctly represented in Fig. 14.

The curves given in the experimental section of my paper were obtained by measurement directly from the original oscillograms and checked by sphere spark gaps, the standard for measuring high voltages. Therefore, I cannot agree with Mr. Palueff that these values are so far in error.

It has not been my intention to give the impression that all transformers have a natural frequency of 5000 cycles. Power transformers of modern design over a wide range in size have been tested and natural frequencies as high as 12,500 cycles recorded, but a frequency of 5000 cycles is considered a representative value in order of magnitude. In this connection, Fig. 9 was given to show the variation in amplitude attained by internal oscillations with the variation in the length of applied wave. The waves used covered sufficient range in length to show the effect of any fundamental frequency expected in modern commercial transformers when subjected to natural lightning surges. As indicated, transformers having a higher fundamental frequency would have internal stresses somewhat increased but not sufficiently to alter any of the conclusions drawn.

Curve *A*, Fig. 7, is a measure of the maximum voltage to ground produced by a 5-microsecond surge, but at the same time it is a measure of the initial distribution of voltage as the natural frequency is such that the initial voltage is also the maximum voltage to ground. This curve was determined by measuring the voltage at the starts and finishes of every coil.

The company with which I am associated has supplied a large number of graded-insulation shell-type high-voltage transformers which are operated in very severe lightning districts. It is definitely known that lightning has struck the lines close to several banks of these transformers with no disastrous results to the transformers, in spite of the fact that these lines were considerably over-insulated. This does not prove conclusively that these transformers or any transformers are immune from all possible lightning strokes but it does indicate their adequacy for this service. It is only necessary to refer to service records in general to learn that failures to ground through the major insulation of such transformers is practically unheard of.

With reference to Mr. Peek's discussion, it may be of interest to note that the company with which I am associated has been building both shell- and core-type transformers for many years. Contrary to Mr. Peek's conclusions, laboratory tests and service records do not indicate that the core-type transformer is superior to the shell-type. The type of construction best suited for a particular application is generally used.

Analyzing Miss Macferran's question concerning the effect of connecting a reactor between the neutral of a bank of transformers and ground, it is possible for the reactor to enter into oscillation with the transformer and somewhat increase the voltage on the grounded end. The degree to which the reactor effects the oscillations here depends upon the characteristics of the reactor and of the transformers and the shape of the surge striking the transformer terminal. For a short surge, such as the 5-microsecond surge, it has been shown that only a small amount of energy penetrates the winding to the portion near the grounded end, consequently the potential at the reactor will be low. For a long surge more energy passes through the winding and the oscillations at the reactor will be proportionately increased as in the case of the transformer itself.

Mr. Nyman has attacked the problem of improving the voltage distribution in the opposite phase from that described by Mr. Peek. In so doing he has reached a perfectly logical conclusion. I completely agree with him that the distribution can be improved by increasing the relative capacitance between coils, as this in turn decreases the ratio of the capacitance between coils. However, the introduction of condensers in the transformer means the addition of another device or complication in the construction and it is desirable to keep the construction as simple as possible.

Mr. Terman has illustrated an interesting method of effecting a good voltage distribution in air-core coils but I do not believe that it is applicable to power transformers.

# An A-C. Low-Voltage Network
## Without Network Protectors

BY LESTER R. GAMBLE[1] and EARL BAUGHN[1]
Member, A. I. E. E. Associate, A. I. E. E.

***Synopsis.***—*The object of this paper is to present a description of the Spokane, Washington, underground network system, and to describe briefly the operating experience and problems which have resulted from the installation of ring primary feeders and a four-wire, 120/208 volt secondary network supplying a universal service.*

*Reasons for the choice of the system described are presented with particular reference made to the use of a fuse in the secondary circuits instead of the device commonly known as the "Network Protector."*

*The general design of the primary feeders, secondary network, pilot wire relays and fuse protection, and transformer vaults is discussed.*

*Descriptions are given of all apparatus and equipment used.*

*A report is included covering tests made on the system under fault conditions. The report shows that the tests which simulated actual operating conditions indicate the system will operate as designed. The voltage regulation of the network having been recently investigated, is covered in detail.*

*The procedure in the change-over from d-c. to a-c. service is discussed and the problem of customer consideration analysed.*

*The paper is concluded with a statement that no difficulties have been encountered on the system and that its operation up to this time has been perfect.*

### Introduction

In 1923 a general survey was made of the three-wire Edison d-c. system, which served the downtown business district in the city of Spokane, Washington. The survey indicated that the demands for electric service were placing many limitations on the d-c. system. Some of the limitations were: (a) excess transmission loss; (b) poor voltage regulation; (c) limited duct space because of the large number of feeder cables required; (d) limited feeder capacity because of the inability of duct lines properly to dissipate energy losses.

However, the d-c. system had been very satisfactory considering the continuity of service. There had been very few cases of trouble, with a record of only one complete interruption since the mains and feeders were placed underground in 1910. Because of this excellent record there was considerable opposition to any suggestion of substituting an a-c. system in the downtown business area. It was realized that such a substitution positively eliminated the stand-by battery, which gives to the d-c. system its high standard of service.

Nevertheless later investigations showed that the industrial customers, in general, preferred a-c. service, because of the lower first cost and the lesser maintenance required in the operation of the a-c. motor and its control equipment. Also, that numerous requests were being made for a-c. service for neon signs, a-c. radio sets, radio broadcasting stations, telechron clocks, and many other uses where alternating current is necessary or preferred.

Fig. 1A shows the area as originally covered by the Edison d-c. system. Areas Nos. 1, 2, and 3 represent the territory served by underground distribution and area No. 4, that served by overhead distribution. The system was supplied from the substation located as shown on the sketch.

Area No. 1 with a d-c. load of 7000 kw. represents the heart of the downtown district and is the area having the highest load density. Area No. 2, which had a d-c. load of 1000 kw., represents the district changed over to a-c. network operation in the fall of 1928. Area No. 3, with a d-c. load of 2300 kw., represents the section which will be changed over during 1929 and 1930. Area No. 4 represents the overhead d-c. distribution system which was changed over to a radial a-c. distribution system during 1925, 1926, and 1927. This latter area, with a load of 1000 kw., contained residential, warehouse, and industrial customers whose service requirements did not seem to demand the high quality of service needed in commercial districts represented in areas 1, 2, and 3.

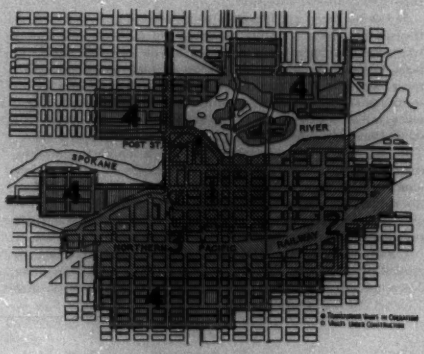


Fig. 1A—Spokane Business District

It will be seen, by the above, that the plan was to limit the growth of the d-c. system by surrounding it with an a-c. network system, which would make it unnecessary to expand the d-c. service into new districts.

1. Both of the Washington Water Power Company, Spokane, Wash.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.*



29-127

After changing over the outer districts the d-c. system will be further curtailed by extending the a-c. network into the central area.

### Type of A-c. System Selected

In order to overcome the limitations of the downtown d-c. service as cited above, it was apparent that large expenditures were necessary and at the same time it was recognized that the income from the service rendered could not justify the expenditure of any considerable sum of money. Therefore, a number of plans was considered and an attempt was made to provide an economical system without the sacrifice of reliability and quality of service.

After comparing the d-c. system with an a-c. system having equal reliability, it was found that the a-c. system had certain outstanding advantages, namely, high efficiency and low cost per kilowatt delivered.

The particular type of a-c. system decided upon was determined after making a thorough investigation of all types of a-c. systems then in use in various parts of the country. No one system was taken in its entirety, but parts of several systems were combined into one, which it was felt would give Spokane's commercial area a distribution system of the highest order and one which would have no part or element that had not been tried out in service.

The system adopted consists of three-phase, 4000-volt primary ring feeders, sectionalized by oil circuit breakers operated by means of a pilot wire relay circuit, and a three-phase, four-wire, 120/208-volt secondary network supplying a combined light and power service.

The ring type of feeder seemed preferable to the radial, first, because it made it possible to give a two-way feed to certain isolated loads, which could not be connected to the secondary network and which due to their importance would require a very expensive service from two primary feeders with special throw-over equipment, and second, because an analysis of the annual costs of the two types of feeder systems (ring and radial) gave for the particular shape of area to be supplied, a somewhat lower cost for the ring feeder. Although the costs of the two types were relatively close, it was apparent that the characteristics and shape of the area served made the ring type feeder more desirable. However, in comparing these costs, cognizance was taken of the advantage the radial feeders offered to the saving of certain amounts of transformer excitation losses during light load periods, by taking one or more feeders out of service.

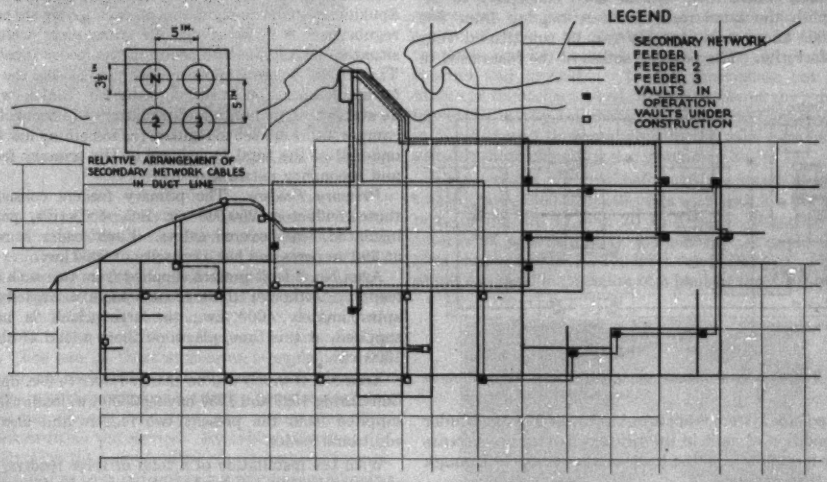


Fig. 1B Secondary Network and Primary Feeder Arrangement

The primary voltage to be used was given considerable study and after a thorough investigation of the future load requirements it was found that 4000 volts would be the most economical voltage. This was governed particularly by the fact that the substation supplying the load would be within approximately 2000 ft. of the load center, and thereby defeat the necessity of higher voltages to secure better regulation and reduce losses.

The plans for an a-c. secondary network were adopted, at the beginning, because it was felt that the high standards of service which had been provided by the

d-c. network should in no way be lowered through the substitution of a radial type of secondary.

The plan of combined light and power service was selected because of the savings attendant to such a type of system, notwithstanding the fact that such a system had certain inherent disadvantages which must be eradicated by proper design features. These features are discussed at length throughout the paper.

Because of the particular type of primary feeder installed, the protective and sectionalizing devices which have been used are radically different from those used on systems with radial feeders. In general, the device known as the "Network Protector" has been used in other cities for sectionalizing faults on such systems. With the ring feeder, however, the network protector does not become an absolute necessity, especially where fuses can be used effectively to accomplish the same result. Fuses ranging from 800 to 2000 amperes in capacity can be substituted very satisfactorily. The positive action of the fuses used in

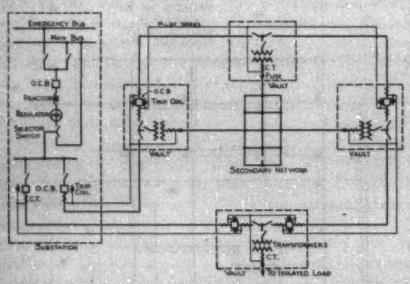


Fig. 2—One-Line Diagram of One Primary Ring Feeder

the Spokane system is apparent from the fact that under no condition of fault in the primary feeder do currents to the fault flow from the low-voltage network, through more than one fuse.

## Description of System

*Power Supply.* The power supply for the Post Street Substation on which the a-c. underground network is entirely dependent is obtained from five independent sources, namely, the Upper Falls, Monroe Street, Nine Mile, Long Lake, and Little Falls hydroelectric plants. Of these, the first two are located in the city of Spokane and generate at 4000 volts and supply power directly to the bus to which the feeders are connected. The power from the other three plants is carried over 60-kv. and 110-kv. lines and brought into the substation over several 13-kv. distribution circuits.

This gives a number of power sources connected to the main substation and provides a very reliable service to the network system, where service continuity is of the utmost importance.

*Substation Equipment and Bus Arrangement.* The layout of the system from the substation to the secondary network is shown schematically in Fig. 2. The feeders are connected to either one of two buses, thence through reactors and regulators to an auxiliary bus where the feeder divides into two parts, forming the ring feeder.

The arrangement of the main oil circuit breaker, reactors, and regulators is such that in case of trouble in any of this equipment it can be by-passed conveniently without interrupting the feeder.

There is a set of three single-phase regulators on each feeder. No special connections have been used between different sets of regulators to obtain stable operation. It has been found by other users of the a-c. network that stable operation is possible if due care is taken in setting the line drop compensators. On the Spokane system the regulators on each feeder are set to regulate on the low side of the transformer which is situated nearest the load center of the feeder involved. This, it will be seen, approximates very closely the rule for stable operation as laid down by Mr. Blake,[2] where he states that no hunting of regulators will occur if the compensators are set to regulate for something less than one-half of the total impedance of the primary feeder and secondary network.

*Primary Feeders.* The primary feeders consist of three-conductor, 250,000 cir. mil, 4000-volt, paper-insulated, lead-covered cables. Each feeder is rated at 300 amperes and has a capacity of 2000 kw.

Area No. 2 is at present supplied from two such ring feeders. Although these feeders have a capacity of approximately 4000 kw., the area which is being supplied, at this time, places on them a load of about 1500 kw.

Area No. 3 which will be changed over to a-c. operation during 1929 and 1930 having 2300-kw. load, will be supplied from the present two feeders and also an additional feeder.

With the installation of a total of three feeders, approximately 6000-kw. load can be supplied. The three feeders will cover the area of the underground system sufficiently so that it will be possible at any time to add transformer vaults and change over loads in the more densely loaded district.

The feeders are interlaced and the transformer vaults connected so that by the loss of more than one section of a ring feeder or, by chance, the loss of the entire feeder, the service on the secondary network can be maintained. If such a condition should occur at peak load there would be possibly, in some remote sections, a drop in voltage, usually of a relatively small amount. However, the loss of two sections of the same feeder simultaneously or the loss of one complete feeder is so remote that no apprehension is felt regarding the service.

The area which will be covered by the a-c. low-

2. *General Elec. Rev.*, May 1928, p. 248.

voltage network when the present construction program is finished, is shown in heavy lines on Fig. 1B. The location of the vaults in operation and under construction, together with the general arrangement of the three primary loop feeders, is also shown.

*Oil Circuit Breakers.* The oil circuit breakers which are installed in the transformer vaults for sectionalizing purposes in case of faults in the primary feeder are rated at 15,000-volt, 400-amperes, with an interrupting

Fig. 3—Typical Vault Showing Installation of Condit Oil Circuit Breaker

capacity of approximately 20,000 amperes at 4000 volts. The maximum short-circuit current in case of a fault on a primary feeder is about 10,000 amperes. Figs. 3 and 4 show the two types of oil circuit breakers used.

Each oil circuit breaker contains six bushing type current transformers, three on each side, with a ratio of 60 to 1. The breaker also has two five-ampere trip coils. The use of these auxiliaries is explained in a later paragraph describing the pilot wire relay circuit.

Because of the secondary network a transformer bank can be disconnected from the system at any time without jeopardizing the service. By taking advantage of this situation the number of oil circuit breakers in each ring feeder has been reduced to a minimum by allowing one transformer bank to be cut out of service in case of primary feeder trouble somewhere in the ring. Fig. 2 shows clearly the general plan used, and indicates that on any one ring feeder, those vaults with transformers which supply a secondary network have a breaker in all vaults except one. The reason for this one exception is readily apparent from the fact that the substation breakers on the two ends of the ring feeder are controlled by the pilot wire relay circuit and operate as a part of the underground system. Referring again to Fig. 2, a vault is shown having two breakers. This becomes necessary only in cases where those vaults supplying isolated loads are at some distance from one another, and for that reason it is not expedient to network their secondary circuits. Two breakers are then required to give complete reliability to the loads being served. However, as other vaults are constructed and the distances between vaults shortened, the secondary circuits in the isolated cases can be connected into a network and one breaker removed from each vault to give the same conditions of operation as that obtained in the general network plan. As will be seen, the layout reduces materially the investment costs per feeder and at the same time does not jeopardize the service being supplied.

*Primary Junction Boxes.* Two types of primary boxes are in use, one being a three-phase, four-way, and the other being a single-phase, four-way. In either type, two of the four-ways are used for the incoming and outgoing feeder, one is for the transformer tap leads and the fourth is a spare.

The single-phase type is shown in Fig. 3, mounted directly to the left of the oil circuit breaker. This type of box is oil-filled. The arrangement is such that the cables can be easily removed from the box. If a section of cable is to be taken out of service for repairs the ends can be removed from the box and properly shorted and grounded. In the three-phase box the same can be accomplished, not by removing the cables, however, but by removing disconnecting bars located in the box and then applying to the cable terminal a suitable short-circuiting and grounding cable.

*Transformers.* The transformers are standard type, single-phase, 2400-120/240 volts with two, five per cent taps, giving 18, 19, and 20 to 1 ratio. Standard reactance of approximately 4.3 per cent is used. The sizes used are 50 kv-a., 100 kv-a., and 150 kv-a. Fig. 5 shows a typical installation of a bank of three 100-kv-a.

Fig. 4—Typical Vault Showing Installation of General Electric Oil Circuit Breaker

transformers. A 6000 to 5 ratio current transformer placed on one of the secondary leads is located inside the tank of each transformer and is used as a part of the pilot wire relay scheme as described later. The transformers are Y-Y connected. The Y point of the high-voltage and low-voltage windings are connected together inside of the case. The secondary neutral is then brought out of each transformer of the three-phase bank and connected to the neutral of the secondary network, which is grounded only by being connected at

many points to the d-c. Edison neutral. The Edison neutral consists of an extensive grounding grid composed of 1,000,000-cir. mil, paper-insulated, lead-covered cable to which the 500,000-cir. mil neutral secondary mains are connected. This grid has but one earth connection which is located at the substation. The connection from grid to earth is through seven 1,000,000-cir. mil, paper-insulated, lead-covered cables, thus forming a very substantial ground for the a-c. network.

In the connection of transformers to a network system they are of necessity operated in parallel and it therefore

Fig. 5—Typical Installation of Three 100-Kv-A. Transformers

The small cable entering the low-voltage terminal compartment contains the current transformer secondary leads.

is of great importance that the impedance of the transformers and connecting tie cables be studied with a view that the transformers, as nearly as possible, share the loads on the network. To give the best operation, the impedance of the transformers should be somewhat higher than the impedance of the secondary circuit between the transformers. Although the secondary circuit is of high reactance due to the cables being placed in separate ducts, it was felt that the standard reactance transformers were justified for use on the system, first, from the point of view of voltage regulation and second, that the transformers in the network would at this time be generally underloaded, thereby making the standard reactance transformer suitable. As the network grows and areas in more densely loaded sections are changed over to a-c. operation, surveys of the load division will be made and additional reactance, through the use of cable type reactors, placed in the circuits where required.

*Secondary Junction Boxes and Fuses.* The transformer secondaries are fused to the mains by open, link-type copper fuses mounted in a water-tight box shown in Fig. 6. The secondary leads from the fuse box in the transformer vault are run in a duct line to the nearest manhole where they enter single-phase, five-way boxes for connection to the mains. Copper strips are used for connecting or disconnecting the secondary mains in these boxes. The boxes are used instead of making up solid wiped joints because it was felt that under certain conditions of operation or in case of severe trouble, sectionalizing at certain positions in the network would be of considerable value.

*Secondary Cable.* The mains are 500,000-cir. mil, single conductor cables and are installed in separate ducts. The mains, which had been in use on the Edison three-wire system, were used as installed and the fourth conductor was added to give the third phase. The neutral of the former d-c. system was made the neutral of the a-c. system. Because the existing d-c. cables were used the installation of all the conductors in one duct to get advantage of lower reactance or to economize on duct space, was not resorted to, especially in view of the large amount of labor involved in pulling out the three old cables and pulling them back into one duct with the fourth cable. It was also felt that considerable advantage was secured in having each single conductor cable in a separate duct, thereby reducing to a considerable degree the possibility of copper-to-copper short circuits, which for the cables as large as 500,000 cir. mils may be difficult to burn clear and thereby cause serious damage to the cables.

The size of ducts and the relative arrangement of the secondary network cables is indicated by the sectional view in Fig. 1B.

The power supply from transformers to the secondary

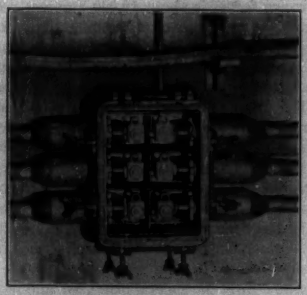

Fig. 6—Secondary Fuse Box with Cover Removed

mains in the manholes is through 1,000,000-cir. mil, paper-insulated, lead-covered cable for 50- and 100-kv-a. transformers and 2,000,000-cir. mil for 150-kv-a. transformers.

Trouble from sheath currents in single conductor secondaries has not been encountered up to this time. Evidence of such currents will be watched as the demand on the system increases and remedial measures will be taken where they become objectionable.

*Control (Pilot Wire) Cable.* The control cable for the pilot wire relay circuit consists of a three-conductor, No. 8, seven-strand, 600-volt rubber-insulated, lead-

covered cable. This cable and the signal cable described below are placed together in the same duct and follow, in general, the route of the primary circuit. They enter each transformer vault where connections are made to the auxiliary equipment of the oil circuit breakers and transformers through a specially designed junction box.

*Signal Cable.* The signal cable is for giving indications at the substation as to the oil circuit breaker positions. This cable consists of four-, eight-, and nineteen-conductor lead-covered cables. Each conductor is No. 12, nineteen-strand, 600-volt, rubber-insulated.

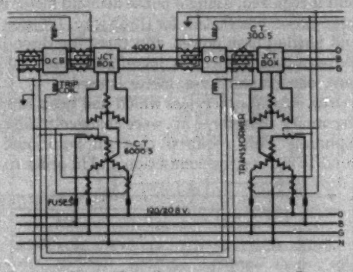


Fig. 7—Pilot-Wire Relay Connection Diagram

The circuits for the indications are supplied from a 125-volt d-c. bus in the substation. One common wire in the signal cables enters each vault so that this wire and the grounded side of the 125-volt d-c. circuit forms a telephone circuit which can be used to communicate between any two vaults or between any vault and the supply substation. It was found that during the installation of the system much time was saved in having telephone communication between various vaults. Portable telephones are used. It is anticipated that the portable telephones will be of real value in the job of maintaining and operating the system.

*Pilot Wire Relays and Fuse Protection.* The connections used in the pilot wire relay scheme are shown in Fig. 7. This scheme of connections was proposed by Mr. Baughn and it is thought that it differs from any scheme formerly used in that the current transformer secondary on the middle phase, is, in all instances, reversed with respect to the other two current transformers.

Assuming balanced three-phase current in the primary, the reversal of one current transformer secondary causes the vector sum of the secondary currents to be twice the current in any one secondary. The vector sum of the currents circulates continuously through the pilot wires and the two groups of current transformers in series. Two trip coils, one in each of the circuit breakers at either end of the primary feeder section, are connected in series by means of a third wire and are connected to two points in the pilot wire circuit, which are at the same potential above ground under normal conditions. Consequently, no current can flow in the trip coils as long as there is no fault in the primary cable included in the pilot wire relay section.

The current transformers in the secondary leads of the power transformers are also connected in a similar manner and the resultant current added to the currents from the current transformers in the primary feeder oil circuit breakers. This is done in order that faults or large loads on the low side of the transformers will not unbalance the pilot wire relaying to such an extent as to cause the circuit breakers to be opened.

The advantage of having one current transformer reversed with respect to the other two is that protection is secured against three-phase faults and also single-phase faults between the phase having the reversed current transformer and either of the other two phases, as well as faults to ground which latter is the only protection secured with this type of connection if one current transformer is not reversed. The only possible fault which this scheme does not protect against is a short circuit between the two phases which do not have the reversed current transformers. However, a fault of this kind will quickly involve either the other phase or ground and cause the breakers to be opened.

A further advantage of this connection is that there is no current through the trip coils, except when a fault occurs within the section protected, no matter how much resistance the pilot wires may have. This allows the use of a fairly small size pilot wire and places

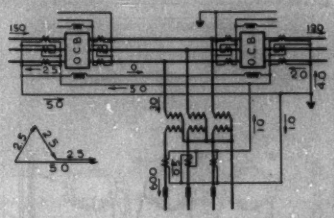


Fig. 8—Wiring Diagram Showing Currents in Pilot Wires under Normal Conditions

no limit on the length of section of cable which can be protected.

When a fault occurs in the high-voltage feeder or in a transformer, current is fed into the fault from both ends of the high-voltage loop feeder and from the low-voltage network. Under this condition the currents in the pilot wires oppose each other and the trip coil circuit provides the only path for these currents. The oil circuit breakers are therefore opened instantly, clearing the fault from the high-voltage feeder. The low-voltage network continues to feed power through the one bank of transformers connected to the section

of cable in which the fault occurred, until the fuse in the low-voltage side of the transformer is blown.

Fig. 8 shows the currents in the power cables and pilot wire circuits under normal conditions for an assumed load of 150 amperes per phase in the high-voltage feeder and 30 amperes per phase in the primary of the transformer bank. Fig. 9 shows the conditions under an assumed three-phase short circuit in the length of cable included in the section of pilot wire relay pro-

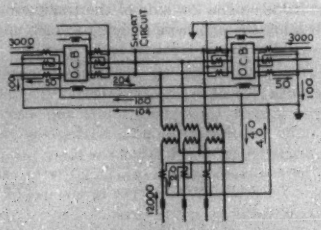


Fig. 9—Wiring Diagram Showing Currents in Pilot Wires under Short-Circuit Conditions

tection shown in the diagram. The values of current shown are assumed for illustration purposes only.

The size of the copper link fuses in the transformer banks varies from 800 to 1500 amperes, rated capacity depending on the size of the transformer and the distance from adjacent vaults. The sizes were chosen

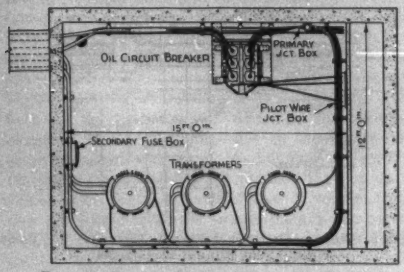


Fig. 10—Plan of Typical Transformer Vault

so that the fuses on the transformers connected to the section of cable on which the fault occurs will be blown in from one-half to three seconds. On the other hand the fuses on the transformers which are supplying the power fed back by the network into the primary fault will not be blown in less than ten times as long, because under all conditions there will be at least three transformer banks supplying the current.

A fault on the secondary mains or services will be burned clear. The fuses on the bank of transformers nearest the secondary fault may be blown, but this will cause a still greater reduction of voltage and assist in extinguishing the arc.

*Metering.* Single-phase meters are used on small two-wire, 120-volt services or on small two-wire, 208-volt motor or heating load.

Three-phase, three-wire, two-element meters are used on all three-phase, 208-volt power or on all three-wire, 120-volt lighting load or mixed load of lighting and single-phase power.

Three-phase, four-wire, three-element meters are used on mixed lighting and three-phase power.

On those classes of loads where a measurement of the demand is required, a single-phase demand meter is used for three-phase power, two for three-wire, 120/208 lighting and single-phase power, and three for three-phase, four-wire mixed load. On installations of 100 kv-a. or more, one graphic kv-a. meter is used.

*Services.* All d-c. services which had been supplying a larger motor than three hp. were changed to four-wire, three-phase. This required that an additional wire be added to the service connection and in order to expe-

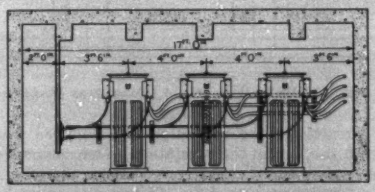


Fig. 11—Sectional Elevation of Transformer Vault Showing Arrangement of Transformers

dite the work on the final change-over of any certain district, these services were made ready beforehand. Practically all services were in iron pipes and in many instances these had to be changed to larger size to accommodate the four cables. In the cases of large services, however, separate fiber ducts were placed, one for each cable.

Very little changing was necessary in the interior wiring of the individual buildings to accommodate the new service.

*Transformer Vaults.* The transformer vaults have been placed in the street, it having been found impractical to place them in the areaways under the sidewalks.

The vaults are of two general sizes: one 7 ft. high, 12 ft. wide, and 17 ft. long, where one oil circuit breaker is used and one 7 ft. high, 12 ft. wide, and 21 ft. long, where two oil circuit breakers are used. The two oil circuit breakers are installed in vaults only where radial secondaries are supplied. In some cases a vault of special dimensions is required because of the congested conditions in the street.

Figs. 10, 11, and 12 show the vault outline and the arrangement of the electrical equipment.

Natural ventilation is provided and is accomplished

by means of steel grates in the roof at each end of the vault. The proper chimney action is provided by carrying the inlet on one end to approximately 12 in. from the floor. This is clearly shown in Fig. 12. The effective opening of the grates at each end is 900 sq. in., which is calculated to take care of a 450-kv-a. bank of subway transformers.

In order to provide entrance for equipment, the manhole is made with a 40-in. clear opening. A cover for such an opening would be extremely heavy to handle so it has been made in two parts, an outer

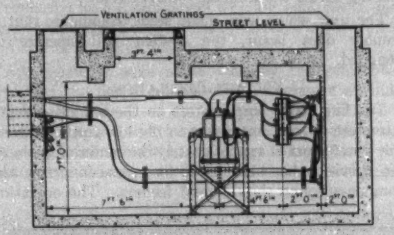


FIG. 12—SECTIONAL ELEVATION OF TRANSFORMER VAULT SHOWING OIL CIRCUIT BREAKER, JUNCTION BOXES, AND ARRANGEMENT FOR VENTILATION

annular ring with a 26-in. central hole and a 26-in. standard manhole cover which can be easily handled by one man. The ring and cover are of cast steel manufactured by the electric furnace process. The roof of all transformer vaults, including manhole cover and ventilating grids, was designed for a concentrated load of 30,000 lb. placed at any point on the roof.

Wherever possible the vaults are drained to the sewer through suitable traps; where no sewer connection is possible a sump is provided.

There are two outlets provided for lighting each vault, the wiring being in conduit and connected onto the outgoing side of the secondary fuse box.

*Emergency Substation.* Fig. 13 shows a portable type emergency substation to be used in connection with the a-c. system for emergency supply in case of failure of subway transformer banks whose secondaries have not as yet been tied into the network system.

The substation consists of three 100 kv-a. distribution transformers complete with an oil circuit breaker and sufficient lengths of primary and secondary cables to drop into the vaults and connect to the junction boxes. These cables are supplied with the proper terminals so the connections can be made to the junction boxes in a minimum of time. Each cable is marked with a color scheme identical to that followed out in marking the cables of the underground system. This eliminates the necessity of phasing out and the attendant confusion usually prevalent when making up hasty connections.

## TESTS UNDER FAULT CONDITIONS

After the network had been in operation for some time, without any trouble developing, it was decided to test its operation under conditions of short circuit by placing artificial grounds and short circuits on both the primary and secondary cables at a time when the results could be observed.

*Tests on Primary Cable.* The first test on primary cable was made by connecting to the primary feeder through a temporary oil circuit breaker a short piece of three-conductor, 4000-volt cable, with one of the conductors grounded to its lead sheath. When the temporary breaker was closed the subway primary breakers on each side of the ground opened instantly, clearing the fault from the primary feeder. The test was made at the edge of the network where the vaults are far apart and the transformer banks installed in each vault had a capacity of 150 kv-a. The feed-back of current from the secondary network was 1800 amperes, which was not sufficient to blow the 1000-ampere fuses which were in use. The fuses have since been changed to 800 amperes. The secondary voltage was reduced from 123 volts to 20 volts at the vault where the test was made and from 123 volts to 110 volts at a vault 682 ft. away.

The second test was made at the same location and

FIG. 13—PORTABLE TYPE EMERGENCY SUBSTATION

consisted of placing a three-phase short circuit on the primary feeder. The subway breakers operated satisfactorily and the feed-back of current from the network was 3000 amperes per phase, which blew the 1000-ampere fuses in 3.25 seconds, completely isolating the fault. The secondary voltages at the two vaults mentioned under the first test were 20 volts and 101 volts respectively.

The three-phase short-circuit test was repeated at another location where the vaults are closer together and the transformer banks larger. The pilot wire relaying worked perfectly, and opened the subway oil circuit breakers instantly. The feed-back from the network was about 7000 amperes and blew the 1500-ampere fuses in 2.5 seconds on the first trial and 2.0 seconds on

the second trial. The secondary voltages at the vault under test and a vault 500 ft. away were reduced to 35 volts and 95 volts respectively.

*Tests on Secondary Cables.* The first test on the secondary cables consisted of taking a short length of 500,000 cir. mil cable and driving a nail through the lead sheath into the copper. This piece of cable was attached through a temporary breaker to one phase of the secondary mains. The test was made at a point 336 ft. from one vault, 346 ft. from a second, and 867 ft. from a third, each having three 50-kv-a. transformers installed. The cable with the nail in place was put in an 8-ft. length of fiber conduit. When the temporary breaker was closed there was a slight explosion accompanied by a puff of smoke, after which the short circuit immediately cleared. An examination of the cable showed the lead had been burned back about 1/16 in. from all sides of the nail.

The second test consisting of a copper-to-copper short circuit at 208 volts, was made by baring the ends of two No. 2 paper-insulated, lead-covered, 1500-volt cables for a distance of three inches, laying them side by side, and binding them together by means of a copper wire. The ends were then slipped about half way through an 8-ft. length of conduit. The power was applied and at the same instant there were two violent explosions separated by a fraction of a second. The short circuit was cleared in approximately one second. Examination showed the copper to be burned so that the two cables were separated by about ⅛ in.

A third test was made in a manner similar to the second test, except that two No. 00 cables were used and that a small iron washer was placed between the ends of the cables and bound in place with tape. Upon applying the power, the results were found to be quite similar to those obtained in the test on the No. 2 copper cables except that the short circuit was somewhat longer in clearing, the time being about one second.

A fourth test was made using two 250,000-cir. mil cables prepared the same as in the third test. When the power was applied the short circuit held for about one second, and then an explosion cleared the fault in approximately two seconds. The voltage across the phase used in testing dropped from 215 volts to about 150 volts at the two vaults nearer the point of test, which indicated that these two vaults supplied about 1600 amperes each to the fault.

A fifth test was made using two 250,000-cir. mil cables prepared in the same manner as in the fourth test, but connected to the mains at a point about midway between two 300-kv-a. banks of transformers in vaults 500 ft. apart. In this case the short circuit was cleared with one violent explosion in considerably less than one second.

In no case did the secondary fuses show signs of heating during the secondary short-circuit test.

The tests which were made seem to indicate that if trouble does occur, the system will operate as designed.

## Voltage Regulation

The line drop compensators on the induction regulators are set to compensate to the low-voltage side of the transformer at approximately the center of the loop. No provision has been made for cross-connecting the compensators on the different feeders. The operation of the induction regulators has been entirely satisfactory, without any tendency for the regulators on the different feeders to buck each other.

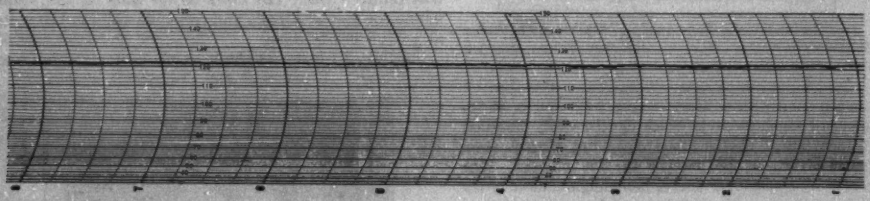

Fig. 14—Graphic Voltmeter Chart Taken at the Service Switch of Typical Customer with Combined Power and Light Load

Tests made by graphic voltmeters show that the voltage at the customer's service switch normally varies from 122 volts to 120 volts and that there are no sudden variations of sufficient magnitude to cause flickering of lights except in one instance where an a-c. elevator motor of 20 hp. on the end of a service 95 ft. long attached midway between two vaults 670 ft. apart caused a fluctuation of 3 to 4 volts.

Sections of two charts, one taken at the service switch of a typical customer having combined light and power load and the other at the customer with the elevator motor referred to above, are shown in Figs. 14 and 15.

In order to avoid lamp flicker, the maximum starting current taken by any motor which may be connected to the network is limited to the amount which will cause a drop of three volts at the customer's service switch. Carefully prepared tables applicable to the particular size of mains, spacing of cables and reactance of transformers used in Spokane, but based on the general

discussion of lamp flicker by Mr. D. K. Blake[3] are used to predetermine the maximum allowable size of motor.

### General Procedure in Change-Over from Direct Current to Alternating Current

*Customer Consideration.* Some time prior to the change-over, records were obtained covering the amount and condition of the customer's d-c. equipment. The customer was then advised of the change which was anticipated and of the approximate date the change in service would be made. He was also asked to have estimates made by an electrical contractor on the cost of replacing his d-c. equipment with a-c. equipment, and the cost of making any necessary changes in the wiring and service entrance facilities.

Arrangements were made whereby the contractor furnished the power company with a copy of all bids which were submitted to clients. These bids were carefully checked and then used as a basis for drawing up an agreement between the power company and the customer. This agreement provided for the changes which were necessary in each individual case with a definite statement as to the part of the cost which would be paid for by the power company.

A salvage was allowed on the old apparatus and all d-c. equipment removed from the customer's premises became the property of the power company.

A number of special cases arose during the process of the negotiations which called for other considerations than those stated above, but as a general rule the procedure was as outlined.

*Equipment Involved in Change-Over.* The d-c. motors on the passenger elevators, serving some of the office buildings and hotels, were not changed. The power supply to these motors was provided by means of motor-generator sets installed on the customer's premises.

A-c. motors were substituted for the d-c. motors on all freight elevators and on passenger elevators in those office buildings and hotels where motor-generator sets were not installed.

3. *General Elec. Rev.*, April 1928, p. 186.

Some of the heating and cooking equipment used in the area was found equipped with 230- and 240-volt elements. This equipment was taken care of by the installation of auto-transformers, which raised the 208-volt service to 228 volts.

No operating difficulties have been encountered in customers' equipment up to this time. All motors have operated satisfactorily on 208 volts.

*Plan and Schedule for Making Change from D-C. to A-C.* In order to inconvenience the customer the least possible amount during the change-over, plans were carefully laid out and a complete schedule of the changes arranged. A block or two, depending on the density of the load, was changed over at a time. The plan required the closest cooperation between the customers, contractors, and the power company.

In some cases it was necessary to maintain a temporary d-c. service in certain sections which were changed to the a-c. service. Such cases were rare, however, but where necessary it was found that some d-c. feeder which had previously fed the d-c. network could be utilized for the service without interfering with the rest of the work.

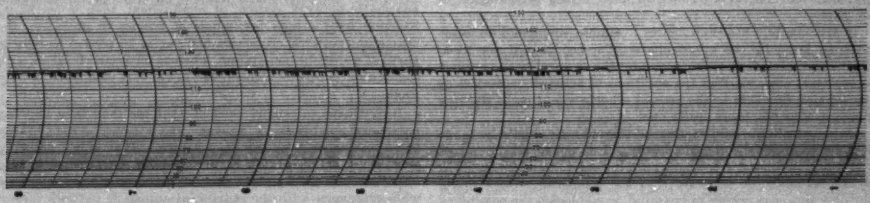

Fig. 15—Graphic Voltmeter Chart Taken at the Service Switch of Customer Having 20-Hp., A-c. Elevator Motor on the End of an Exceptionally Long Service

The total number of customers involved in the 1928 change-over was approximately 700.

### Conclusions

There have been no difficulties encountered on the system since its installation. The operation to date has been one hundred per cent. There have been no complaints because of low voltage or unsatisfactory motor performance.

In order to create some sort of a check on the system and its operation under fault conditions, numerous tests were run which have indicated that the system functions perfectly on the worst type of fault.

The fuse operation proves its complete dependability and can be relied upon to sectionalize the system properly when conditions exist for its predetermined action. The pilot wire control also gives complete assurance of its service in sectionalizing primary faults. The very small reduction in power supply to the secondary network due to a primary fault eliminating only

one transformer bank is a distinct value to the service rendered.

The tests simulating copper-to-copper faults in the secondary cables indicate that the cables will burn clear with very little disturbance to the network.

In general, there is every reason to believe that the universal type of a-c. network without network protectors, as now installed in Spokane, will continue to prove its worth as a means of supplying energy to one of the highest types of electric service.

## Discussion

**V. B. Wilfley:** Many engineers are strong advocates of the distribution system employing radial feeders and interconnected three-phase, four-wire secondaries with network protectors for the general case of the normal large city. This stand on their part has been taken only after considerable study of all types of systems and after observing this particular type of system in operation in about 40 cities.

The fact that the Washington Water Power Company engineers have adopted a system using ring feeders and fuses instead of network protectors should certainly not be taken to mean that this system will be desirable in other cities. We feel certain that Mr. Gamble had no such idea in mind in the presentation of his paper.

If Mr. Gamble has such figures available, we should be interested in knowing the approximate difference in cost per kv-a. (both original and operating costs) for the two systems as applied to his case; also, whether the additions of network protectors or low-tension breakers to the present scheme would make the ring feeder system the more costly one.

Our suggestion would be that additional tests should be made in order to check the operation fully. I do not recall that a test was made involving a secondary fault near a transformer bank. It can certainly be expected that the transformer fuses would blow for this case, which to my mind, would lessen the possibility of burning the fault clear. A network protector would, of course, function satisfactorily and no trip to the vault would be necessary to replace fuses. Such faults may be infrequent now but they may be expected in greater numbers as the system grows old.

The pilot-wire scheme is particularly interesting and Mr. Baughn is to be complimented on his originality. As pointed out, only three pilot wires are required and only two trip coils per breaker. Its weakness is its inability to function in the case of a particular phase-to-phase feeder fault until that fault has developed into either a phase-to-ground or a three-phase fault. I am inclined to agree with Mr. Gamble that such a development may take place provided the time and energy conditions are right, but these are uncertain factors.

Let us assume that such a phase-to-phase fault occurs on the Spokane system near a vault. With the pilot-wire system inoperative, it can be expected that the main substation breaker will open, clearing the feeder entirely from any feed except that from the network. The fuses on the nearest bank will blow as for any other feeder fault provided the fault is near the bank, and later the fuses on the banks in adjacent vaults may be expected to blow unless fused fairly high. If they do, then energy available for developing the fault into the type which can be cleared is very small and low voltage will exist over the network for a considerable length of time. It is my opinion that it would be worth while to arrange a test involving a specially faulted piece of feeder cable to check the resulting action. Such a test would be difficult to bring about under actual conditions but would certainly be desirable.

If we consider the action of network protectors in the above picture, matters are worse as all protectors on the faulty feeder would open leaving the faulty feeder entirely out of service, making it necessary to segregate the faulty section by hand before putting the feeder back in service. I believe Mr. Gamble has considered the idea of low-voltage switches which would be operated by the feeder pilot-wire circuit. This would give much better operating characteristics but would really be equivalent to a network protector system without many of its advantages, such as reclosing automatically, efficient operation of transformers, etc. I am wondering what effect the additional cost of low-tension switches would have on a cost comparison as mentioned previously.

Was the *Z* pilot wire connection considered? This involves five wires and four trip coils per breaker but gives complete protection.

Another question: What was the principal reason for the selection of *Y* transformer connections? It fits in well with a pilot-wire system but I am wondering if any other reason existed. It is interesting and gratifying to note that Mr. Gamble and his associates seemingly had no fear regarding the use of the odd voltages involved in a three-phase, four-wire secondary. This is one of the principal causes of hestitation in adopting the system in many cases.

**H. Richter:** At the outset this paper states that a general survey of the downtown distribution system was made in 1923, and the context leads one to assume that the decision on the type of a-c. system described was made soon thereafter, or some time in 1924. It will be recalled that there was only one a-c. automatic network system, of small extent, then in operation. Starting with a high percentage of failures in operation, the automatic network protectors had yet to be proved as reliable parts of a distribution system, whereas oil circuit breakers with differential pilot-wire control, and fuses, were common everyday tools.

It is therefore readily evident that for that time and the particular conditions in Spokane the network system chosen there was as good as any then known. That it will probably give satisfactory service in Spokane for some years is also apparent. But subsequent study of this type of system and the wide experience with the radial-feed automatic network system bring the conviction that the latter has now been proved superior to the former for the heavily loaded underground areas in almost all cities.

The paper says the system was so chosen that no part or element had not been tried out in service. The first difference between the two types of systems, then, is a matter of confidence. But today loads that are among the most important and exacting in the country, such as in New York City, depend entirely on automatic network protectors, and this system is being installed where direct current with storage batteries used to be the rule. On the other hand, several companies that formerly applied fuses in the low-voltage leads of the transformers for network protection have abandoned them after several years of experience, due to minor troubles, severe outages, or to a realization of the advantages of the automatic protectors.

Forty operating companies have put their confidence in the radial-feed automatic network system since the first one was started in 1922, the increase in the number having been 16 during the past year; but after the introduction of the first loop-feed fused network five years ago there has been only the one addition, in Spokane.

It may be noted that in 1924 the star-connected combined light and power scheme chosen for the secondaries of the Spokane network system was considered by many operating engineers to be just as experimental as the automatic network protectors. Developments since then have justified the confidence of the small group of men who in the early days had faith that both innovations would be successful.

Fig. 1A in the paper shows a railway cutting through areas 2 and 3, and in Fig. 1B the transformer installations are clearly separated into two groups. This special condition may have

accounted for the cost of the loop-feed network being somewhat lower. But it would be hazardous to generalize along this line. Even where conditions may closely parallel those in Spokane the latest methods of designing the radial-feed automatic network system and the improvements in network protectors may throw the difference in cost against the loop-feed fused network system.

There is in addition some doubt that the loop-feed network is cheaper than the radial-feed network for an important isolated load away from the main network. Suppose such a load were an average of 2000 ft. from the two nearest transformer banks connected to the network mesh. As these banks are supplied from two different feeders in the radial-feed system, two laterals each about 2000 ft. can be run out from these installations to the isolated load and the copper section might be tapered to suit the size of the load. With the loop feeder the length of cable out from the main network and back would be very little less than the same 4000 ft., and the cable size would be identical with that throughout the extent of the feeder. In addition there would be the pilot cable, so that the cost of cable would be greater for the loop-feeder method.

At the isolated load in the loop scheme there are two high-rupture-capacity high-voltage oil circuit breakers, and primary and pilot-wire junction boxes. With radial feeders there might be an oil circuit breaker on each of the two incoming lines, but they would be of low rupture capacity; and an automatic throw-over panel to control connection of the transformer bank to the emergency feeder when the preferred feeder trips out. Or, if the load be important enough to require a standby transformer bank or one bank for light and another for power, the two radial feeders could be connected directly to the two banks, an automatic network protector installed in the low-voltage leads of each bank and these leads tied together through a small reactor to form an isolated network. Neither of these radial-feed methods is likely to cost more, as a whole, than the loop feed and the network protectors would give more reliable service in case of transformer trouble. There appears to be a growing tendency throughout the country to treat important isolated loads in this manner.

The primary junction boxes described are omitted in the radial-feed automatic network system because there is no need to make changes in the primary cable connections in a hurry at the time of a fault or for extensions. Ample capacity is allowed to carry the peak load indefinitely with any feeder out.

Reference is made to secondary junction boxes for sectionalizing the secondary network in case of severe trouble. Some companies operating automatic network systems also started with them, mostly because the boxes were inherited from the radial secondary system; but in most of the applications they are now largely dispensed with. To make this practicable, care is taken that all transformer banks remain connected to the network on a secondary short circuit to pump every possible ampere into the fault and burn it off quickly.

Such auxiliary equipment as the pilot-wire junction box is, of course, non-existent in the radial-feed automatic network, and the same applies to the pilot and position-indicating cables.

The use of only one regulator (or set) per loop feeder is brought out. Where the feeders are longer than in Spokane, as in the majority of cities, proper voltage regulation may require a regulator in each leg of each loop. There are several examples of this. As each side of the loop must be able to carry the entire load of the feeder should the other side become disconnected at the station, the two regulators are of greater capacity than for radial feeders. This is true even considering the spare capacity that is allowed in the network system for the possibility of one radial feeder out of service.

As regards the single regulator per loop, should it be put out of service during the peak of the year it is likely that the entire loop would have to be shut down. This might result in blowing protective fuses all over the system, causing a complete outage.

Likewise, if there occurred simultaneously a fault in an end section of the loop and a failure of the circuit breaker separating this section from the rest of the loop, the entire loop feeder would go dead. This might be termed too remote a possibility to warrant special precautions but not by engineers who have witnessed similar "impossibilities" come true.

Figs. 3 and 4 show two kinds of subway type high-rupture-capacity oil circuit breakers for sectionalizing the loops. There is now available a third type in which an effort has been made to obtain improvements affecting accessibility, proof against water leakage, safety, and standardization of parts.

Turning now to the protective fuses, experience with networks of all kinds indicates the advantages of clearing the fault current from the system as quickly as possible. The older the cables and apparatus the more important does this become. The paper gives 3.25 seconds as one of the periods required in clearing a primary fault, and for 1800 amperes on the 800-ampere fuse the time would probably be longer. The automatic network protector has the decided advantage of tripping within about 0.4 second on a phase-to-neutral primary short circuit and about 0.25 second if phase-to-phase.

With respect to the failure of the 1000-ampere fuse to blow on 1800 amperes, as described, tests on similar fuses indicate that 2000 amperes would just melt them. Considerably more than this would be needed to clear in a short enough interval of time to come within the safe operating thermal capacity of the transformers. It is thus very doubtful whether the 1800 amperes available would blow the 800-ampere fuse quickly enough under the test conditions assumed.

In designing a radial-feed network system it is the general practise to determine primary and secondary short-circuit current with any feeder out of service for repairs, etc., as this condition may sometimes occur. Likewise in the loop-feed fused network, a transformer bank may be out when a primary fault takes place at an adjacent bank. From the description of the tests it appears that no nearby bank was disconnected. It is easily possible that if one had been, only about 1400 to 1500 amperes might have been obtained instead of 1800 and the 800-ampere fuse would not have blown at all. And so the tests appear to indicate that the fuses might not be dependable in always clearing primary faults. Yet this is one of the fundamental requirements of a network protector.

In the loop-feed fused network the fuses must be reasonably low in rating to blow on primary faults, as already indicated. Should a phase-to-phase short circuit occur on the low-voltage mesh close to a transformer bank, it is almost certain that the fuses at that bank would quickly blow. The resulting sharp decrease in current would make more difficult the completion of the burning-off process, and in some cases might make it impossible. As time went on the fuses at adjacent banks would melt. On some systems that have depended on secondary fuses the whole network has thus become involved, resulting in complete shutdown. As an example, in one city in the South this occurred three different times and then network protectors were substituted for the transformer low-voltage fuses.

It might be doubted that a phase-to-phase short circuit would occur with each secondary cable in a separate duct, as in Spokane. Such faults have occurred in the manhole, however. For instance, on one medium-size a-c. network all three-phase wires on the low-voltage side in a manhole recently became involved in a severe fault.

It would thus have been of value, when the secondary cable burning off tests were made, to establish a short circuit close to a transformer bank, allow the protective fuses at that bank to blow, and determine whether the fault would clear itself under this condition. Otherwise it is not certain that no serious trouble may develop due to failure to burn clear. As severe phase-to-phase as well as minor phase-to-neutral short circuits must be cleared, it would likewise have been valuable to have made phase-

to-phase tests on the 500,000-cir. mil cables as well as on the smaller sizes.

The paper states that the blowing of fuses near a secondary fault assists in extinguishing the arc by reducing the voltage. This may be true but it is so important a matter that it should have exhaustive tests to substantiate it. Even if it were found true, there would still be the large percentage of cases wherein it takes considerable time for the arc to develop. Here the all-important factor is the heating, and this decreases as the square of the current. The reduction of voltage resulting in a decrease of the heating at the point of fault would thus be just the opposite of beneficial.

Although there is a reference to secondary single-conductor cables each in a separate duct as the present practise in Spokane, there is no indication as to the future policy. Three 500,000-cir. mil cables in the same duct improves regulation by reducing the reactance, reduces sheath currents, and saves two to three ducts. The neutral needs no extra ducts as it can be pulled in with the three-phase wires, or made common with the primary neutral or existing d-c. neutral, or buried in the concrete of the duct bank in pouring the concrete. There is a trend of thought toward eliminating the lead sheath on network secondary cables; this will be interesting as regards cutting down the developing of copper-to-copper faults when three single-conductor cables are in the same duct. The experience of operating companies shows, however, that where ordinary care is taken in the design and construction of an automatic network system, such faults on 500,000-cir. mil lead-covered cables will burn clear every time.

Considering the Spokane system as a whole, it is only natural that no trouble should be encountered with a new underground system. The real test will come after a few years. At that time the basic principles of simplicity of system, low-voltage switching, instantaneous isolation of faults, automatic reclosing of network protective equipment, etc., typical of the radial-feed automatic network system, will probably prove preferable. It is because of such considerations that over 95 per cent of the companies that have adopted a-c. networks have chosen this particular system.

As an example of what the 40 companies think of the automatic network system, the following report is taken at random: "Since this network was started under automatic control there has not been a single interruption in the district served, except one due to a general system shutdown. The operation of the apparatus is practically perfect." This network is in a foreign country; it has a peak of about 5000 kv-a. and has been in operation over a year.

One system with several years of experience gets 0.1 per cent operating failures on all network protectors together. Compare this with the average of about 1 per cent for protective relays and oil circuit breakers in many generating stations and substations and the reliability of the network protectors can no longer be questioned. Hence, if there was a need for the loop-feed fused system it has passed. In addition to the advantages inherent in the radial-feed automatic network system it also carries with it such promising improvements as operating synchronized at the load. It is rapidly becoming the standard for heavily loaded applications.

**L. R. Gamble:** I rather hesitate to say much on the question of costs. We have some figures, but as they are more or less tentative at the present time I should prefer not to have them go in the record now. However, in analyzing the loop-feeder plan, and the radial-feeder plan for the Spokane underground system, we found that the loop feeder would be the least in cost by a considerable amount. This was one of the primary reasons for adopting the loop type of feeder.

In regard to the question asked about fuses blowing with a short circuit occurring near a vault: The tests indicated, of course, that the fuses did not blow. However, our tests were made about halfway between vaults and represented practically the same conditions for low voltage as a fault near a transformer bank on which the fuses had blown. I think that the test is representative of a short circuit on the secondary mains at any location.

The *Z* connection was brought up. Such a connection was considered, but we did not use it because it required more conductors in the control cable. The *Y-Y* transformer connection was provided, but not on account of any relay consideration. Such a connection has been more or less normal practise with various companies throughout the country and it seems to be working out very satisfactorily, especially where the connection is such that a circuit is provided for the third harmonic. Our 4000-volt supply is through a 13,000-volt transformer bank which is delta-connected on the high side.

In regard to the ventilation system, we found that in order to properly dissipate the heat from a 450-kv-a. bank of transformers it would be necessary to have approximately 900 sq. ft. of ventilating area. This area was provided by means of gratings at each end of the vault, and chimney action secured by building a curtain wall at one end of the vault extending from the ceiling to approximately 18 in. from the floor.

We are running tests now to determine the efficiency of the ventilating scheme. I am sorry we do not have the results to report now.

We wanted to get away from forced ventilation because we desired the vaults to be as simple in operation as possible. We didn't want fans or anything of that nature which would require maintenance.

In replying to some of the questions brought out in Mr. Richter's discussion, I shall attempt to answer them in the order in which they were asked.

The decision on the type of a-c. system as described in our paper was made in 1926, about three years after the general survey of the downtown distribution was made. At that time it was apparent that the operating characteristics of the network protector were still far from what would be desired and much hesitation was felt in its use where service reliability was paramount. In recent papers before the Institute we can still find reports of many faulty operations of the network protector, showing there are still some features in their design which must receive further thought and study to make them more reliable. I certainly agree with Mr. Richter that the difference between the two types of systems is a matter of confidence.

It may be a fact that many companies are abandoning the low-voltage fuses for network protection, but it is only natural since the particular combinations of circuits on which such fuses were applied made their use unsatisfactory.

It is very gratifying to realize that so much confidence is at last being placed in the network protector and that 16 companies have resigned themselves to its use in the past year; such wide application will, no doubt, tend to bring the protector into perfection more rapidly.

It is a fact that the railway shown running through Areas 2 and 3 on Fig. 1a had some influence in making the loop feeder the lower in cost. Nevertheless, later estimates, extending over a period of years, when practically the entire underground system would be changed to alternating current, show the costs of the two types to be about equal. However, in the beginning there was quite a differential in favor of the loop.

The case cited of the cost of serving important isolated loads does not fit the conditions in Spokane. It was found that the cost to serve such loads radially was considerably higher than by means of the loop feeder. The question of transformer reliability I feel can be left out of the picture.

The primary junction box is considered a very convenient piece of equipment because it is a point at which short circuits and grounds can be applied in cases where the primary is being worked upon. The secondary junction boxes, which are mentioned in our paper, are used only at street intersections, mainly

for convenience in making the numerous cable connections and to speed up the work in making the change-over from direct to alternating current. They may also be of some value in emergencies in case of fires, etc., when the network could be split up and service in the effected area could be cut off without seriously interfering with the balance of the network.

Regarding the regulator problem, it is apparent that the situation in Spokane is ideal; the relatively short loop feeders make only one set of regulators necessary for each loop. However, it appears to me that in those cities where the feeders are longer the economics of the situation should be studied to determine whether or not substations cannot be more economically located to make the feeders shorter.

It is a fact that regulating equipment gets out of order at times and to provide for any breakdown a pass-by switch is made available. Also by referring to Fig. 2 of the paper in the "Substation," there are three oil circuit breakers, two at each end of the loop feeder and one connecting the loop to the main bus. An electrical interlock is provided between to the two loop switches and the main breaker, so that any trouble in the auxiliary bus regulator or reactor opens the main breaker and the two loop breakers, and prevents any feedback from the secondary network. It is suggested that the loss of a loop feeder during peak will result in blowing fuses all over the system. This is impossible and with the proper interlacing of feeders no inconvenience should be experienced at all, not even low voltage. Yet I wonder what would happen on a radial-feeder system if at the time one radial feeder was out for repairs, a second one got in trouble, and at the same instant, which is not entirely unlikely, a network protector ceased to function.

The sizes of protective fuses have been worked out by the use of accurate test data. Various locations in the loops require different sizes. Any change in the loop or addition of vaults to the loops requires a complete check of the fuse sizes and perhaps a change of the sizes in the vicinity where alterations are made. With this plan followed up the fuses, beyond a doubt, will give us 100 per cent reliability.

As stated in the paper, one of the tests was made on the outer edge of the network where the load density was extremely small and the distance between vaults very great. This simulated the condition Mr. Richter mentions for the case of a near-by bank being disconnected. Therefore, the adequacy of the fuses to blow where there are larger and more closely spaced transformers is entirely vindicated.

The question of the proper functioning of the fuses in the case of short circuits on the low-voltage network was clearly demonstrated by the tests. The tests as applied in one case simulated again the result of a fuse on a nearby vault blowing and thereby reducing the current to a point where the fault would not clear. We applied the worst condition and the fault cleared without any apparent over-stressing of the fuses. I am not aware of any city in the South having fuse trouble due to short circuits on the secondaries, but if the conditions were as reported there must have been some set-up in their circuits and in size and type of fuses used that were entirely different from the conditions in Spokane.

I am not sure that Mr. Richter understood that all of the copper-to-copper tests were phase-to-phase tests and not phase-to-neutral tests. However, the suggestion that tests using 500,000 cir. mil cables would have been of value is well taken, but time did not permit and it is hoped that some further tests can be made when the opportunity arises.

It is planned to leave the present secondary cables as installed (each in a separate duct); however, future extensions will be made by placing all the three-phase wires in the same duct. Some thought is being given to the use of non-leaded cable, starting first by making use of such cable in service connections.

It is a fact that our system is new and so it is with a large number of the radial type and it is surprising, therefore, that the radial systems have not given a better record. The simplicity of the radial system would, of course, be very evident if the network protector did not have to be considered; otherwise, it seems that the loop feeder is preferable.

I am sorry to see that operating failures of network protectors have been compared with protective relays and oil circuit breakers and not with a pilot-wire scheme with subway-type breakers.

The loop-feed fused system provides unquestionably an adequate service for underground network systems.

# High-Voltage Low-Current Fuses and Switches

BY ROY WILKINS[1]

Fellow, A. I. E. E.

*Synopsis.—For interruption of small currents at relatively high voltages, fuses and air-break switches are most commonly employed. This paper treats of these devices which are suitable for such service as protection on the transmission lines supplying small blocks of power such as rural lines. The requirements for this service are outlined and a discussion is given of the ability of the devices to meet these requirements.*

* * * * *

FROM the beginning of the commercial use of electricity one of the problems has been the interrupting of the flow of current in time of need. This is still, after forty or more years, the major problem in the operation of the transmission networks supplying power throughout the world. On its successful accomplishment depends the continuity of electric service so essential to modern life and industry.

In those parts of the transmission network handling large blocks of power, the economic apportioning of cost allows both a high initial capital outlay and a high maintenance cost, and because of its importance demands the best in research and development that the industry affords, resulting in advanced types of circuit breakers and relays to control them.

On the other hand very small blocks of power, found for instance in rural communities, have economic limitations which limit the amount that may be spent and still expect a reasonable return on the investment. They must be supplied by a moderately high-tension line because of the distances covered, and the efficiency of the lines and transformers corresponds within reasonable limits to those on the major circuits. Circuit-interrupting equipment for this class of service is notably deficient if kept within the usual economic limits, particularly so, since the advent of automatic service restoring equipment now in common use on the low-tension side of the transformers used. The greater portion of such installations now are protected on the high-tension side by fuses of various designs and automatic airbreak switches are employed to a smaller extent.

The second important application of high-tension fuses at the present time is for the protection of potential transformers used as metering equipment. Since it has become almost universal practise to sacrifice the transformer when it gets into trouble and depend on the fuse to clear the system from it, the necessity for very low-current fuses has disappeared and the place filled by a fuse having a rating of from five to ten amperes in series with a resistor. For these conditions present day fuses perform reasonably well.

1. Consulting Engineer, Pacific Electric Mfg. Corp., San Francisco, Calif.

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## Fuses

The original circuit-interrupting equipment was simply a reduced section of the conductor which opened the circuit by melting. As the demands increased, various alloys melting at lower temperature than the usual conductor were employed. For the use on high-tension circuits, however, the more durable metals are required for sturdy construction.

The melting curves for ideal conditions follow a logarithmic law, and if the time is short enough or the fuse heat-insulated, as for instance sealed in a vacuum, the law holds quite closely for long fuses. For very short sections a correction for heat transfer to the terminals must be made.

Theoretically there is a definite quantity of heat required to melt a given quantity of each metal to be supplied as watt seconds by $I^2 R$ in the fuse. Practically the various indeterminates, such as conduction and radiation, make the calculation of fusing time for a given fuse on a given current very difficult and generally unsatisfactory, so that various empirical or semi-empirical formulas have been proposed similar for instance to:

$$C = K d^{3/2}$$

where $C$ = amperes
$K$ = a constant for each metal and
$d$ = the diameter of the fuse

Such formulas were determined empirically for each fuse for given conditions.

Of the more general formulas in common use those having a factor for the fusing time are the most serviceable, for example:

$$t = \frac{0.262\, \pi^2 d^4 s\, w}{I^2 r_0\, \alpha} \log \frac{1 + \alpha T_m}{1 + \alpha T_r}$$

where $t$ = time in seconds
$d$ = diameter of wire cm.
$s$ = mean value of specific heat of wire in calories per gram per deg. cent. for temperature range
$w$ = density in grams per cu. cm.
$I$ = current in amperes
$r_0$ = resistivity of wire in ohms per cm.$^3$
$\alpha$ = temperature coefficient of wire (average value for temperature range)
$T_m$ = melting point of wire in deg. cent.
$T_r$ = initial temperature.



29-136

Such formulas give approximate values, since no account is taken of latent heat radiation, conduction and the effect of wave form, etc. All values are considered as effective values of uniform sine waves of current and voltage.

It is especially difficult to secure accurate values for the power absorbed by the fuse even with modern oscillographic wattmeters because of phase angle, ratio errors, and inductive effects. Unless exceptional care is taken to eliminate such errors, the records of individual trials of watts may vary as much as 1000 per cent. For the same reasons integration of the current and voltage waves is equally unsatisfactory.

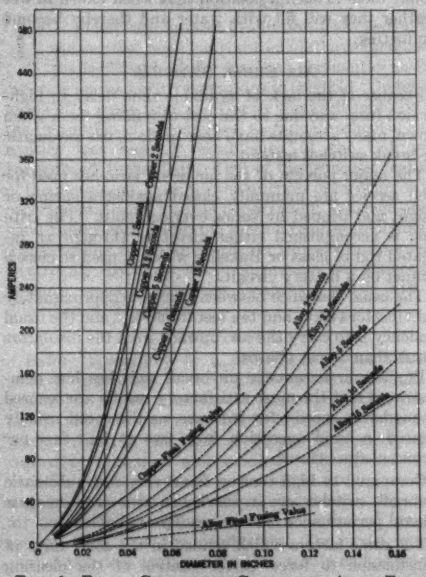


FIG.—1 FUSING CURRENT OF COPPER AND ALLOY FUSES

Comparative data can be secured, however, by averaging a considerable number of trials of each type and the average performance deduced therefrom, as shown in Fig. 1.

In general, if the fuse be tested at low voltage using preferably a good oscillograph and proper control, three or four points plotted on logarithmic paper are sufficient to determine its time-current characteristics. The time clearing characteristics at high voltage, however, do not follow the time fusing curves, since it requires more than the melting of the fuse to clear the circuit, and this time taken up by contact travel or expulsive action is recorded as arc current and is not definitely separated from the true fusing time on the record. The arcing time is moreover dependent upon recovery voltage which is in turn controlled by the connected circuit. The available current is also controlled by the connected circuit and may be many times that required to melt the fuse, frequently volatilizing it directly, whereupon the major portion of the required clearing time is taken up in arcing time.

Since the time of melting is controlled by the size and resistance under control in manufacture, and by the current controlled by the circuit, those fuses having a relatively good conductor of small section such as silver or copper show the most uniform action in service. Silver is particularly desirable since it is not easily corroded under the usual service conditions and the small amount necessary does not form a conducting cloud of vapor such as some of the commoner metals used in low-tension fuses. Nearly all fuses now available have too much metal to be volatilized before they clear, the common expedient of threading a shotgun wad on the element of the expulsion type in order to clear the tube, being a practical demonstration of this fact.

The same limitations which are driving time-current relay settings out of transmission networks in favor of some form of differential or impedance control, operate to limit the success of high-tension fuses for selective clearing of faults. Fuses usually require a far higher current rating on a given installation than the relay setting would be for the same case were it economically possible to use an oil circuit breaker and relays.

The operating requirements of an acceptable fuse may be outlined as follows:

1. Must fuse on a given current in a given time;
2. Must clear circuit under all conditions;
3. Must remain an insulator after clearing.

There might be added desirable requirements calling for the fulfilling of all of the functions of a good relay controlled oil circuit breaker but the above three are fundamental and serve to bar most present day high-tension fuses from being classed as successful when viewed from the user's standpoint.

The present day high-tension fuses may be grouped according to their method of functioning as follows:

1. Plain fusible links
2. Expulsion types
3. Mechanically retracted contacts
4. Explosively propelled contacts.

They all have in common several faults which limit their usefulness. First, the time-current control is very limited; so much so that it is not practical to operate fuses and circuit breakers in series and get selective action where the short-circuit current range is more than two or three to one, because for heavy currents the fuses approach ½-cycle clearing time whereas the relay oil circuit breaker combination have several cycles minimum. The better the fuse as regards its own clearing performance the worse this objection becomes, resulting in a higher rating for a quick acting fuse

for the same duty than for one of the heavier slower acting types.

Practically all fuses now manufactured emit flame and incandescent gas on operation and in addition some types metallic parts and jumpers as well. Few high-tension fuses in commercial use at present are entirely free from this serious objection.

In addition to the above the several types have the following troubles:

Classes one and two above both fail to clear on normal voltage at very slightly above their melting point since the containers, glass, porcelain, or organic material, are all conductors when heated; it follows that if the fuse is gradually heated to incandescence the container will be rendered conducting. Fig. 2 shows examples of such failures. Some rather spectacular results can be expected from either type if the load is gradually increased at normal voltage for several hours and finally allowed to melt the fuse.

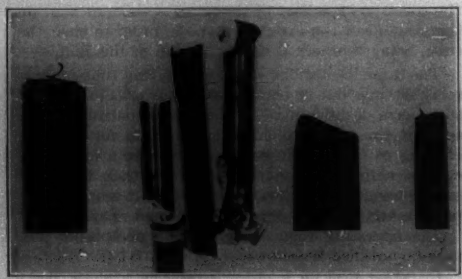

Fig. 2—Fuse Containers Which Have Become Conductors by Being Heated

Class three has the primary objection of cost particularly where liquid filled, because of the necessary close supervision in manufacture and careful handling necessary.

They also have to be carefully vented with some form of baffle between the fuse chamber and the liquid in order to prevent shattering the container. In effect this results in an expulsion fuse with a very small chamber and a liquid insulation chamber below.

Under-rating, such as using a 10-ampere fuse in 100-ampere casing, increases the safety but exceeds the economic limit except in very special cases.

In practise considerable care must be exercised in order to prevent liquid leakage either direct or by evaporation.

There are at present very few examples of number four type in service, the so-called shotgun fuse being the best known example. In this type the contact movement is caused by an explosive, usually powder such as is commonly used in fire arms. The fuse itself imbedded in such powder ignites it as soon as either sufficient temperature is reached or an arc is started. The clearing speed is always the same and for this reason the general type is easily adapted to very small fuses at high voltage.

One disadvantage is the necessary clearance required for the exit of flame and contacts.

In application some thought must be given the location of the fuses when blown, a common trouble being to mount them in such a position that when blown in wet weather they will fill with water and thereby become conducting.

## Air Break Switches

Because of the lack of available time delay in high-tension fuses and due to the cost of refilling them when blown, many attempts have been made to use automatic air-break switches instead.

The major portion of the air-break switches used for such service are manually closed against a spring or weight and tripped by series overload coils. The tripping is accomplished either direct or through an insulated rod of glass or Bakelite which is used to close a contact on a battery circuit.

The usual clearance between phases is approximately eight feet for 44-kv., and ten feet for 66-kv., and the usual tendency is to carry the arc upward from the insulators rather than across phases.

Practise in automatic air-break switches has demonstrated that the most satisfactory results are secured by moderate speeds, for instance, as the speed usually secured in hand operation from two to four feet per second contact travel.

Compared to high-tension fuses very few automatic air-break switches are in service so that data on their general performance are not readily available.

The same factors which tended in the early days of transmission to force better control of the clearing action and thereby caused development of relays and modern circuit breakers, are operating now to limit the use of the same class of equipment in modern high-voltage distribution lines to those locations where selective clearing action is not essential. For service where overload protection only is desired and moderate interrupting capacity sufficient, present day fuses are reasonably satisfactory.

For higher duties, underrating both in current and voltage minimizes trouble, but is usually not economically feasible.

# Motor Control for Wind Tunnel

## Precision Speed Regulation for the Wind Tunnel Motor at California Institute of Technology

BY WILLIAM A. LEWIS[1]

Associate, A. I. E. E.

*Synopsis.—A wind tunnel for testing model airplanes and their parts requires accurate control of the air velocity. This paper describes a tunnel having electric drive for producing the air movement and explains a system of control, which allows a wide range of speeds and holds the speed very constant at any set value. Either hand or automatic regulation may be employed. The hand control is used for fairly constant speed while the automatic control gives very close regulation.*

### Introduction

THE widespread interest in aviation developed during the last few years has resulted in a large increase in the facilities both for teaching aeronautics and for carrying on further investigations in this field. Under the terms of a grant from the Daniel Guggenheim Fund for the Promotion of Aeronautics, a graduate school of aeronautics was recently established at the California Institute of Technology. One of the principal features of the laboratory, built for the purpose of carrying on the experimental work in this department, is a high-speed wind tunnel with a working section ten feet in diameter. The propeller which forces the air through the tunnel is electrically driven, and the equipment and its control present several interesting features, which will be described in this paper.

### Wind Tunnels

Before proceeding to a discussion of the drive, a general description of the tunnel and its use would be desirable. Wind tunnels are used for testing model airfoil sections and new plane designs to determine performance, in the case of planes particularly with regard to taking off and landing. The model to be tested is supported in the center of the working section, usually in an inverted position, and when a stream of air passes the model, the relative motion of air and model simulate flying conditions. The model is supported by wires attached at three points and is held in position by the wires and a series of counterweights. The supporting wires are attached to a set of balances either directly or, as in this case, through a subframe. The reactions of the model may be separated into two components, a force downstream or drag, and an upward force or lift. Since the model is inverted, the upward force with respect to the model is downward with respect to the balances. These forces are instantly felt at the balances and can be computed from the balance readings. The values of the forces together with the temperature, pressure, and velocity of the air, are the data for determining the performance of the model.

This tunnel is of the closed-circuit type, the same air being recirculated. A longitudinal section is shown in Fig. 1. The tunnel occupies a height of nearly four floors, the over-all vertical dimension being about 45 ft. It consists of sections of circular cylinders and cones, connected end-to-end to form the closed circuit shown in the illustration. The four sections in the observation room are made of redwood staves held together by hoops of steel rod and angle iron on the outside. If desired, one or more of the sections may be removed and the tunnel operated with open throat, the circuit being closed by the observation room itself. The remainder of the tunnel is made of reinforced concrete, the interior surface of which was formed by the Gunnite spraying process. At the intersections of the vertical and horizontal sections a series of deflecting vanes changes the direction of the wind with minimum loss of energy. The completed vane installation in the lower 20-ft. intersection is shown in Fig. 2. The vanes in the two left-hand corners are arranged so that at a future date, cooling water may be circulated through them to assist in cooling the air in the tunnel. The entire tunnel is supported on its own foundation free from the building, to minimize transmission of vibration.

### Wind Velocity Requirements

For preliminary work it is desirable to control the velocity of the wind from the observation room, but for accurate testing the performance is determined entirely from the balance readings so that the balance operator must have instant and accurate control over the propeller speed. Because of the many variables involved, engineering accuracy requires that the variation in each, particularly wind speed, be kept as small as possible. The maximum allowable variation in propeller speed for satisfactory operation is $\pm$ 0.25 per cent. At the same time, in order to make a complete series of tests it is necessary that the air speed be adjustable over a wide range.

To fulfill these requirements the equipment described below was designed and installed. With it,

1. Formerly Teaching Fellow, California Institute of Technology; General Engineer, Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

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29-129

any wind velocity past the model from a slight breeze produced by a propeller speed of only about 40 rev. per min. to a cyclone of approximately 200 mi. per hr. at a propeller speed of 850 rev. per min., can be easily obtained by operating a single control, located at any point desired. Within the range from 130 to 850 rev. per min. the speed control can be transferred to a regulator which will maintain the speed constant with a

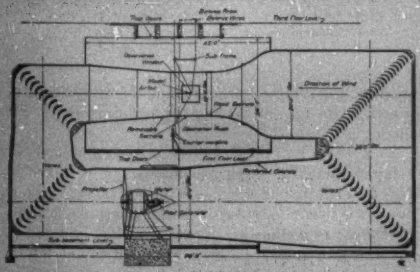

Fig. 1—Longitudinal Section of the Wind Tunnel (Vertical Plane)

very high degree of accuracy. This range corresponds to air velocities of 10 to 200 mi. per hr. By adjusting the positions of a coarse and fine rheostat, one of which is located at each station, the speed held by the regulator may be easily adjusted to any value in its range.

Fig. 2—One of the Lower Deflecting Vane Installations

## Propeller Motor

The propeller is made with four detachable blades mounted in a central cast hub. The diameter of the propeller is 14 ft. 11 in. and of the tunnel at the section where the propeller is located approximately 15 ft., so that clearance between the propeller and the tunnel wall is very small. After consideration of all advantages and disadvantages, it was decided to place the motor inside the tunnel, supporting it on a structural steel frame extending out through the walls of the tunnel into a heavy concrete base, and to mount the propeller directly on the end of the motor shaft. The obstruction introduced is not serious if the motor and its framework are not too large, since aerodynamical considerations require that the wind stream be contracted just beyond the propeller.

To drive the propeller at the maximum speed requires an input of approximately 750 hp. However, the time for obtaining a set of readings is not great and it was estimated that a machine of 500 hp. continuous capacity with short-time overload ratings, would be satisfactory. The standard machine of this size is equipped with bed-plate and pedestal bearings, and was not well adapted for the type of mounting required. A special

Fig. 3—Propeller Motor, 500 Hp. Continuous Rating

design, with bearings mounted in end brackets supported directly from the motor frame, developed for submarine and other transportation purposes, solved the problem. In this way a motor having a completely cylindrical frame and an over-all diameter of only 4 ft. 8 in. was obtained. The motor, before installation, is shown in Fig. 3. The feet shown in the figure were used for transportation only, it being found that a smaller over-all diameter of motor and covering would result if the feet were eliminated, and the supporting framework made to fit the motor frame. Because of the errors which would be introduced into the speed regulation by vibration, the framework was made very heavy and rigid so that its natural frequency is far higher than any introduced by the propeller. A semi-cylindrical steel-plate cradle fits the lower half of the motor frame and is bolted directly to the motor. Four heavy H-section columns form the supporting legs and are riveted to the cradle. In assembling, the heavily reinforced concrete base for the framework was first cast complete, with the exception of four pockets for the legs. The legs were then inserted in these pockets, and

the cradle riveted to the legs. Next the motor was mounted, the entire structure alined as a unit, and the pockets filled with concrete to unite the framework and base into a continuous whole. The U-shaped pockets in the rear H-section legs were covered with steel plates and used for wiring gutters, cored ducts in the concrete base forming a continuation of these gutters to accessible locations. The details of the structure can be seen in Figs. 4 and 5.

### Cooling the Motor

One serious problem, introduced by mounting the motor inside the tunnel, is that of securing adequate

Fig. 4—Propeller Motor and Pilot Generator Mounted in the Tunnel and Partly Covered by Stream Line Fairing

ventilation and cooling. The entire output of the propeller is eventually converted into heat by friction of the air, and since the air is recirculated, this heat, together with that due to the losses in the motor, will be taken up by the air and walls of the tunnel. As data for determining the heat transfer from the air to the tunnel walls were meager and inaccurate, it was impossible to predict the temperature to which the air would rise or the time required to reach equilibrium. If the tunnel air remained within reasonable temperature limits, it could be used for cooling the motor, but an air temperature much in excess of 50 deg. cent. would make a separate cooling system necessary. Several estimates placed the average air temperature in the tunnel at 45 deg. cent. Because of the expense of external cooling and in view of the difficulty of carrying on work in the observation room when the temperature of the tunnel is excessive, it was felt that use of the tunnel air for motor cooling would be satisfactory. Part of the air from the propeller is deflected through the motor air passages.

In order to keep the friction loss caused by the air passing outside the motor at a minimum, it was necessary to enclose the motor and its support in a stream line fairing, broad nosed at the propeller end and tapering off to a point at the tail. An opening in the nose and louvres in the sides allow the ventilating air to pass through the motor. In order to keep the pilot generator, (a small generator connected to the main shaft and used with the speed regulator) at as constant a temperature as possible, it is ventilated separately. A baffle inserted between the two machines produces the desired result. A second set of louvres behind the baffle and a third set in the tail provide the necessary cooling air circulation. The fairing is composed of a skeleton framework, Fig. 4, covered with steel plates screwed in place. The section covering the propeller hub revolves with the propeller but the remainder is stationary. To obtain access to any part of the motor it is necessary merely to remove the adjacent plates. An ingenious assembly of the skeleton frame allows a large section of the fairing to be removed as a unit in case of major repairs. Views of the fairing framework with several of the plates mounted are shown in Figs. 4 and 5. After the fairing of the motor itself had been completed, the legs on each side of the shaft were enclosed in additional fairings. Views of the completed installation are shown in Figs. 6 and 7.

### Motor-Generator Set

The propeller motor is a d-c. commutating pole machine, since such a speed range could not be obtained with constant frequency alternating current. For furnishing the direct current and providing a simple means of speed variation, an individual synchronous

Fig. 5—End View of Motor Showing Supporting Legs Used for Wire Gutters

motor-generator set is provided. In order to make available the maximum possible amount of direct current for physical experiments, the nominal d-c. voltage was established at 230 volts, although the actual voltage varies from residual of the generator up to about 300 volts, depending upon the speed of the propeller motor. Both the synchronous motor and the d-c. generator are provided with direct-connected exciters, separate machines being required because of the speed regulator.

### Method of Control

As the motor-generator set had to be located quite

close to the propeller motor, because of the large currents involved, it was placed in the sub-basement of the building, just outside the tunnel. The most desirable location for the control station being near the balances in the balance room, five floors above, electrical remote control was adopted for all equipment requiring operation during normal running of the tunnel. Direct current was considered the most suitable for control power, and continuity of service not being absolutely essential, a small induction motor-generator set, giving 125 volts direct current was provided instead of the more expensive storage battery. The former type of control, however, is not absolutely reliable and provision had to be made for disconnecting all the main machines upon failure of control voltage, thus complicating the control circuits considerably.

Fig. 6—Propeller End of Main Motor with Fairing Completed

Fig. 7—Down Stream End of Main Motor Showing Completed Installation

The apparatus for starting and controlling the a-c. end of the motor-generator set is practically standard automatic equipment and need not be described here. However, since the propeller motor is neither visible nor audible from the point of normal operation and the operators are in general non-electrical men, it was considered worth while to design the entire installation for unattended operation and most of the features common to automatic stations, such as lock-out relay-bearing temperature relays, reverse-phase voltage, current relays, etc., are provided. Also the switching operations of starting are automatically controlled so that the field is applied and the transfer to full voltage is accomplished without the intervention of the operator.

To secure the wide speed range necessary for the propeller motor, the armature voltage or Ward Leonard system of control is necessary. To obtain good efficiency and regulation with this system it is necessary to vary the voltage of the generator which supplies the motor armature. Control is exercised in this case by varying the excitation of the generator either by changing the position of the generator field rheostat or the voltage of the exciter or both. The field of the motor must, of course, be supplied from a separate constant voltage source and in this case was connected to the control generator because the voltages of both direct-connected exciters for the motor-generator set are subject to excessive changes. This connection also resulted in the smallest installed auxiliary capacity, since field for the propeller motor is not required until all the large oil circuit breakers have been closed and the closing solenoids deenergized, thus making possible joint use of the same control-generator capacity. The main d-c. connections are shown in Fig. 8, and the armature and field circuits may be easily traced on the diagram. It will be noticed that a series of double-throw switches is inserted in the armature circuit of the main generator and that the two right-hand switches must be closed in the lower position in order to connect the propeller motor. Under these conditions the differential series field is in circuit, acting to stabilize the speed by opposing a change in current. When the

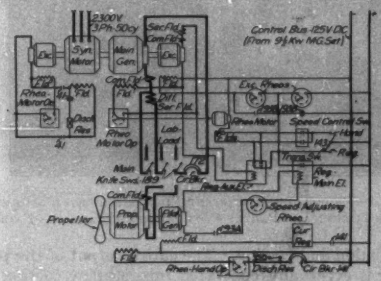


Fig. 8—Schematic D-c. Circuits for Automatic Speed Control and Power Supply

generator is used for other experiments, the differential field may or may not be desired and the third switch allows a choice to be made.

It may also be noticed that no starting resistance is provided in the propeller-motor circuit. The starting current is kept within sufficiently low limits by reducing the generator voltage to its minimum value before closing circuit breaker 172. It is also necessary, of course, that the field circuit be closed before the armature circuit is closed, and that the armature circuit open whenever the field circuit opens. These conditions are obtained by means of suitable interlocks so that circuit breaker 172 cannot be closed until the motor-operated rheostat is "all in," and as soon as the circuit breaker opens, connections not shown in the diagram run the rheostat to this position. The motor is started by operating a single control switch. If the rheostat is in the proper position, the motor starts immediately. If not, the motor will start as soon as the rheostat reaches the "all in" position. The connections are arranged so that field circuit breaker 141 closes first, followed by the closing of circuit breaker 172. When stopping, whether by hand or by one of the protective features, the breakers open in the reverse order. If the field breaker opens for any reason, the armature circuit breaker opens immediately.

After the motor has been started, two types of speed control are available. Under hand control the speed of the motor is brought to the desired value and remains nearly constant due to the inherent regulation of the system, although small variations and a gradual creep in speed, due to temperature effects, occur. However, this type of control is much simpler and is very satisfactory for rough or preliminary work. Under regulated control the speed is set at a given value corresponding to the position of the speed adjusting rheostat, consisting of a coarse and fine section, separately adjustable, and is held at that speed with a high precision by the speed regulator. Although several control stations of both types are provided, only one of each is shown in the diagram. To accommodate additional stations the number of positions of transfer switch 143 is increased, and additional speed adjusting rheostats and relays, 193, are provided for each regulated station and additional speed control switches for each hand control station. For hand control, the entire adjustment is obtained by control of the generator field rheostat, whereas the two elements of the regulator control both the voltage of the exciter and the position of the generator rheostat.

For hand control, transfer switch 143 is closed in the hand position, thus connecting the speed-control switch to a source of power, and the operation of this switch will cause the rheostat to be driven in one direction or the other, thus increasing or decreasing the generator voltage and consequently the speed of the propeller motor. It may be noticed that there are two rheostats in the exciter field circuit, so that the voltage of the exciter is dependent on the position of both rheostats. However, under hand control, relay 193-B is deenergized so that its back contact is closed, short-circuiting the right-hand rheostat, and the exciter voltage is thus determined in this case entirely by the position of the left-hand rheostat. The latter is set at a position which will give normal exciter voltage and is left unchanged, so that the generator rheostat has complete control of the propeller-motor speed.

To obtain regulated control, transfer switch 143 is changed to the "Reg." position. Auxiliary circuits, not shown, immediately run the generator rheostat to the "all in" position, and energize relays 193-B and 193-A. Relay 193-A connects the pilot generator armature to the main element of the speed regulator through the speed adjusting rheostat. Relay 193-B short circuits the left-hand exciter rheostat and inserts the right-hand one in the circuit. The field of the pilot generator is energized through an auxiliary contact of the field circuit breaker 141 and the current regulator, and therefore carries a constant current whenever the propeller motor is running. Under these conditions the voltage generated by the pilot generator is directly proportional to speed. A definite fraction of this voltage, depending upon the position of the speed adjusting rheostat, is impressed upon the main element of the regulator. If this voltage is below the amount required to open the regulator contacts, the contacts close and short-circuit the exciter rheostat. This raises the exciter voltage, hence also the generator voltage, the motor speed, and the pilot generator voltage. If the increase in pilot generator voltage is sufficient, the contacts will open, the exciter voltage will fall and with it, the generator voltage, the propeller motor speed, and the pilot generator voltage, until the contacts close again. The process repeats continuously. An auxiliary coil and plunger, not shown in the diagram but connected across the exciter terminals, react on the contacts in the same manner as the d-c. coil in an a-c. generator voltage regulator, preventing hunting and keeping the oscillations in speed, produced by the above described opening and closing of contacts, within the most minute limits. Under this condition the mean speed is a function of the position of the speed adjusting rheostat, since the average current in the regulator coil must be a constant and the drop across the rheostat then depends only on its position.

If, in the first instance, the increase in pilot generator voltage was insufficient to open the contacts, the vibrating action does not occur and a speed balance is not obtained. The speed range over which a balance can be obtained with a fixed position of the generator field rheostat is very small, and to increase this range, the auxiliary element of the regulator is provided. If the main contacts remain closed, the exciter voltage will rise above a predetermined value at which one of the contacts of the auxiliary element closes, and this contact changes the position of the generator rheostat until the

regulator contacts open, the exciter voltage falls, and the auxiliary contact opens again. Conditions are now satisfactory and the vibrating action of the contacts is immediately set up and a balance obtained. In case the resistance in the speed-adjusting rheostat is reduced, the regulator contacts immediately open, reducing the exciter voltage, the generator voltage, the motor speed, and the pilot generator voltage in turn. If the drop is sufficient, the contacts will close again, a new vibrating action will be set up and a new speed maintained. If the contacts do not close, the exciter voltage will fall so low that the other contact of the auxiliary element will close, increase the resistance in the generator field, reduce the speed of the propeller and finally the pilot generator voltage, until the contacts again close and a new vibrating point is established. Thus, the quick-acting vibrating regulator maintains a precision control over a narrow range and this range is shifted to the proper part of a much broader range by means of the auxiliary element, thus providing a precise speed control over a broad range.

### Operating Results

The installation described above is giving entire satisfaction in the operation of the wind tunnel at California Institute of Technology, both with regard to ease of control and accuracy of speed regulation. Although no precision instruments are available for measuring the actual instantaneous variations, observations of an accurate electric tachometer indicate instantaneous variations of less than 0.2 per cent plus or minus, after the regulating equipment has assumed operating temperature, requiring about one half-hour.

There are innumerable causes of instantaneous speed variation, the principal ones being resistance changes due to temperature variations in the armature and field of the propeller motor, main generator and exciters, change in load due to change in angle of attack of the model, change of supply frequency, etc. However, none of these changes can exceed the limit given above of $\pm 0.2$ per cent without bringing about a corrective action from the regulator, so that none of these effects produce any permanent variations or any beyond the stated limits unless they are of such extreme magnitude and so rapid that the regulator is unable to respond and correct them before the limit is reached.

The only causes of permanent variation are those which affect the accuracy of the speed regulator, and include changes in resistance of the regulator circuits and change in permeability of the pilot-generator field with temperature. Such effects cause a gradual increase in speed of approximately 0.25 per cent per hour after operating temperature has been reached, and may be easily corrected for by adjustment of the speed-adjusting rheostat.

As explained above, no permanent speed change is caused by variation in a-c. line voltage or frequency, the changes being immediately corrected for by action of the speed regulator. No data are available regarding the speed of corrective action of the regulator or the amount and rate of change necessary to prevent the regulator keeping the speed within the allowable limits. Although the assembly was developed for a special application, it is composed entirely of standard apparatus and has several features which may be adaptable to other purposes requiring a wide speed range with a high degree of accuracy in speed regulation.

### Acknowledgment

The author wishes to acknowledge the kind cooperation of many members of the staff of the California Institute of Technology, especially Mr. L. G. Fenner, Superintendent of Wiring; also of many members of the engineering staffs of the Westinghouse Electric & Manufacturing Company and General Electric Company.

## Appendix

### Apparatus

Propeller Motor: 500-hp., 230-volt, 700-rev. per min., at full load, shunt connected.

Main Generator: 430-kw., 230-volt, 1000-rev. per min., differential compound.

Main A-C. Motor: 610-hp., 2200-volt, 3-phase synchronous.

M-G Set for Control Supply: 9½-kw., 125 volt, 1500-rev. per min. compound generator; 220-volt, 3-phase induction motor.

Pilot Generator on the Propeller Motor Shaft: Rated 1.5 kw. (but in a larger frame for negligible temperature rise) 600-volt, 700-rev. per min., separately excited.

Automatic Switchboard contains: 3000-ampere automatic circuit breaker, accelerating relays, misc. relays, field contactor, overload relays, annunciator relay.

Speed Control Switchboard contains: Phase balance relay, voltage balance relay, control switches and indicators and regulator operating from the pilot generator.

Much additional apparatus such as exciters and switchboard meters have not been listed in detail.

# The Electrical Engineering of Sound Picture Systems

BY K. F. MORGAN[1] and T. E. SHEA[2]
Associate, A. I. E. E. Associate, A. I. E. E.

***Synopsis.***—*The paper describes the technique and apparatus of sound picture recording and reproduction, with emphasis on their electrical engineering aspects.*

*The various steps in the processes of disk and film recording are outlined as they take place in the Western Electric systems. Microphone placements, sound insulation, monitoring and mixing, and the circuits for amplifying currents and distributing them to recording machines are discussed. This is followed by a description of the disk and film recording machines.*

*The changes which have been required in theater equipment to provide for the reproduction and projection of sound in synchronism with motion pictures are outlined.*

*Some of the laboratory developments and studies out of which recording and reproduction methods have grown are given brief mention.*

THE sound motion picture, youngest of the arts, is a development of electrical, mechanical, and chemical science. The electrical development in the motion picture industry was at first a normal one which kept pace with the demands of the industry with respect to light and power. Then came an event which was sudden and dramatic. The motion picture industry was, literally and figuratively speaking, electrified. It was realized that laboratory research work directed toward improvement of the telephone and the radio could be combined with the motion picture and the silent screen given a voice. The sound picture is a combination of the silent motion picture and the electrical pick-up, amplification, transmission, recording, and reproduction of sound. The essentials of the sound processes are the recording and synchronizing of sound on either film or disk records with a satisfactory method of synchronized reproduction.

At first sound pictures were a novelty. People attended the theaters out of curiosity. Motion picture actors were vitally interested in voice tests. Many mishaps and troubles occurred as well as amusing incidents regarding the use of the strange recording equipment. Finally, sound recording methods have been adapted to motion picture production requirements and the motion picture industry has started the serious production of sound pictures for entertainment with success a certainty.

That the development of sound recording and reproduction should be closely related to that of the telephone is only natural since many of the fundamental principles are similar. In what follows the authors will have in mind principally the Western Electric systems of recording and reproduction.

Sound picture production requires the *faithful recording of sound in synchronism with a motion picture*, and the *faithful reproduction of the sound in synchronism with the projected picture*, in order to create the illusion that the actor in the picture is actually talking or singing.

## Sound Picture Recording

The electrical recording of sound requires a method of transforming sound vibrations into electric currents, then the transmission, control, and amplification of these currents, and finally a method of changing the electrical energy into mechanical energy in order that a permanent record may be had on the recording medium either by modulated light on a sensitized film or the movement of a cutting stylus in soft wax. What the purely electrical operations involved chiefly do is to assist in the pick-up of different sound sources, the transmission of these vibrations, and their amplification (or reinforcement) in any desired amount.

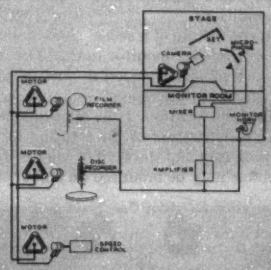


FIG. 1—SCHEMATIC DIAGRAM OF RECORDING SYSTEM

A schematic drawing of a studio recording system in simplest form is shown in Fig. 1. The essential parts of such a system consist of microphone pick-ups on the stage, a mixer and volume control in the monitor room, system and monitor amplifiers, recording machines, and a synchronous motor system for synchronizing the recorders with the cameras. These various component parts of the system will be explained in more detail.

The recording stages (called sound stages) are constructed in such a manner that external noises may be excluded. The reason for this is, of course, obvious. Usually soundproofing is accomplished by the use of double or triple walls with intervening air spaces for deadening. The interior treatment of the sound stage is also of interest. The walls and ceiling are usually covered with sound absorbing materials. The choice of a particular material depends upon the amount of sound absorption needed, and upon the frequency absorption characteristics of that material, since all materials do not absorb the various frequencies uniformly. If a

1. Electrical Research Products, Inc.
2. Bell Telephone Laboratories, Inc.

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29-142

large amount of material of high absorbing ability is used, the stages become "dead," which means that very little reflection of sound from surfaces takes place. If too little or too inefficient absorbing material is used, the stage is objectionably "live." A condition between these extremes must be generally sought. Portable damping in the form of large flats covered with acoustic material is also used. A cross section of a typical wall construction is shown in Fig. 2.

The monitoring rooms are sound treated somewhat in the same way as are the sound stages. This is done

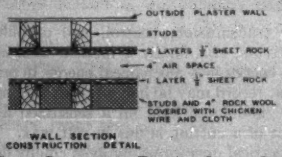


Fig. 2—Cross Section of Typical Sound Stage Wall Construction

in order to exclude all sounds except those which the monitor man wishes to hear, and to provide the proper acoustical conditions.

During the recording of a scene, there are many problems that confront the monitor man. The microphone or microphones must be placed in such positions as to pick up satisfactorily the speech or music occurring on the set. Often the location of the microphone is complicated by the construction of the set, and by the necessity for keeping it out of the field of view of the camera. The microphone may be mounted on a floor stand, hung

Fig. 3—Interior of Sound Stage

Note monitor window and horn used by monitor man when talking to people on stage

from the ceiling, or as is more often the case, suspended from the end of a long boom which has numerous adjustments for vertical and horizontal motion. The type of microphone used is the condenser transmitter. Fig. 4 shows a view of this instrument, with its associated amplifier. It is essentially a condenser, in which one of the plates is a very thin stretched sheet of duralumin, which may be set in vibration by sound waves. Thereby the capacity of the microphone is varied and an electromotive force set up in the electrical circuit to which the microphone is connected. If the microphone is made to have its diaphram resonance above the range of frequencies being recorded, it will transmit this range with very little distortion. Fig. 5 shows a typical frequency response characteristic of a microphone of the condenser transmitter type.

Various kinds of materials are used in the con-

Fig. 4—Condenser Transmitter Microphone with Associated Amplifier

struction of sets, although the general tendency is to use those materials which are sound absorbing. The sets may have two or three walls, very seldom being completely closed. These varying conditions make it necessary for the monitor man to locate his pick-ups carefully in order to achieve the best results. Some monitor men prefer to use only one microphone while others are accustomed to use a number of microphones.

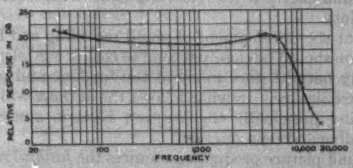


Fig. 5—Frequency Response Characteristic of Condenser Transmitter Microphone

All these factors, together with the personal element introduced by the actors themselves, constitute a difficult and important problem for those who operate sound equipment.

During actual recording, the director, as well as all other onlookers, must remain absolutely quiet. Rustling movements, footsteps, or a cough, are readily recorded.

In order to eliminate camera and motor noise camera booths have been used which are constructed of sound proof material with a clear glass window in front for the camera to "shoot" through. The booths are usually

Fig. 6—View of Stage and Sets from Monitor Platform

constructed in two sizes, accommodating one or two cameras. When two cameras are used, one, by means of a special lens, provides the "close up," the other camera being used for the "long shot." The camera

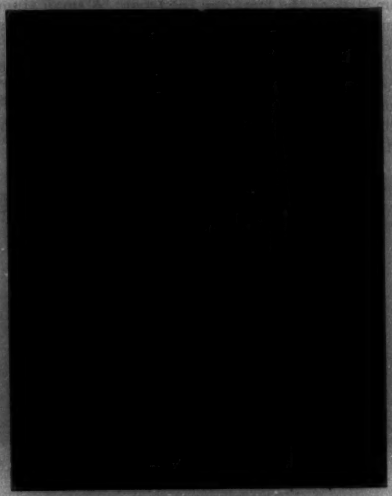

Fig. 7—Interior of Camera Booth

Note motors and flexible drives to cameras. Prologue set of "The Iron Mask" may be seen through the glass window

booths are mounted on rollers so that they may be moved about, but at best they have proved a clumsy and awkward expedient. The development of silent cameras and drives is now under way so that camera men may employ methods similar to those used in photographing silent motion pictures. The new sound devices have placed many rigid technical obstacles in the path of motion picture production, but gradually these various obstacles are being eliminated so that the freedom of silent motion picture days may again be realized. Several camera booths are used in photographing a scene. In this way various angles may be photographed simultaneously in synchronism with one sound track. The film cutter is then free to use any camera angle or close up that will enhance the dramatic and artistic effect of the finished picture.

The monitor man is responsible for the balance, quality, and volume of the recording. It is his duty to be thoroughly familiar with the action being photographed, the acoustic conditions of the set, and to properly locate the microphones for the best over-all results. He sits at a bay window in the monitor room with a clear view of the stage. (Fig. 8.) Sounds are heard from the stage by means of electrical pick-up and monitor horns

Fig. 8—The Monitoring Bay and Controls

only, since the monitor room is insulated from the stage by sound-proof walls. The monitor room simulates theater reverberation conditions, thus assisting the monitor man in obtaining the best recording results from the theater patrons' "auditory viewpoint."

The mixer table is the centralized control of the system. Controls are located here for fading in and out microphones, maintaining the volume balance between several microphones, and regulating over-all volume; also for operating communication systems, signal lights, and relay control switches. The volume indicator provides a visual method for the monitor man to keep the sound volume range within the limits of the recording system.

Fig. 9 shows a more detailed schematic of the amplifier and recording systems. The microphone junction box which permits the interconnection of different microphones, is located on the stage. Flexible cables from the microphones are connected to this box. The microphone circuits enter the mixer on the control platform where the mixing operation is performed and amplification obtained before trunking to the recording building. In the recording building, which is usually separated from the stages because of the fire

hazard, is concentrated all the recording, power, and auxiliary equipment except that mentioned above. In this building are located the wax shaving room (for preparing wax records), battery room, motor-generator room, "dubbing"[3] room, film loading room, recording rooms, test laboratory, and amplifier room. (Fig. 10.)

The amplifier room contains the system amplifiers, monitor amplifiers, and power control panels for all the channels. "Channel" is the designation for all the equipment associated with one stage.

Bridging amplifiers with impedance relations and circuit arrangement such that little or no loss or distortion is introduced into the circuit, divide the electrical circuit four ways. The bridging amplifier outputs are connected to the wax and film recording machines in the recording room. The electrical wax recorder requires approximately +8 to + 10 db. volume level, the light valve on the film recorder about +0 db.[4] (Fig. 11.)

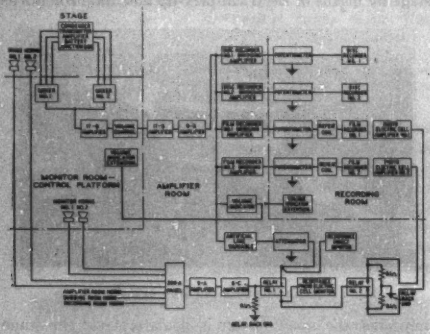


Fig. 9—Schematic Diagram of One Complete Recording Channel

The volume level for each recording machine may be adjusted by variable attenuators adjacent to the machines. If the picture is to be released with the sound recorded on film, it is common practise to operate two film recording machines for the permanent film record and one wax recorder for playback purposes.

Monitoring is accomplished in two ways,—direct and indirect. The direct monitor circuit originates at the bridging bus and by means of an artificial line, attenuator, relay, and amplifier system is connected to the horns in the monitor room. This affords a very accurate method of determining the balance, volume, and quality of the stage pick-up and is useful in predetermining during rehearsal the location and number of microphones necessary for a particular scene. The indirect monitor provides an opportunity to judge the quality of the recording at the point where the sensitized film is actually exposed. Possible overloads of the light valve and noise or distortion are easily detected. This method of monitoring insures favorable recording conditions, or the immediate detection of trouble.

In the film recorder a photoelectric cell is located in back of the film and in line with the modulated light

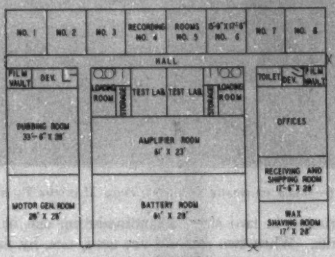


Fig. 10—Recording Building Floor Plan

beam striking the film from the front. A small amount of modulated light is transmitted through the film and reaches this photoelectric cell which transforms the light into a weak electric current. This current is amplified by a photoelectric cell amplifier attached to the recorder. The output is connected to the monitoring circuit in the amplifier room where sufficient amplification is obtained to provide loud speaker volume. By

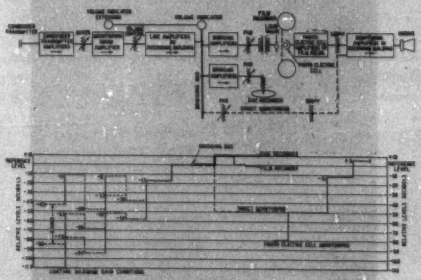

Fig. 11—Schematic Circuit of Recording Channel and Volume Level Diagram

means of relays controlled from the monitor platform, the monitoring horns may be connected to either direct or indirect monitor during the recording process, and by the use of an artificial line the volumes of the direct and indirect monitor are balanced.

The recording rooms usually contain two film recording and two disk recording machines. These machines are associated with one recording channel. They are

3. "Dubbing" signifies a copying or combining process effected through re-recording.

4. The zero reference level is an arbitrary reference level which is determined by the output of a particular type of vacuum tube. *Each* 10 db. above or below this level signifies a multiplication of the power *tenfold* or a diminution to *one-tenth*.

all driven by synchronous motors in synchronism with the camera motors on the stage.

The wax recording machine, used in the Western Electric system of disk recording, may be compared to a high-grade lathe. (Fig. 13.) The machine consists of the following parts: a motor drive, a reduction gear

Fig. 12—Amplifier Room—Power Control Panel and Amplifier Equipment for Eight Channels

with a belt drive connected to the lead screw, which moves a recorder radially across the surface of the wax disk, and a second reduction gear driving a turn-table on which the wax is placed. The second reduction gear reduces the motor speed of 1200 rev. per min. to a turn-table speed of 33⅓ rev. per min. A damping arrange-

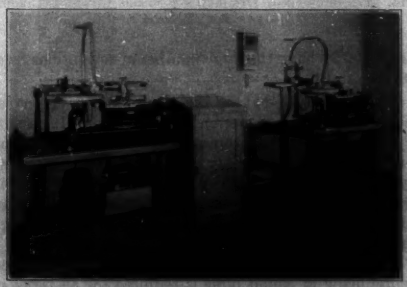

Fig. 13—Wax Recording Machines

ment, consisting of two sets of vanes placed in oil, damps natural periods of oscillation.

After the disk has been polished it is placed on the turn-table of the recording machine. The recording is made with an electrical recorder which receives its power from the system amplifiers. The electrical energy drives a recording stylus. The recording stylus, made of sapphire or ruby, must be sharp and of a shape to insure a clean cut, since any roughness in the walls of the groove introduces extraneous noise in the reproduced sound. The records used in the Western Electric system are lateral cut records, in which the grooves are of constant depth and oscillate about a smooth spiral. To maintain the cut at the correct depth, a so-called advance ball is used which rides lightly on the polished surface of the disk and supports the stylus. A microscope is employed to observe the groove during this adjustment and during the recording process. The recorders have been designed to operate over a range of frequencies from 30 to 6500 cycles per second.

After a record has been cut, two procedures may be followed,—the record may be processed for use in theaters, or the sound may be reproduced directly from the wax records by means of a "playback" reproducer. The "playback" reproducer does not rest on the record as those used in theater or phonograph reproduction, but is supported by the carriage and driven by the lead screw of the recording machine. The vertical pressure

Fig. 14—Film Recording Machines

of the needle point on the record has been reduced to a minimum. Since the groove has to drive the needle point of the reproducer properly, reduction of the vertical pressure means reduction of the mechanical impedance offered by the needle point to transverse vibration. To accomplish this, the mass and stiffness of the playback reproducer have been determined so that the response of the playbacks in use at present compares favorably with that obtained from finished records. The use of the wax playback has proved advantageous to the director and actors in immediately judging the dramatic effect and the quality of a recorded scene without the necessity of waiting for the film or wax record to be processed.

The film recorder (Fig. 14) and its driving motors are usually mounted on the same base which in permanent installations is a concrete slab insulated from the building structure by means of cork mats to prevent the transmission of excessive vibrations to the recording machine.

The machine contains a mechanical damped film

drive mechanism, and by means of a lamp, lens assembly, and light valve, records sound on the film.

Referring to Fig. 14, the film recorder control and power panel may be noted on the wall. Adjacent to the panel is a dessicator for storing light valves.

The light valve[5] is an electromechanical shutter actuated by amplified sound currents. It modulates a

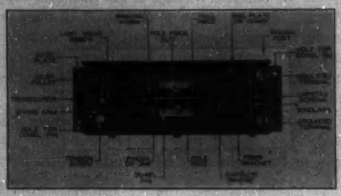

FIG. 15—LIGHT VALVE

light beam of constant intensity which is projected by means of the lens system on to the film, thus producing a film record of variable density.

The image of the light valve aperture is projected on to the film half size, so that it appears on the surface of the film in an unmodulated state as a line 1 mil wide and 128 mils long.

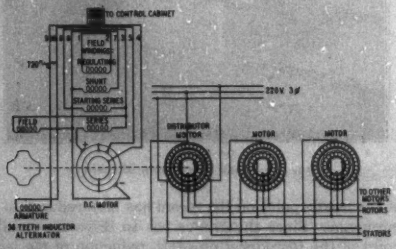


FIG. 16A—SCHEMATIC DIAGRAM OF MOTOR SYSTEM

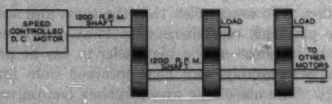


FIG. 16B—MECHANICAL ANALOGY OF MOTOR SYSTEM

The interlocking[6] of the motor system employs a principle known for many years in the electrical power field. It consists of connecting the stators and wire wound rotors of polyphase slip ring induction motors with similar electrical impedance characteristics, in parallel, and the placing of an alternating voltage across the stator. Each motor acts as a transformer. The rotors of all driving motors are brought into the same electrical phase relation as is presented by the distributor motor. This system gives a strong interlocking action between all motors. Mechanical rotation of the distributor rotor produces a corresponding rotation of all other interlocked rotors. Hence, if the rotor on the distributor is driven at a constant speed, all interlocked motors are likewise driven at the same speed independently of the power supply frequency and the actual number of revolutions from start to stop is exactly the same for all motors. (See Fig. 16A.)

The system may be thought of as a long shaft (see Fig. 16B) with all loads geared directly thereto. The shaft is then driven by the distributor motor at a constant speed and all loads will then run in synchronism

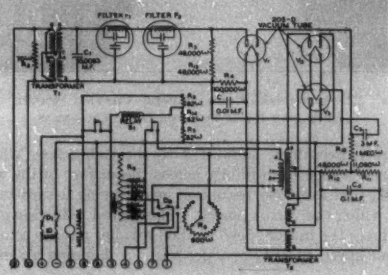


FIG. 17—SCHEMATIC DIAGRAM OF SPEED CONTROL CIRCUIT FOR D-C. MOTOR

and likewise have the same number of revolutions from start to finish.

This feature of having the same number of revolutions from start is rather an important one. It permits the marking for synchronization of the sound film and picture film while stationary while still having complete synchronization throughout, and is also important in the transferring of the sound record from one film or disk record to another film or disk in a "dubbing" process.

Accurate speed control for both the recording and reproducing of sound films is required for all types of sound pictures. It is well known that the musical pitch varies directly with frequency and, therefore, in order that the reproduced sound may have the same pitch as the original, the record or film must run at an assigned constant speed.

The control cabinet (see Fig. 17) is the means for obtaining the constant speed of 1200 rev. per min. All recording and reproducing equipment is driven by 1200 rev. per min. motors. Referring again to the two drawings, Fig. 16 and Fig. 17, the driving unit is a compound

5. For a more detailed discussion, see "Sound Recording with the Light Valve," D. MacKenzie, *Bell System Tech. Jl.*, January, 1929.

6. For a complete discussion of the synchronizing and regulating methods used, see "Synchronization and Speed Control of Synchronized Pictures," H. M. Stoller, *Bell System Tech. Jl.*, January, 1929.

wound d-c. motor, which has, in addition to the regular series field, a special series field which is used to give extra torque at starting and is automatically cut out before the motor reaches full speed. It also has a shunt regulating field in which the current is governed by the vacuum tube control circuit. The motor is equipped with a small inductor generator which delivers 720 cycles to the control box at 1200 rev. per min. The armature winding of the motor is tapped at two opposite points, through slip rings; by this means 720 cycles

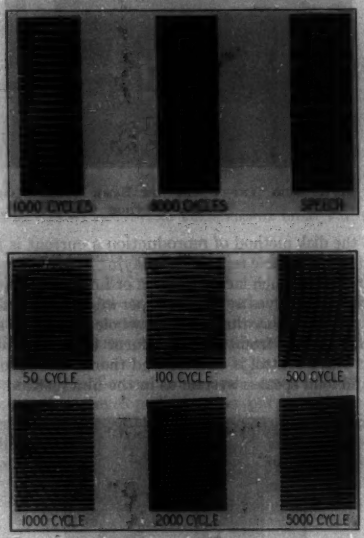


Fig. 18—Typical Film and Disk Sound Records

a-c. is delivered to the control box for vacuum tube filament and plate supply.

The operation of the control circuit is governed by the low pass filters $F_1$ and $F_2$ with a 720-cycle cut-off. Below the cut-off frequency, a voltage is applied to the plate of tube $V_1$ which in turn produces a comparatively high negative potential on the grids of tubes $V_2$ and $V_3$ by means of the voltage drop across $R_5$. Hence the space current of $V_2$ and $V_3$ through the shunt regulating field is small and the motor speeds up. When up to speed (1200 rev. per min.) the 720-cycle current is regulated by the frequency cut-off characteristic $F_1$ and $F_2$ and the space current of $V_1$ is decreased which reduces the negative grid potential of $V_2$ and $V_3$. This permits a larger flow of direct current from $V_2$ and $V_3$ to the shunt regulating field and hence the motor slows down. In addition to the above controlling action, a feedback circuit for tube $V_1$ is provided. This circuit is made up of $R_{16}$, $R_{14}$, and $R_{13}$ and $C_3$ bridged across the regulating field terminals, and gives a compensating action so that the speed is held within a fraction of one per cent.

The motor system is usually started and stopped by motor controls operated by the film recorder attendant in the recording room. When a "take" is about to be made the signal is received to "interlock." One phase of the 220-volt, three-phase power supply is closed, thus locking all the motors in a stationary position. Film in the cameras and film recorders is punched. A synchronizing start mark is also placed on the wax disk. Various colored signal lights controlled in the recording room, monitor room, and stage, when lighted indicate that all is in readiness. The system is started by closing the third wire of the three-phase, 220-volt power supply and the 110-volt d-c. supply for the d-c. distributor drive motor. A meter indicates when the system is up to speed and that the speed control is operating properly. When the motors are up to speed all operating stations receive a red bull's eye signal and the director starts the action. Red lights serve as a warning that recording is actually in process and that quiet must be maintained on the stage.

The wiring arrangement of the recording system provides full flexibility so that any stage may be connected to any recording room or amplifiers of one channel substituted for those of another. A dual set of storage batteries supplies filament and plate current to all amplifiers, recorder lights, and auxiliary equipment. A constant potential system of charging is used.

Maintenance routines similar to those employed in large telephone repeater stations have been found expedient. In this way any potential trouble hazard in the electrical system is anticipated since a failure during recording is very serious and expensive. The test laboratory is equipped with oscillators and suitable testing apparatus so that every channel may be tested daily before going into production.

## Sound Picture Reproduction[7]

The introduction of sound into the motion picture theater has also necessitated changes. It has been necessary to redesign and rebuild the projection booths to take care of the special sound reproducing equipment. Towers have been built to support the horns behind the screen. In some instances theaters have been treated acoustically in order to improve the reproduction. Speech, music, and incidental sounds must be reproduced with fidelity in order that the effect be realistic.

A typical installation layout for talking motion pictures, as shown in Fig. 19, consists of: (1) film and disk

7. The sound reproduction system used in theaters will be discussed only briefly, on account of the rather complete description given by E. O. Scriven in *Bell System Tech. Jl.*, January, 1929, "A Sound Projector System for use in Motion Picture Theaters."

reproducing attachments, by means of which small electric currents are generated with variations corresponding to the sound waves produced in recording, (2) vacuum tube amplifiers which greatly magnify these electric currents, and (3 )sound projectors consisting of receivers and horns which convert this electric energy into sound.

Sound film is run through a standard projector modified by the addition of the sound reproducing at-

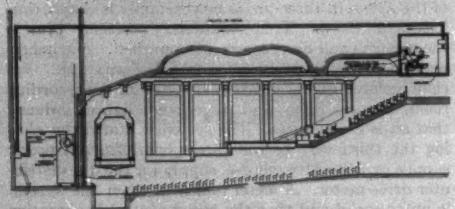

Fig. 19—Theater Cross Section Showing Sound Reproducing Equipment

tachment. This is located between the head mechanism and the lower take-up magazine.

A light beam of high intensity is concentrated by an optical system containing a slit and focused to a fine line across the sound track of the film which passes through the sound gate. The film at this point moves with a uniform recording speed of 90 ft. per minute. On the film the sound record consists of a narrow margin (the sound track of Fig. 21).

Fig. 20—Projection Booth, Showing Universal Picture Projection and Sound Reproducing Machines

The spacing of the light and dark bands along this track determines the pitch of the sound, while the varying density determines the quality and the loudness, *i. e.*, the greater the contrast between light and dark bands, the louder the sound. On the other side of the sound gate and back of the film is a photoelectric cell which produces a small electric current with variations corresponding to the modulated light which strikes it. The photoelectric cell output is strengthened by a small amplifier built into the sound attachment and then carried to a fader which is used to control the sound volume during the showing of the film. From the fader the current is carried to an amplifier of size and power suitable for the theater, (Fig. 22). The output of this amplifier passes through a distributor panel to the loud speakers and horns located behind the screen from which the sound issues in synchronism with the picture.

Fig. 21—Picture and Sound on Same Film—Variable Density Method

In the disk method of reproduction a current is generated by an electric reproducer playing on a disk record. The record is much larger than an ordinary phonograph record and revolves at 33⅓ rev. per min., thus enabling each record to play throughout a whole reel. The small electric current from the reproducer is carried to the fader where control is effected and thence to the amplifier and loud speaker system as in the film method.

Fig. 22—Theater Amplifier Equipment

By using two projectors alternately, a continuous program can be run as with silent picture projection. This is accomplished by using the fader as a sound control at the same time that the changeover is made from one reel to the next. At the end of each disk or film record there is an overlap into the next, so that with proper operation the audience is unaware of any

change being made. Unlike silent motion picture projection where the film is generally projected at a faster speed than it was photographed, the sound picture must be shown at exactly the same speed at which it was made, or 90 ft. per minute. If a faster speed were used in reproduction, the pitch would be changed, causing the voice or music to be distorted. A constant speed is maintained by means of a special type of motor and a vacuum tube controlled electrical governing system similar to the distributor controlled system used in recording.

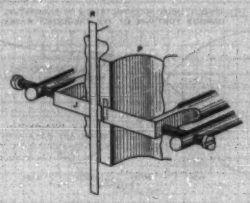

Fig. 23—The Picture Transmission Light Valve

## Dependence of Sound Pictures on Other Electrical Engineering Developments

The general processes involved in disk and film recording and reproduction have been discussed. From studio microphones to theater loud speakers the dependence of this new technique upon other electrical engineering developments has been heavy. Many kinds of apparatus, developed for other purposes, have been borrowed or adapted for use here, and many kinds of studies having other objects in view, have aided the commercial application of sound to motion pictures.

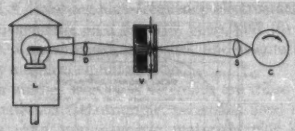

Fig. 24—Picture Transmission Receiving Optical System

We need but to survey the series of steps involved in the processes of recording and reproduction to see these relationships. Let us consider a few of the types of apparatus employed:

*1. Microphones, or Condenser Transmitters.* The condenser transmitter, as will be noted later, was developed originally in connection with studies of high quality telephonic speech. The transmission required for high quality studies does not differ greatly from that required for effective illusion in sound pictures. Originated by Mr. E. C. Wente,[8] the condenser transmitter comprised a substantial step beyond the earlier carbon microphones. While the latter are suitable for the commercial transmission of speech, they do not give the frequency range of transmission and the freedom from noise necessary in sound pictures.

Since the condenser transmitter is inherently an inefficient instrument, it has required to have closely associated with it a specially designed amplifier which increases the transmitter output but does not degrade the transmission nor introduce appreciable noise.

One of the most important uses to which the condenser transmitter has been put is in connection with experimental quality studies on speech and music. These studies will be referred to below.

*2. The Light Valve.* The light valve, also developed by Mr. Wente, has been adapted from the light valve used regularly in the commercial transmission of pictures over telephone lines.[9] The latter instrument uses but a single duralumin ribbon, the former a loop of duralumin ribbon of lighter weight. The smaller frequency range required for transmitting still pictures,

Fig. 25—Photomicrograph of Variable Density Type Pictures as Transmitted over Telephone Line

as compared with the transmission of high quality speech and music, accounts for the heavier construction permissible there.

Fig. 23 shows the picture transmission light valve, and Fig. 24 its arrangement in the receiving optical system.

Fig. 25 shows a photomicrograph of a portion of a picture of the variable density type produced by this valve and transmitted over a telephone line.

*3. Amplifiers.* The use of amplifiers for telephone, radio, public address, and other purposes is too well known to require much emphasis here. Suffice it to say that this type of apparatus has greatly altered practically all types of transmission systems for communication purposes. In sound picture recording, the currents derived from the condenser transmitters are so weak in comparison with those required to actuate a recording stylus or a light valve that amplification is

8. See "Electrostatic Transmitter," E. C. Wente, *Phys. Rev.*, May 1922, pp. 498-50

9. See "The Transmission of Pictures over Telephone Lines," Ives, Horton, Parker, Clark, *Bell System Tech. Jl.*, April, 1925, pp. 187-214.

vital. Not only this, but the many sources of noise which affect commercial recording systems would create very serious adverse effects if amplification of desired currents were not available. In this connection, it will be recalled that until the present electrical methods of phonograph recording were developed, it was found necessary to sacrifice quality of recording to obtain sufficient volume for phonograph reproduction. It is, moreover, amplification which makes possible the addressing of large audiences in the presentation of sound pictures in theaters.

For purposes of illustration, and as rough average figures, at a moment when the power of normal speech is about 10 microwatts, the power used to operate film

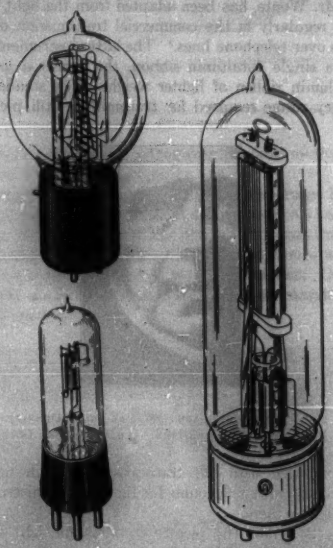

Fig. 26—Vacuum Tubes Used in Sound Picture Systems

and disk recorders would correspond to 0.006 and 0.018 watts, respectively; the power delivered by loud speakers in a large theater, however, would for the same conditions be about 2 watts.

Fig. 26 shows a variety of vacuum tubes used in various parts of recording and reproducing systems.

4. *Loud Speakers.* As in the case of amplifiers, loud speakers have already been widely used in telephony, radio broadcast reception, and public address reinforcement. The loud speaker was originally called "the loud speaking telephone" and differs from the usual type of receiver chiefly in power-handling capacity and frequency range transmitted. While there are various types of loud speakers available, the horn type has been adopted in Western Electric systems chiefly because of its high efficiency and large power-handling capacity, consistent with high quality reproduction.

In addition to these types of apparatus, there have been special incandescent lamps developed as light sources for the recording and reproducing systems, photoelectric cells have been employed in improved form, special motor systems have been used for synchronizing, regulated reproducer motors have combined vacuum tube technique with special motor design, monitoring circuit arrangements have been adapted from

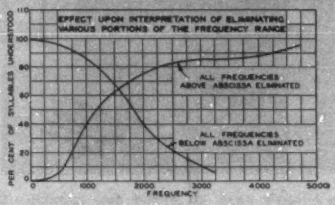


Fig. 27—Relative Importance of Different Frequencies in Articulation

communication systems, signaling circuits have been suited to sound recording needs, mixing apparatus has grown out of that used for combining the output of public address and radio broadcasting microphones, and electrical test sets of various kinds have been designed for special purposes.

Almost innumerable research and engineering studies carried on in the communication field have influenced the design of sound picture apparatus and the manner in which it is used.

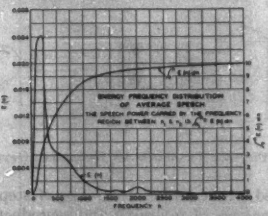


Fig. 28—Distribution of Energy of Average Speech

Thus, extensive studies of the relative importance of different frequencies in speech from an intelligibility standpoint have been essential to the attainment of high quality transmission. (Fig. 27.) Likewise, measurements of the relative distribution of energy in speech and music have been important in estimating load-carrying capacities of apparatus and the magnitudes of interference currents between circuits (Fig. 28). Again, studies of the influence of various amounts of noise on the audition of speech and music have furnished design requirements on *quietness* in apparatus and circuits. In

this connection, it should be noted that in the use of commercial communication circuits, there is a continuous effort to reduce the interference to signal transmission from extraneous noises. Akin to the investigations just mentioned have been those (1) on the volume range of audition (Fig. 29), (2) on the average power of speech and music, (3) on the effects of overloading of vacuum tubes and other devices not entirely linear in their characteristics, and finally (4) on the effects of changing the pitch of speech and music.

With regard to circuits for transmitting frequency ranges, an extensive and well-developed art has grown

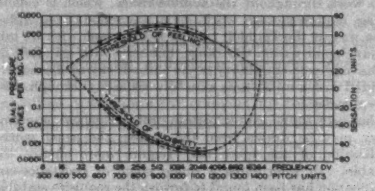


Fig. 29—Volume Range of Audition

up in communication engineering which has been effectively applied to sound picture work. Examples of contributions from this source are (1) the method of comparing sound intensities by the use of power levels (Fig. 9) based on transmission units called *decibels*, (2) the method of *matching impedances* which secures optimum transmission, (3) the use of *gains* in amplifiers and *transmission losses* in mixing and other networks, (4) the method of avoiding resonances by annulling reactance effects over wide frequency ranges, (5) the method of designing high-frequency electrostatic shielding arrangements on a network basis, and (6) the correlation of mechanical, electrical, and magnetic vibrations by means of circuit analogs.

Other studies worthy of reference are those on magnetic materials (for example, *permalloy* used in transformers) and non-magnetic materials (for example, *duralumin* used in condenser transmitters and light valves), and studies of room acoustics and the properties of acoustic absorbing materials.

It may be observed that one of the most important reasons, in purely communication engineering, which led to the development of high quality recording and reproducing systems was in connection with laboratory studies of quality of transmission. For if in these tests the human element was to be eliminated, this could only be done by providing high quality records which might be used over and over again as sources of electrical currents to be analyzed. In such tests, likewise, the condenser transmitter and other high quality transmission devices were necessary.

Fig. 30 shows the various steps of recording and reproducing sound. These drawings indicate the rather unusual transformation which takes place during the interval from the picking up of the original sounds to their restoration in the theater. It is of considerable interest to trace these changes. Beginning as sound waves, mechanical motion is imparted to the diaphram of the condenser transmitter. This mechanical motion is in turn translated into a minute electric current. After being amplified the power of this current modulates a light to which film is exposed. The resultant latent image is treated chemically and when developed, again modulates a light to produce the positive. After development this positive, when run through a projector, modulates a beam of light, thereby controlling a minute electric current. After amplification the resultant power is sufficient to impart mechanical motion to a loud speaker diaphram, thereby producing a very close approximation to the original sound. Beginning as sound, fourteen changes of condition must be passed through before the sound is reformed. The same number of changes occurs in recording on disk.

## General

The sound photoplay has revolutionized the work of the scenario writer, director, and actor and has been instrumental in building up large musical departments.

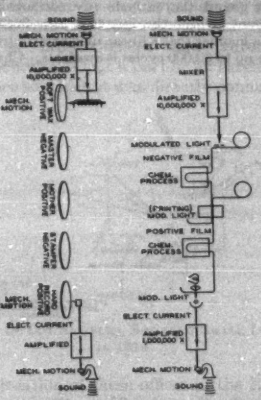


Fig. 30—Recording and Reproducing Sound, Showing Intermediate Processes

In the days of the silent photoplay it was often the practise to schedule a feature almost before the story was written. During the actual photographing of the picture many thousands of feet of film were "shot" at random on large scenes in order to be sure that enough material would be available for the film cutters and editors to patch into a good story. Actors were directed so that the memorizing of lines was not important. With sound it has been necessary to thoroughly plan and re-

hearse each scene beforehand. Actors must memorize their lines and directors remain silent during the recording.

The director must broaden his artistic and dramatic efforts to include the new technical branch. Sound engineers with more electrical engineering experience than motion picture experience have found it necessary to adjust themselves to the new environment. These two different types of personalities have joined forces. To the motion picture producer, nothing is impossible. The entertainment value of a photoplay depends upon novelty and creative ability; consequently each new picture reveals some limitation of the recording system which must be surmounted. The sound equipment must be adapted to every conceivable use. Due to the characteristic methods employed in motion picture production and the financial resources of the industry, the future development of sound pictures is certain to be swift and far reaching. In this development the electrical engineer is certain to have an important place.

## Discussion

**D. H. Loughridge:** In the design and development of the various units used in sound-picture reproducing channels it becomes essential to know the kind and magnitude of electrical distortions which enter at various points along the sound channel. In connection with work done in collaboration with Dr. R. C. Burt, I have found the cathode ray oscilloscope invaluable. This instrument utilizes the standard No. 224A cathode ray tube in such a manner that a linear time axis for frequencies from a single cycle up to 60,000 cycles is available. Changes from one frequency to another are simply accomplished by three toggle switches and two dials, the latter being a fine adjustment on the former. Adjustments are provided so that a wave, or waves, may be drawn out horizontally, or the zero line shifted vertically, horizontally, or diagonally so that any part of a wave may be moved to the optimum point of observation. Stabilization of the wave, in order to take photographs of it, is provided by a specially designed circuit controlled from the operating panel.

Using a rotating disk to modulate the light beam passing through a slit, its circumference cut so as to produce a polar sine wave, the question arises as to whether a certain photo cell gives out an electrical sine wave. The oscilloscope answers this question immediately when used in connection with a head amplifier which has previously been shown to be sufficiently free from distortion.

To work throughout the audible range, which is essential in talking motion-picture work, puts unsurmountable difficulties in the way of the Duddell type of oscillograph with its inherent resonant point within this range, but tests with standard oscillators have proved the ability of the cathode ray oscilloscope, when provided with a linear time axis, to work easily through this band of frequencies.

It has been found that in certain problems where practically no energy may be drawn from the source, the usual method of stabilization of the wave may require more energy than is available. In such cases a single stage of resistance-coupled amplification has been found to furnish the requisite stabilization so that the wave is perfectly stationary on the fluorescent end of the tube, with a very minimum of energy consumption.

Comparison and adjustment of phonograph pick-ups is also readily done by using constant-frequency records in conjunction with the oscilloscope. Distortions due to poor design or bad adjustment of this pick-up head are immediately apparent, and correction can be made without recourse to the doubtful test of the ear.

# Dial Telephone System Serving Small Communities of Southern California

BY F. O. WHEELOCK[1]

Member, A. I. E. E.

***Synopsis.***—*This paper briefly reviews the history of the step-by-step dial telephone system in small communities of metropolitan areas and notes some of the reasons for its recent rapidly growing use in small towns and communities apart from metropolitan areas. The wider appreciation of improved service by the public in the last three years is noted and requirements of the service now being rendered are discussed. The equipment is described and the methods of operation and maintenance are given. The effect on outside plant, building design, and other related subjects are discussed as are also the results obtained in the use of this telephone system.*

* * * * *

## Introduction

In rendering telephone service, two systems are in general use, the manual system and the dial system. The fundamental difference between these two systems, as the names imply, is that the principal central office operations for completing telephone calls are made by hand in the manual system, and are made by machine in the dial system. Dial telephone systems

Fig. 1—Map of Southern California

are in use in a great many places today, largely in exchanges of considerable size with equipment arranged as a single unit having a capacity of ten thousand terminals or multiples thereof. The idea of providing telephone service by means of dial system equipment housed in small buildings and normally unattended for serving the small community is by no means new, but its use in this manner has been limited for reasons explained later on.

It is the purpose of this paper to describe the small step-by-step dial telephone system. A brief history is first given of its development, followed by a discussion of some of the considerations which led to its rather wide use in southern California. A description is then given of the equipment employed and its operation and maintenance. The exchanges specifically referred to are located in the area shown in Fig. 1.

1. Southern California Telephone Co., Los Angeles, Calif.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., September 3-6, 1929.*

## Former Equipment of Small Exchanges

In eight counties of southern California, prior to 1927, the number of offices and type of equipment used in providing exchange telephone service in the smaller towns were:

42 Magneto manual offices
20 Common battery offices
9 Semi-automatic offices (machine switching equipment controlled manually by means of operators)
4 Dial system (step-by-step) offices.

## Reasons for Adopting Present System

More than fifteen years ago there were several small dial offices of the step-by-step type serving portions of the Los Angeles and San Diego exchanges. These were then known as "branch offices" and "automatic sub-offices." Each was in fact a part or an extension of the large dial office to which it was directly connected. Fig.

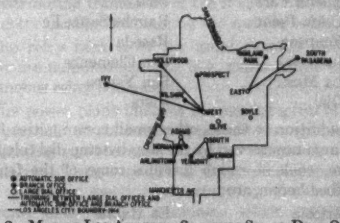


Fig. 2—Map of Los Angeles, Showing Small Dial Offices in 1914

2 shows the location of these offices in the Los Angeles exchange at that time. The branch office was fully attended and while the sub-office was smaller and was more of a complete unit in itself it also required rather constant attendance.

The endeavor to operate economically was probably the chief factor responsible for the establishment, years ago, of a 16-hour or 14-hour service day for the subscriber in the very small exchange. The recent growing demand for full 24-hour service in progressive communities, and an effort to secure greater economy and



29-128

efficiency in giving better service were probably the motivating forces exerted in promoting, in 1926, the idea of using dial equipment for serving the small community with equipment operating independently of the larger or nearby exchange except for trunking and for trouble alarm signals.

A study was made in the latter part of 1926, and plans were formulated for installing a modern small dial telephone system in the rapidly growing new town of San Clemente, California. This was the beginning of the dial system program for serving small communities as discussed in this paper. Other installations have since been completed so that fourteen towns at the

FIG. 3—SMALL DIAL OFFICES, MANUAL OPERATING CENTERS, AND MAINTENANCE SERVICE CENTERS

close of 1929 are similarly equipped. These are shown in Fig. 3 and include the following exchanges:

| | |
|---|---|
| Arcadia | Pacific Beach |
| Buena Park | Piru |
| Dana Point | Rancho Sante Fe |
| Fontana | Reseda |
| Imperial | San Clemente |
| La Mesa | San Ysidro |
| Ojai | Vista |

In addition to these, other small communities in the same area now served by the step-by-step dial telephone system, each of which includes some of the features described herein, are:

| | |
|---|---|
| Artesia | La Habra |
| Barstow | Lynwood |
| Beaumont | Mar Vista |
| Bellflower | Norwalk |
| Downey | Palm Springs |
| Hynes | Rivera |
| Indio | Victorville |

## SERVICE REQUIREMENTS

A fundamental requirement in rendering universal telephone service is to have an operator readily available to the user in case assistance is necessary in completing a connection. This precludes the use of a telephone system that is mechanically operated in its entirety. In the small dial telephone system this feature is taken care of by operators located at a center serving usually more than one exchange.

The equipment requires routine supervision of its operation at various periods to insure satisfactory operation when called upon by the subscriber while dialing a number. It also requires attention to predetermine defects, potential and actual, that may cause trouble. From the standpoint of maintenance, therefore, it is also not entirely unattended.

Successful operation of a dial telephone system depends, in addition, upon a third human factor, the subscriber. The equipment may be designed, installed, and maintained properly with an operator readily available, but its operation will not be a success unless the subscriber uses his telephone properly. For this reason an early requisite in a dial system program is a comprehensive education of the public who are to use the dial station. The instruction is given the individual subscriber by experienced operators visiting them, and by installers when they are on the premises to install the new telephone. Pamphlets telling briefly how to use the dial telephone are also distributed to the subscriber as a part of the instruction program.

## DESCRIPTION OF THE EQUIPMENT

The dial used at the subscriber's station in the small exchange of this system is marked in black with the ten numerals, 1 to 0. The word operator is also associated with the numeral 0.

The outstanding items of improved central office equipment used are as follows:

Line finders rather than line switches.

Self-protecting apparatus which permits of omitting heat coils in the battery supply leads.

Reverting call selectors.

10-Party code ringing connectors.

Choice of postpayment dial or postpayment manual coin box equipment.

Trouble alarm signals extending to the center from which the dial office is supervised.

Power plants with start and stop of charging current automatically controlled.

Ringing machines automatically controlled by selectors for the smaller exchange and continuously running for the larger exchange.

The picture in Fig. 4 shows, in the four rows of frames from left to right, connectors, line finders, local and incoming selectors, and toll selectors, respectively, with other central office equipment.

A complete central office consists of the following equipment:

| | |
|---|---|
| Subscriber line equipment | Long line equipment |
| Line finders | Trouble alarm equipment |
| Selectors | Testing circuits and equipment |
| Connectors | |
| Repeaters | Distributing frame |
| Coin box equipment | Relay rack |

Power plant

The regular subscribers line equipment consists principally of line and cut-off relays. Dial coin box

subscribers line equipment consists of similar relays and associated equipment to furnish the necessary tone to indicate to the subscriber when to deposit a coin. Manual coin box subscribers line equipment consists of a concentrating switch of the rotary type to connect the line to a trunk leading directly to the manual operating center, and relays similar to those in the regular subscribers line.

The line finder, in appearance, is similar to an ordinary selector but in addition has a commutator and associated wiper for level hunting; it is a part of the call originating equipment and is used to connect the line of a calling subscriber to a first selector. Line and line finder equipment is arranged in units consisting of a maximum of 200 line and cut-off relays and a group of line finders and their associated banks. When mounted on 11-ft. 6-in. frames they are arranged three units of 200 lines each per frame in three sizes to mount 16, 20,

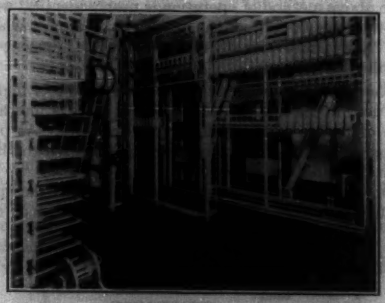

Fig. 4—Photograph, Interior View Showing Switch Equipment, Arcadia

or 30 line finders depending upon the amount of originating traffic. Partial units of any size and the required number of line finders can be installed to meet any requirement. Additions can readily be made without disturbing existing equipment. Frame heights less than 11 ft. 6 in. have been used and it is expected that another height of 7 ft. will be standardized for the lower ceiling heights.

Local selectors are of the usual two-wire type universally wired for local or incoming service. Toll selectors also are of the type used in the larger dial office. They are equipped with contacts that close with the vertical operation of the switch to operate a relay for controlling the start of the ringing machine in the offices where continuously run ringing machines are not employed.

Connectors are of the type used for the various classes of service, including:

One-bell
Two-bell
Rotary hunting
10-Party code ringing
Toll

Toll selectors and toll connectors are not provided where transmission is satisfactory over the local train.

Repeaters are of the usual type for the particular kind of trunk they are associated with, *i. e.*, one-way and two-way. One-way trunks are used principally in the larger offices where the volume of out of town traffic warrants separate trunk groups to handle the service in both directions. Two-way trunks are used where there is a small volume of out of town traffic. The two-way dial trunk at the manual center is arranged so that the operator may distinguish coin box calls from other local calls. This is accomplished by associating two lamps with each trunk, a red lamp which lights when a coin station is calling and a white lamp which lights when a flat rate station is calling.

Long line equipment consists of the usual relay, resistance, repeating coil, and condenser equipment to increase the normal impulsing and signaling range of the subscribers line.

The arrangement of the trouble alarm equipment includes visual and audible alarms which are extended to the adjacent manual operating center.

Ample testing equipment for all central office equipment and for subscribers line and station equipment is furnished.

Distributing frames are of the floor or wall type, the protector usually terminating the outside cable.

The relay rack is of the usual channel iron type. On it are mounted the long line, alarm, and other miscellaneous relay equipment.

The power plant includes storage batteries of either the portable or stationary type and arrangements for facilitating maintenance, such as automatic voltage regulators, Tungar rectifiers, ampere-hour meters for the automatic starting and stopping of the charging current, and ringing machines, either continuously running or those controlled by selectors. A picture of the charging equipment and ringing machines at Arcadia, California, is shown in Fig. 5.

When the present movement toward the wider use of dial equipment for the small community was started it was with a thought that the central office quarters could be provided at much less expense than for manual equipment by omitting operators' rest rooms, facilities for preparing lunches, etc. The ideal small dial central office equipment was pictured as a few self-contained units possibly divided between dial equipment, distributing frame, and power equipment, these to be of a rather portable type and installed in units as the office and community grew. It was suggested that this equipment might even be located so as to be on display

in windows of business places such as public garages, drug stores, or banks.

Up to this time, however, the equipment available has not been of a self-contained type. Use has been made of the standard 11-ft. 6-in. frames and racks, as in the large dial exchanges. Frames of a height 9 ft. 1¼ in. and 8 ft. 5¾ in. also have been used in some offices. These have required rooms with a fairly good ceiling height. It is expected, however, as previously mentioned, that within a short time there will be available an equipment using frames and racks limited to 7 ft.,

Fig. 5—Photograph, Interior View of Charging Equipment and Ringing Machines, Arcadia

together with self-contained units for the mounting of line finders, selectors, and connectors which will permit of installing equipment in rooms 9 ft. in height.

While in a few cases satisfactory rented quarters have been obtained, the majority of these dial offices are installed in company owned buildings which have been built expressly for housing the equipment. This has been done at a cost corresponding favorably with rented quarters. The arrangement and floor space occupied by the equipment for one of the exchanges is shown in Fig. 6.

Some of the earlier offices were not provided with heating apparatus. It has been found necessary, however, to place either gas or electric heaters in the majority of the small dial offices. These are regulated when in use by thermostatic control, and during cold or damp weather are operated continuously.

## Method of Operation

On an ordinary call when a dial system subscriber removes his receiver the line finder automatically connects the line to an idle first selector. The subscriber hears the dial tone which indicates that he is connected to a first selector and that he may dial the number. The first digit of the desired number is dialed. The selector responding to the dial impulse is raised to the desired level, and finding an idle trunk cuts the line through to the connector. In offices where the total terminals exceed 1000, a second selector is inserted in the circuit between the first selector and the connector. With the dialing of the last two digits the connector steps up vertically and around horizontally until the dialed number is reached, at which time the ringing starts if the line is not busy. The ringing tone is heard by the calling party until the called party answers. If the line called tests busy a busy signal is heard by the calling party. Fig. 7 shows the path of the call for a completed connection. If the called number is on a 10-party line an additional digit is assigned. When this final digit is dialed a minor switch which is part of the connector operates in a rotating motion and upon completion of the dialing completes a circuit to relay equipment which sends out the required number of rings on the tip or on the ring side of the called line. The above method of operation is nearly identical with the method of operation in use in large exchanges where the line finder step-by-step type of equipment is employed.

Numbering plans, consisting of three and four digits, are used in the smaller exchanges and those of four and five digits are used in the larger exchanges. As previously mentioned, where code ringing is used the last digit indicates the code ring.

On out of town calls and assistance calls the subscriber dials "O" to connect with the operator at the

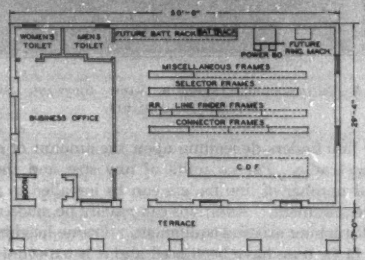


Fig. 6—Floor Plan, Ojai

manual center as shown in Fig. 8. The operator completes the call to the distant toll point. In handling assistance calls from the small dial exchange the operator may dial the desired number over the regular paths to test for busy or don't answer. No test connectors in the dial office are provided for verification and testing, so that the actual condition of the line in case it fails to connect through is not always known. Fig. 9 shows the path of an incoming call through the manual operating center to a dial system subscriber.

Where rotary hunting connectors are not provided,

private branch exchange service is given by listing all the trunk numbers in the directory. In most small dial exchanges no intercepting service is given for changed numbers, disconnected numbers, and vacant terminals; failure to hear the audible ringing signal is an indication to the subscriber that he has selected a vacant level or terminal.

Reverting calls, *i. e.*, calls to other stations on the same line, are obtained by calling a three digit number, first dialing nine then the last digit of the calling

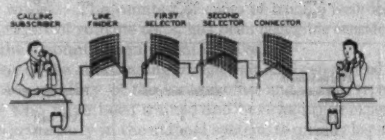


Fig. 7—Path of Local Call—Small Dial Office

subscriber's number, followed by the last digit of the called subscriber's number. The calling subscriber's receiver is then placed on the hook and the code ringing is received on the line. If the bell is on the same side of the line the called party's code ring is heard by the calling subscriber as an indication to him that the connection is completed; if the bell is on the opposite side of the line only the calling party's code ring is heard by the calling party. The ringing continues until the called party answers or it may also be stopped by the calling party removing the receiver from the hook. The reverting call switches are multipled in level No. 9 of the local first selectors.

No special provision is made for absorbing false pre-

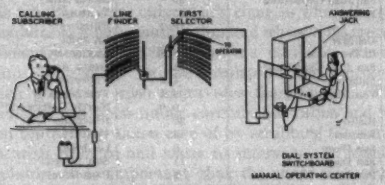


Fig. 8—Path of Call from Small Dial Office to Manual Operating Center

liminary impulses other than that level No. 1 of first selectors is not ordinarily assigned, but is used as a vacant level, initially.

Coin box stations are of the multi-slot postpayment type. Local numbers are dialed from dial coin box stations in the same manner as from any other dial station. When the called party removes his receiver from the hook a distinctive tone is heard by both parties which is an indication to the calling party to deposit a coin. When the coin is deposited the tone is removed, clearing the circuit and connecting it through for the conversation. This is accomplished with relay equipment that depends on marginal current for its initial operation, which releases by the momentary introduction of about 2000 ohms resistance in the station loop as the coin is being deposited.

Some service features of operation of ten of the small dial exchanges are shown in Table I. Length of trunks between small dial exchanges and manual operating center and the distances to the regular and secondary maintenance service centers are shown in Table II.

It has been possible, so far, to convert all magneto stations to dial stations. From the standpoint of economy and uniformity of operation and of equipment this arrangement is desired. Where it is not possible to make this change several methods of handling these stations are presented, such as selecting a trunk and signaling the operator by means of the subscriber's magneto, the operator then completing the call if within the local dial exchange by dialing back on the same trunk. Other bells on calling party's line are bridged and are called directly by the subscriber, the operator

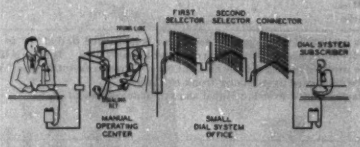


Fig. 9—Path of Incoming Call through Manual Operating Center to Small Dial Office

disregarding the signal on such calls. Another method is to provide a dial at the magneto station arranged for dialing over a simplexed leg to ground connected at the station, converting the impulses, by means of a repeater at the central office, to ordinary dial impulses.

## Maintenance

In the operation of any telephone plant some maintenance effort is necessary to keep the equipment in good workable condition. The proper amount to give a good balance between maintenance effort and the quality of service rendered is desirable. In the larger central offices this is accomplished through systematic methods whereby the equipment is made to function on test on a somewhat more stringent margin than would normally be met with under the worst operating condition. Tests are made through the medium of test circuits designed to simulate the various conditions under which the apparatus is designed to function.

While the equipment specified for small dial offices is practically the same as that used in large dial offices and requires the same treatment, the amount of maintenance effort necessary to keep the apparatus functioning, due principally to the low calling rate, is considerably less than that required for the large office. The routine methods employed in a great many instances are

SERVICE FEATURES OF SMALL DIAL EXCHANGES

TABLE I

| Exchange | 1929 stations | Equipped capacity | | Service | | |
|---|---|---|---|---|---|---|
| | | Lines | Terminals | 2-Party terminal per station | 4-Party semi-selective terminal per station | 10-Party semi-selective code terminal per line |
| Vista | 86 | 100 | 100 | No | No | Yes |
| Piru | 86 | 120 | 200 | No | No | Yes |
| Rancho Santa Fe | 88 | 120 | 200 | No | No | Yes |
| Imperial | 173 | 200 | 200 | Yes | No | Yes |
| San Clemente | 203 | 200 | 200 | Yes | No | Yes |
| Reseda | 296 | 300 | 400 | Yes | No | Yes |
| Fontana | 359 | 320 | 400 | Yes | No | Yes |
| Pacific Beach | 305 | 400 | 600 | Yes | Yes | No |
| La Mesa | 613 | 470 | 500 | Yes | No | Yes |
| Arcadia | 918 | 740 | 1200 | Yes | Yes | Yes |

| Exchange | Treatment of | | Postpayment coin service | Alarm service | Ringing current |
|---|---|---|---|---|---|
| | Vacant terminal and disconnect | Temporary disconnect | | | |
| Vista | 1 | 2 | Dial | 4 | On call |
| Piru | 1 | 2 | Dial | 4 | On call |
| Rancho Santa Fe | 1 | 2 | Dial | 4 | On call |
| Imperial | 1 | 2 | Dial | 4 | On call |
| San Clemente | 1 | 2 | Dial | 4 | On call |
| Reseda | 1 | 2 | Dial | 4 | On call |
| Fontana | 1 | 2 | Dial | 4 | On call |
| Pacific Beach | Intercepted | Intercepted | Manual | 5 | Continuous |
| La Mesa | 1 | 2 | Manual | 5 | Continuous |
| Arcadia | 3 | 3 | Manual | 5 | Continuous |

1 No audible ringing signal. Subscriber is instructed to dial "0" to verify call when no ringing signal is heard.
2 Bell circuit is opened at station on 4-and 10-party lines. Jumper is lifted on connector terminal on 1 and 2-party lines with results as outlined in 1 above.
3 No audible ringing signals on local calls. Results as outlined in 1 above. Intercepted on toll connector groups only.
4 Alarms routed over regular trunk equipment.
5 Alarms routed over individual alarm circuit equipment.

TABLE II

| Exchange | Miles to manual operating center | | | Manual operating center | Miles to maintenance service center | Maintenance service centers |
|---|---|---|---|---|---|---|
| | Wire | Cable | Total | | | |
| Vista | 9.3 | 1.5 | 10.8 | Oceanside | 39. | La Jolla[1] |
| | | | | | 10.8 | Oceanside[2] |
| San Ysidro | 8.1 | 1. | 9.1 | Chula Vista | 17. | San Diego |
| Dana Point | .. | 5. | 5. | San Juan Capistrano | 30. | Santa Ana |
| Piru | 7.8 | .3 | 8.1 | Fillmore | 35. | Ventura[1] |
| | | | | | 8.1 | Fillmore[2] |
| Rancho Santa Fe | 6.7 | .9 | 7.6 | Del Mar | 18. | La Jolla |
| Imperial | 4.4 | .4 | 4.8 | El Centro | 4.8 | El Centro |
| San Clemente | 7.4 | .4 | 7.8 | San Juan Capistrano | 33. | Santa Ana |
| Buena Park | .. | 4.5 | 4.5 | Fullerton | 4.5 | Fullerton |
| Reseda | .. | 5.8 | 5.8 | Van Nuys | 4.5 | Van Nuys[1] |
| | | | | | 9.9 | North Hollywood[2] |
| Fontana | .. | 4. | 4. | Rialto | 20. | Riverside |
| Ojai | 3.8 | 11.2 | 15. | Ventura | 15. | Ventura |
| Pacific Beach | .. | 12.1 | 12.1 | San Diego | 6. | La Jolla |
| La Mesa | .. | 12.1 | 12.1 | San Diego | 11. | San Diego |
| Arcadia | .. | 8. | 8. | Pasadena | 8. | Pasadena |

1. Regular maintenance service center
2. Secondary maintenance service center

identical, but include some special tests for apparatus peculiar to this type of equipment.

The frequencies with which these tests are made are so arranged and scheduled that each piece of apparatus is routined periodically in proportion to the importance in which it functions. The testing equipment consists of three test sets as follows: a combination line, selector, and connector test set for testing adverse line conditions outside and inside the central office such as crosses, grounds, opens, etc., an interrupter machine for simulating dial impulses under extreme circuit conditions, and a line finder test set used in conjunction with a test panel located on the line finder frame.

In addition to routine testing the trouble signals and alarms provided facilitate maintenance of the equipment. The signals are in some cases concentrated and mounted in panels and in others they are located adjacent to the particular apparatus involved. The alarms generally are arranged individually at a central point to facilitate observance by the maintenance man. In addition to the office alarm equipment the alarm signals are made common and are routed over trunks or

individual circuits to the operating center to inform the operator of trouble during periods when no one is present at the dial office.

Visits to the small dial office by the maintenance men for the purpose of making routine operations and observations of the equipment were first scheduled weekly. Later it was found possible, without causing service reactions, to extend the frequency so that the minimum period between visits is two weeks. For the Reseda exchange the equipment routines require the attention of a central office repairman for about five hours every two weeks. The number of cases of trouble recorded, as a result of routine tests, has been negligible considering the amount of equipment involved.

One of the outstanding things that has been noticed is the adaptability of the central office and outside repair men who have been trained and have had their experience principally in the manual system, to quickly handle the equipment of the step-by-step dial system. The men are trained in advance of placing the new type of equipment in service in schools where maintenance problems are studied. The man who is to care for the office usually works with the installer while the central office equipment is being placed, and thereby gains valuable practical information in testing, clearing trouble, adjusting relays, etc.

## Results Obtained

Some of the results obtained that have caused additional study and action as well as those that are favorable are recorded in what follows.

*Outside Plant.* Some trouble has been experienced from low insulation on open wire trunk circuits which are in operation between San Clemente and San Juan Capistrano, a distance of approximately 7½ miles. This trouble occurs only in dry climates where there is considerable dust accumulation and where rains are not sufficiently frequent to keep the insulators washed clean. Salt spray on the insulators from the ocean which is nearby also aggravates the situation. This condition has been under careful observation and has been tentatively taken care of by scrubbing the insulators with brushes and water at intervals. In washing insulators it is important that the under sides of the petticoat as well as the outside of the insulators be clean. The cleaning has been done with the insulators in place. This is a temporary means of taking care of the situation and has had to be repeated. It is felt, however, that the experience gained in studying the matter has been valuable. While final conclusions have not yet been reached as to the most practical way to permanently take care of this condition, it is thought that the installation of cable for a portion or the entire distance may be warranted.

At Fontana, one of the small communities first provided with dial equipment, rather serious service conditions existed during the first few months of operation due to various outside plant conditions. Winds of great velocity are frequent and several of the open wire leads pass through trees. These lines swinging together operated line finders nearly continuously, causing unnecessary wear and at times tied up the available paths for traffic in the office to an unsatisfactory degree. This condition was met by rather extensive rebuilding of outside plant and the service has been improved to a grade comparable to that of large dial offices. While these conditions were known before cutover they were carefully observed afterwards, and the experience gained resulted in first hand information as to what the limits in outside plant were, in order to render satisfactory service. In general the small dial system does not require any better grade of outside plant than the manual system. Conditions such as existed at Fontana were more of a deferred maintenance nature and ordinarily would have been corrected earlier under manual operation.

*Buildings.* The introduction of the small dial office has involved the construction of many new buildings for

Fig. 10—Photograph, Exterior View of La Mesa

the small exchange which has offered an opportunity to improve their appearance. Considerable thought has been given towards beautifying the outside as well as the inside of the structure. These small dial exchange buildings are scattered over a wide area and all conditions of topography and climate are met. Some are located in the hills, some near the ocean, and one in the Imperial Valley where extreme climatic and dust conditions exist. Figs. 10 and 11 are exterior and interior views of the exchange building at La Mesa.

*Simplicity of Equipment.* The avoidance of a multiplication of refinements in service and in ways of performing one and the same service are essentials to be kept in mind and closely controlled in the continued success of the small dial system. An open-minded public and company, both ready to waive the unessentials for the essentials, have made it possible to omit in most cases, features, such as intercepting service on unconnected terminals, to permit of simplification of the plant.

The small dial system must give satisfactory service at low cost and a careful course must be pursued to keep down the investment to permit of operating economically. Advantage has been taken of past experience in regard to providing the features that have proved most essential and to keep out of the design those that are unnecessary.

*Experience at Piru.* A brief résumé of the operation of the small dial exchange at Piru, California, immediately following the Santa Clara River Valley flood which occurred at midnight on March 13, 1928, is of interest.

On March 1, 1928, a small dial telephone exchange was placed in service at Piru with approximately 50 stations including three public coin box stations located, one in a hotel, one in a drug store, and another in an oil service station. The toll business was handled over

Fig. 11—Photograph, Interior View, Commercial Office, La Mesa

four two-way trunks which terminated at the manual center at Fillmore, about eight miles distant.

Shortly after the dam broke and the waters had reached Piru a repairman visited the office and cleared the "permanents" which totaled three; the main part of the town being on high ground was not affected by the flood. From that time on, Wednesday until the following Saturday, the exchange was given special attention in order that any equipment or operating difficulties might be immediately corrected and also to observe how an exchange of this kind would function under these circumstances. Observations were made day and night. The power was off for about eight hours immediately following the disaster and this necessitated overcharging the batteries as soon as the power was restored. It was also necessary to watch the charge rather closely as there was a slight fluctuation in the power and it was thought advisable to keep the batteries fully charged in case of another failure. However, the batteries were at no time down to the danger point or the voltage below that required for the proper operation of the equipment. From March 14 to 17, the traffic was extremely heavy and several times the equipment and trunks carried an overload, due to the number of calls originating for assistance from the flood in the stricken area. One of the four two-way trunks had a swinging cross which could not be cleared. This trunk could be dialed over but at times it was impossible to signal the operator. It was, therefore, used by the operator for dialing towards Piru. The remaining three trunks gave no trouble.

The calls to Piru were closely supervised and the equipment thoroughly inspected, but only one case of trouble was encountered, this being a failure of the ringing interrupter alarm due to a relay being out of adjustment. No service reactions were caused by this defect.

The number of toll calls during this four-day period constituted a load of approximately 300 per cent in excess of normal. It was absolutely necessary that a good grade of service be rendered as outside help was needed and transportation was extremely difficult owing to all but one bridge over the river being swept away.

The equipment functioned perfectly at all times and would have given a good grade of service with little or no attention, even under the adverse conditions.

*Psychological Aspect.* Visitors to these small offices who know of the quality of the service in these exchanges have commented that they are impressed with the fact that the doors were locked, yet they view in fitting surroundings as they enter, a clean nearly perfect machine which is functioning continuously with very little human aid to give this service.

Today, the maintenance man is sure in his own mind of what the equipment does and will do in the future; he, therefore, goes about his work expecting the proper performance of the system and it functions accordingly. Before experience was gained by actual use it was the natural thing for all to be looking for causes that would prevent proper operation. Now, however, skepticism is a thing of the past, the system has proved satisfactory, and its permanent use is assured. Pessimistic thought has changed to constructive suggestion which can only result in improvement.

## Discussion

**S. Rapp:** Mr. Wheelock brought out that the dial system will give better service to the small community, which has always been a problem. There are one or two items, however, that lead the application of the systems. One is the matter of special service lines or farmer lines. Farmer lines, for example, are not readily adapted to dial operation as signaling on them is done by alternating current obtained from a magneto generator. Dial signals are pulsating direct current. Also, the trunks from the small community exchange to the main operating center require somewhat different design from those used in manual operation. They must be better insulated and additional trunks must be provided to care for special service and maintenance tests.

The community exchange dial systems are being housed in attractive, permanent quarters as contrasted to rented quarters frequently used for manual systems. They have been established at four points in the Northern California and Nevada area, namely, Mountain View, Woodside, and Moraga in the San Francisco Bay area and at Sparks, Nevada.

# Parallel Operation of Transformers
## Whose Ratios of Transformation are Unequal

BY MABEL MACFERRAN*
Associate, A. I. E. E.

*Synopsis:—An equation is developed for use in meeting emergency conditions which necessitate the paralleling of transformer banks whose impedances expressed in percentage form are not equal. This equation makes it possible to calculate what change should be made in the ratio of transformation of the bank with the lower percentage impedance in order to prevent its being overloaded when the total load approaches the combined capacity of the two banks. It is pointed out that such an expedient is a makeshift justifiable only when maintenance of service is the paramount consideration and efficiency is, for the time being, of secondary importance. When conditions arise which do justify such a temporary arrangement, the method developed in the present paper affords a simple, yet accurate, means of solving the problem.*

* * * * *

### Introduction

EMERGENCIES sometimes arise in which it becomes desirable to operate in parallel transformer banks whose characteristics are not ideally suited to such a procedure. It is well known that unless the impedances of the two banks, expressed in percentage form, are approximately equal, one bank will assume too much load in proportion to its rating, the other too little. The question then arises, whether it is possible so to change the ratio of transformation of one bank that under the most severe load conditions which are to be imposed on the combination, neither bank will be overloaded.

The purpose of the present paper is to derive an equation whereby the change in ratio necessary to accomplish the desired result may be calculated. Such an equation is very much needed, as the only method which, to the writer's knowledge, is now extant for attacking the problem is based on the regulation curves of the two banks and involves errors which make it somewhat inaccurate in many cases.

It should be clearly understood that the expedient of changing the ratio of transformation of one bank relative to that of the other is not being advocated as a permanent measure, as it results in marked inefficiency of operation. It is justifiable only as a temporary

Fig. 1—Transformers of Unlike Ratio in Parallel Open-Circuit Condition

step to be adopted under emergency conditions which require a certain peak load to be carried no matter what the cost in efficiency at lighter loads.

### Fundamental Equations for Parallel Operation

The discussion will be based on the simple case of two single-phase transformers in parallel, since the principles governing the parallel operation of two three-phase banks are exactly the same as those governing the parallel operation of two transformers in a single-phase circuit.

It will be assumed throughout the discussion that the load is connected to the low-tension side of the paralleled transformers.

The fundamental considerations which control the behavior of two transformers operating in parallel are very simple. They are:

1. The voltage impressed on the high-tension winding of one transformer is equal to and in phase with that impressed on the high-tension winding of the other transformer.

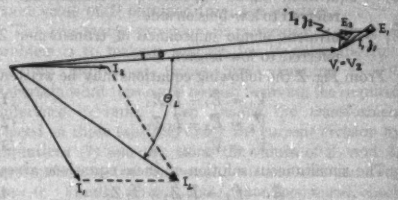


Fig. 2—Transformers of Unlike Ratio in Parallel Load Condition

2. The voltage appearing at the low-tension terminals of one transformer is equal to and in phase with that appearing at the low-tension terminals of the other transformer.

From the first consideration it follows that the low-tension open-circuit voltages of the two transformers are in phase with each other.* The reason is that, neglecting the very small phase displacement caused by the exciting current, the low-tension open-circuit voltage of each transformer is in phase with the voltage impressed on its high-tension winding. The two low-tension open-circuit voltages are not equal in magnitude, however, unless the ratios of transformation are equal in the two transformers. The vector diagram

*Operating Department, Southern California Edison Company.
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29-138

for open-circuit conditions is shown in Fig. 1. In this diagram, $\bar{E}_1$ represents the low-tension open-circuit voltage of Transformer 1, and $\bar{E}_2$ that of Transformer 2.

When a load is applied to the low-tension side of the paralleled transformers, the impedance drop in each transformer must be of such magnitude and direction that the second consideration is satisfied, as shown in Fig. 2.

In expressing these relations mathematically, the following symbols will be used:

$\bar{E}_1$ = low-tension open-circuit voltage of Transformer 1
$\bar{E}_2$ = low-tension open-circuit voltage of Transformer 2
$\bar{V}_1$ = low-tension terminal voltage of Transformer 1
$\bar{V}_2$ = low-tension terminal voltage of Transformer 2
$\bar{I}_1$ = current in low-tension winding of Transformer 1
$\bar{I}_2$ = current in low-tension winding of Transformer 2
$\bar{I}_L$ = current flowing to the load
$\theta_L$ = angle between load current and voltage impressed on the load
$\phi$ = angle between voltage impressed on high-tension side of the transformers and voltage appearing at low-tension terminals
$D$ = arithmetical difference between $\bar{E}_1$ and $\bar{E}_2$
$Z_1$ = equivalent ohmic impedance of transformer 1, referred to low-tension side
$Z_2$ = equivalent ohmic impedance of transformer 2, referred to low-tension side.

From Fig. 2 the following equations may be written:

$$\bar{V}_1 = \bar{E}_1 - \bar{I}_1 Z_1 \tag{1}$$

$$\bar{V}_2 = \bar{E}_2 - \bar{I}_2 Z_2 \tag{2}$$

$$\bar{V}_1 = \bar{V}_2 \tag{3}$$

The simultaneous solution of these equations gives:

$$\bar{E}_1 - \bar{E}_2 = \bar{I}_1 Z_1 - \bar{I}_2 Z_2 \tag{4}$$

Since $\bar{E}_1$ and $\bar{E}_2$ are in phase with each other, if $\bar{V}_1 = \bar{V}_2$ be selected as the reference axis we may write:

$$\bar{E}_1 - \bar{E}_2 = D \angle \phi \tag{5}$$

Equation (4) may then be written as follows:

$$\bar{I}_1 Z_1 - \bar{I}_2 Z_2 = D \angle \phi \tag{4a}$$

It is also necessarily true that:

$$\bar{I}_1 + \bar{I}_2 = \bar{I}_L \tag{6}$$

Equations (4a) and (6), if solved simultaneously, give the following result:

$$\bar{I}_1 = \frac{\bar{I}_L Z_2 + D \angle \phi}{Z_1 + Z_2} \tag{7}$$

$$\bar{I}_2 = \bar{I}_L - \bar{I}_1 \tag{8}$$

It should be noted that the use of the specific vector $D \angle \phi$ in place of the general vector expression $(\bar{E}_1 - \bar{E}_2)$ ties Equations (7) and (8) definitely to $\bar{V}_1 = \bar{V}_2$ as a reference axis.

Equations (7) and (8) make it possible, given the difference existing between the ratios of transformation of the two transformers, to calculate the division of current for any specified total load. It must be borne in mind that *the solution will be correct for only the one load*, and that the currents will shift in relative magnitude and in relative phase position as the magnitude and power-factor of the load are changed.

It will be seen at once that there is one difficulty in the way of obtaining a direct solution for Equation (7). This difficulty is that the value of $\phi$ is not known until $\bar{I}_1$ and $\bar{I}_2$ are known, since the phase position of $\bar{V}_1 = \bar{V}_2$ depends on the magnitude and phase position of $\bar{I}_1$ and $\bar{I}_2$. Fortunately, this difficulty is of little practical importance, since the angle $\phi$ is usually so small that it may be set equal to zero with only a slight resulting error in the solution. If it is desired to carry the calculation to greater accuracy, the method of successive approximations may readily be applied. That is, $\phi$ may first be set equal to zero, the solution made, and the position of $\bar{V}_1 = \bar{V}_2$ calculated. Then with the value of $\phi$ obtained from this calculation, a new solution of Equation (7) may be made.

The impedances substituted in Equations (7) and (8) should be in the form of complex quantities, having both resistance and reactance components. The values used should be those applying to the taps on which the transformers are operating. This requirement will be found to offer something of a stumbling-block in practise, as the data ordinarily available give information only on the full-winding impedance values. It is beyond the scope of the present paper to discuss ways of estimating the tap values of impedance, other than to point out that as the transformer is placed on lower and lower taps, the impedance values referred to the winding on which the taps are situated generally decrease quite slowly, whereas the impedance values referred to the other winding *increase* rather rapidly. The exact mode of variation depends on the type of core, type of winding, and location of the taps. There is urgent need of published data on this subject. Such data being at present lacking, the engineer confronted with a problem in parallel operation must either rely on estimates based on his own experimental tests, or else neglect the variation of impedance with taps altogether. The latter course may be adopted if only an approximate solution is required.

If the problem at hand involves three-phase transformer banks, the application of Equations (7) and (8) is permissible providing the ordinary rules for working with one phase of a three-phase circuit are followed. In Appendix A will be found a more detailed discussion of this subject, with especial reference to the case in which one bank is delta-Y, the other Y-delta.

## Ratio Change to Give a Desired Current Division

It is now easily possible to derive an equation which will give $D$ in terms of the anticipated load current and the desired division of current between the transformers. It is only necessary to specify that:

$$\bar{I}_2 = \bar{A}\,\bar{I}_1 \tag{9}$$

In this relation, $\bar{A}$ is a vector quantity. Its magni-

tude will ordinarily be taken such as to make the ratio of the currents the same as the ratio of the transformer ratings. Its angle would *preferably* be zero, placing $\bar{I}_1$ and $\bar{I}_2$ in phase with each other; but it will be shown that it is not possible to specify *both* the magnitude and the angle of $\bar{A}$.

By substituting condition (9) in Equation (8), there is obtained the relation:

$$\bar{I}_1 = \frac{\bar{I}_L}{\bar{A} + 1}$$

Substituting this in turn in Equation (7), there results:

$$D \angle \phi = \frac{\bar{I}_L (Z_1 - \bar{A} Z_2)}{\bar{A} + 1} \qquad (10)$$

Since $D$ is by definition a pure arithmetical quantity, it is necessary that the expression on the right of Equation (10) come out as some quantity at an angle $\phi$. In general, for a specified magnitude of $\bar{A}$ there is only one angle of $\bar{A}$ that will result in a vectorially correct solution to Equation (10). This means that it is possible to dictate the proportion between the currents $\bar{I}_1$ and $\bar{I}_2$, but it is not possible simultaneously to dictate the angle that shall exist between them.

The correct angle for the vector $\bar{A}$ must be found by trial and error. It is usually sufficiently accurate to assume $\phi$ approximately equal to zero. Then, having selected the desired magnitude for $\bar{A}$, it is necessary to try different angles for $\bar{A}$ until one is found which makes the right-hand side of Equation (10) come out to some quantity at an angle within two or three degrees of zero. $D$ is then equal to this quantity. If greater accuracy is desired, the method of successive approximations may be applied to fix the value of $\phi$ more closely. However, in practical work it is not necessary to make an extremely accurate solution for $D$, because the anticipated load conditions are usually somewhat vague; and furthermore, there is seldom a tap available to conform exactly with the calculated value of $D$.

If $D$ comes out positive, the open-circuit voltage of the transformer which was assigned the designation "2" is the one to be lowered, since Equation (7), from which Equation (10) is derived, is based on the assumption that $\bar{E}_1$ is greater than $\bar{E}_2$. If $D$ comes out negative, then the open-circuit voltage of Transformer 2 is to be raised above that of Transformer 1. In starting out a solution, it is a good plan to assign the designation "2" to the transformer with the lower percentage impedance, because this will be the one whose open-circuit voltage will have to be lowered in order to prevent its taking too much load. Thus the inconvenience of working with a negative $D$ will be avoided.

If the angle which it is necessary to assign to $\bar{A}$ in order to obtain a solution for $D$ is of the order of 90 degrees or more, it is probable that the solution will be of little practical value, since even though the currents divide in proportion to the ratings, each will have to be so large (in order that their vector sum may equal $I_L$ despite the large angle between them) that the transformers will in all likelihood be overloaded.

If it seems impossible to find an angle for $\bar{A}$ that works out satisfactorily, some other magnitudes for $\bar{A}$ will have to be tried. Of course there is no use trying magnitudes which differ markedly from the ratio of the ratings unless there is a very wide leeway between the load to be carried and the sum of the ratings of the transformers.

A minor difficulty presents itself in assigning the correct values to $Z_1$ and $Z_2$. Their values will depend on what taps are employed on the transformers, and these in turn will depend on the value of $D$. Here if desired the method of successive approximations may be applied. First solve for $D$, using the full-winding values of $Z_1$ and $Z_2$. Then if to obtain the required $D$ it is necessary to place one or both transformers on taps, estimate the values of $Z_1$ and $Z_2$ on these taps and solve again for $D$. Repeat if necessary until little change occurs in $D$ on the successive solutions. For practical work it is probable that the first value of $D$ will be quite accurate enough, especially since the actual taps available may be such as to make it impossible to use the exact value of $D$ obtained from the solution.

The reasonable procedure in attacking a practical problem is to make a solution for $D$, using the full-winding impedance values and assuming $\phi = 0$. Ascertain what taps come nearest to giving the required difference in ratio. Then assume the transformers placed on these taps and check the current division by Equations (7) and (8), using the values of $Z_1$ and $Z_2$ appropriate to the taps employed, and still assuming $\phi = 0$. Finally, when $\bar{I}_1$ and $\bar{I}_2$ have been found, check the value of $\phi$ by graphic construction or calculation, and if it differs from zero by more than two or three degrees, make a new solution based on this corrected value of $\phi$.

In most practical cases the magnitude and power factor of the load are a little hard to predict. The best procedure is to select a value of $D$ to fit the most severe load conditions which are anticipated. Then check the current division not only for this but for several other possible values of load and power factor, in order to be sure that there is no possibility of overload occurring on one of the transformers.

If $D$ is selected to give the best possible current division conditions when the total load is of a magnitude approaching the combined capacities of the transformers, it will be found that as the load decreases the current vectors tend to swing further and further apart, until at no load they are 180 deg. apart and constitute a pure circulating current. On account of this increasing predominance of the circulating component at light loads, it is usually advisable to take the smaller transformer out of service when the total load drops to a value within the capacity rating of the larger transformer.

### Conclusions

Equations have been derived which, for a specified total load at a specified power factor, determine the division of current between transformer banks which differ not only in impedance, but also in ratio of transformation.

A formula has been developed for use in meeting emergency conditions which necessitate the paralleling of transformer banks whose impedances expressed in percentage form are not equal. This formula makes it possible to calculate what change, if any, can be be made in the ratio of transformation of the bank with the lower percentage impedance in order to prevent its being overloaded when the total load approaches the combined capacity of the two banks.

It has been shown that when the ratio of transformation of one bank is changed in order to produce approximately correct load division under peak conditions, very inefficient operation results when the load drops below the peak value. Therefore, the expedient of ratio change is justifiable only when maintenance of service is the paramount consideration and efficiency is, for the time being, of secondary importance.

When emergency conditions arise which do justify a change of ratio, the method developed in the present paper affords a simple and yet accurate means of solving the problem.

## Appendix A

### Application of Equations to Three-Phase Transformer Banks

If the banks which are to be operated in parallel are both Y-connected on the low-tension side, Equations (7), (8), and (10) may be applied by using the low-tension line-to-neutral voltage and the impedance of one transformer in each bank. The currents to be used are the line currents flowing in the low-tension side of each bank and in the load.

If the banks are both delta-connected on the low-tension side, the equations may be applied by using the low-tension line-to-line voltage and the impedance of one transformer in each bank. In this case the currents to be used are the low-tension line currents divided by the square root of three.

If one bank is Y-connected on the low-tension side, the other delta, the simplest procedure is to convert the delta connection into a fictitious Y-connection which will have the same percentage impedance as the actual delta-connected bank. In order to derive an expression for the ohmic impedance of each transformer in the fictitious bank, it will be convenient to adopt the following symbols:

$\bar{V}_a$ = Rated voltage across low-tension side of each transformer in actual bank

$\bar{V}_f$ = Rated voltage across low-tension side of each transformer in fictitious bank

$\bar{I}_a$ = Rated current in low-tension winding of each transformer in actual bank

$\bar{I}_f$ = Rated current in low-tension winding of each transformer in fictitious bank

$Z_a$ = Equivalent ohmic impedance of each transformer in actual bank (referred to low-tension side)

$Z_f$ = Equivalent ohmic impedance of each transformer in fictitious bank (referred to low-tension side)

Since the actual bank is delta on the low-tension side, while the fictitious bank is Y, it follows that:

$$\bar{V}_f = \frac{\bar{V}_a}{\sqrt{3}}$$

$$\bar{I}_f = \sqrt{3} \times \bar{I}_a$$

$$Z_a = \frac{\text{Rated voltage} \times \text{per cent impedance}}{\text{Rated current} \times 100}$$

$$= \frac{\bar{V}_a}{\bar{I}_a} \times \frac{\text{Per cent impedance}}{100}$$

$$Z_f = \frac{\bar{V}_f}{\bar{I}_f} \times \frac{\text{Per cent impedance}}{100}$$

$$= \frac{\bar{V}_a}{\sqrt{3} \times \sqrt{3} \times \bar{I}_a} \times \frac{\text{Per cent impedance}}{100} = \frac{Z_a}{3}$$

That is, if the equivalent ohmic impedance (referred to the low-tension side) of each transformer in the fictitious bank is taken equal to one-third that of each transformer in the actual bank for which it substituted, the per cent impedance of the fictitious bank will be the same as that of the actual bank. The same reasoning applies, of course, to the resistance and reactance components of the impedance.

When the calculation of equivalent ohmic impedance referred to the low-tension side is based directly on data giving the per cent impedance of the transformer, the ratio of transformation does not enter the problem, and so it makes no difference whether the high-tension winding of the fictitious bank is Y or delta. However, the ratio of transformation does enter the calculation when it is desired to ascertain the taps to give a specified value of $D$. Here it is necessary to remember the rules as to what types of three-phase connection can and cannot be paralleled, in fixing the ratio of transformation of the fictitious bank. For example, if one bank is Y-Y and the other delta-delta, the fictitious bank which replaces the delta-delta bank must be Y-Y, *not* delta-Y. Or, if one bank is delta-Y and the other Y-delta, the fictitious bank which replaces the Y-delta bank must be delta-Y, *not* Y-Y. The ratio of transformation of the fictitious bank should be fixed accordingly.

In Appendix B an example is worked out which illustrates the method of forming a fictitious delta-Y bank to replace an actual Y-delta bank.

## Appendix B

### Example of Solution for Ratio

Owing to an unexpectedly rapid increase of load in a

certain territory, it is anticipated that a 3000-kv-a. bank will soon be called on to deliver 4000 kv-a. unless given some assistance. A bank to operate in parallel with it has been ordered from the manufacturers, but meanwhile some temporary arrangement must be made. There is available a 1500-kv-a. bank of considerably lower percentage impedance. It is proposed to make a ratio adjustment such that the 1500-kv-a. bank will operate satisfactorily in parallel with the 3000-kv-a. bank during periods of peak load, with the understanding that the smaller bank will be taken off the line when the load drops to within the capacity of the larger bank. What will be the required ratio adjustment?

The data on the transformers involved are as follows:

*Bank No. 1—Three 1000-kv-a. transformers*

| | |
|---|---|
| Impedance volts | = 7.67% |
| Impedance watts | = 0.813% |
| High-tension voltages | = 19,050—18,200—17,300 |
| Low-tension voltage | = 11,500 |
| Present connection | = 18,200/31,500 Y to 11,500 delta |

*Bank No. 2—Three 500-kv-a. transformers*

| | |
|---|---|
| Impedance volts | = 4.25% |
| Impedance watts | = 0.748% |
| High-tension voltages | = 33,000—30,800—28,600 |
| Low-tension voltages | = 7000—6800—6600—6200 |
| Present connection | —To be decided on. |

It is clear that in order to parallel with Bank No. 1, Bank No. 2 will have to be connected delta on the high-tension side, Y on the low-tension side. Therefore it will be convenient to replace Bank No. 1 by a fictitious bank connected 31,500 volts delta on the high-tension side and 6640/11,500 volts Y on the low-tension side. The equivalent ohmic impedance of each transformer in this fictitious bank will then be calculated as follows:

*Equivalent Impedance—fictitious Bank No. 1*

Rated low-tension voltage per transformer

$$= \frac{11{,}500}{\sqrt{3}} = 6640 \text{ volts}$$

Rated low-tension current per transformer

$$= \frac{1{,}000{,}000}{6640} = 150.7 \text{ amperes}$$

Full-winding impedance referred to low-tension

$$= \frac{\text{Rated Voltage} \times \text{Per Cent Imp.}}{\text{Rated Current} \times 100}$$

$$= \frac{6640 \times 7.67}{150.7 \times 100} = 3.38 \text{ ohms}$$

As a check on the correctness of the above value for the impedance of the fictitious bank, the per cent impedance of each transformer may be calculated by the well-known formula:

$$\text{Per cent impedance} = \frac{\text{kv-a.}}{(\text{kv.})^2 \times 10} \times \text{ohms impedance}$$

$$= \frac{1000}{(6.64)^2 \times 10} \times 3.38 = 7.67\%$$

In order to find the resistance component of the impedance, the impedance watts are utilized:

Impedance watts = 0.00813 × 1,000,000 = 8130 watts

Resistance referred to low-tension

$$= \frac{8130}{(150.7)^2} = 0.358 \text{ ohm.}$$

Reactance referred to low-tension

$$= \sqrt{(3.38)^2 - (0.358)^2} = 3.37 \text{ ohms.}$$

Summarizing:

$Z_1 = 0.358 + j\,3.37 = 3.38 \underline{/83.5}$ ohms referred to low tension.

*Equivalent Impedance—Bank No. 2*

Rated low-tension voltage per transformer = 7000 volts

Rated low-tension current per transformer = 71.4 amperes

Full winding impedance referred to low tension

$$= \frac{7000 \times 4.25}{71.4 \times 100} = 4.17 \text{ ohms}$$

Impedance watts = 0.00748 × 500,000 = 3740 watts

Resistance referred to low tension

$$= \frac{3740}{(71.4)^2} = 0.733 \text{ ohm}$$

Reactance referred to low tension

$$= \sqrt{(4.17)^2 - (0.733)^2} = 4.10 \text{ ohms.}$$

Summarizing:

$Z_2 = 0.733 + j\,4.10 = 4.17 \underline{/80}$ ohms referred to low tension.

*Conversion of Impedance Ohms to Tap Values*

Bank No. 1 is operating on the 18,200-volt tap on the high-tension side, whereas the value of $Z_1$ calculated above, is for the full winding or 19,050-volt tap. Hence the impedance, reactance, and resistance should be converted to terms of the 18,200-volt tap. The transformers are of a type which is known by experience to obey the following rules in regard to impedance on different taps:

1. The equivalent ohmic reactance referred to the winding on which the taps are situated remains approximately constant over a fairly wide range of taps.
2. The equivalent ohmic resistance referred to the winding on which the taps are situated varies directly in proportion to the tap percentage.
3. The equivalent ohmic reactance referred to the winding on which the taps are *not* situated varies inversely as the square of the tap percentage.
4. The equivalent ohmic resistance referred to the

winding on which the taps are *not* situated varies inversely as the tap percentage.

In Bank No. 1, the taps are on the high-tension winding, while the impedance to be used in the calculations is referred to the low-tension winding. Hence rules (3) and (4) above should be applied:

$$X_1' = \left(\frac{19{,}050}{18{,}200}\right)^2 \times 3.37 = 3.69 \text{ ohms}$$

$$R_1' = \frac{19{,}050}{18{,}200} \times .358 = 0.375$$

$Z_1' = .375 + j\,3.69 = 3.71 \underline{/85}$ ohms referred to low tension.

The ratio of transformation of each transformer in the fictitious delta-Y No. 1 Bank is $\frac{31{,}500}{6{,}640} = 4.75$. It is safe to assume that the ratio of Bank No. 2 will be greater than this, since No. 2 has the lower percentage impedance and so must have its open-circuit voltage lowered relative to that of No. 1. As a preliminary estimate, assume Bank No. 2 to be on the full winding (33,000-volt tap) on the high-tension side, and on the 6800-volt tap on the low-tension side. This will give a ratio of transformation of 4.85. Applying rules (1) and (2):

$X_2' = 4.10 \times 1 = 4.10$ ohms

$$R_2' = 0.733 \times \frac{6800}{7000} = 0.712 \text{ ohms}$$

$Z_2' = 0.712 + j\,4.10 = 4.17 \underline{/80.3}$ ohms referred to low tension.

*Solution for D*

Assume load = 4000 kv-a. at 0.75 power factor

Then $I_L = 200 \underline{/-41.4}$

$$\text{Let magnitude of } A = \frac{\text{Rating Bank No. 2}}{\text{Rating Bank No. 1}} = \frac{1500}{3000} = 0.5$$

Try first an angle of zero for the vector $\bar{A}$

By Equation (10):

$$D\underline{/\phi} = \frac{200\underline{/-41.4}\,(3.71\underline{/85} - 0.5\underline{/0} \times 4.17\underline{/80.3})}{0.5\underline{/0} + 1}$$

$$= 133.3\underline{/-41.4} \times 1.64\underline{/89} = 218\underline{/47.6}$$

This is not a solution, since $\phi$ must equal zero.

Try $\bar{A} = 0.5\underline{/+30}$

$$D\underline{/\phi} = \frac{200\underline{/-41.4}\,(3.71\underline{/85} - 0.5\underline{/30} \times 4.17\underline{/80.3})}{0.5\underline{/30} + 1}$$

$$= 136\underline{/-51.4} \times 2.08\underline{/58} = 283\underline{/6.6}$$

Try $\bar{A} = 0.5\underline{/+40}$

$$D\underline{/\phi} = \frac{200\underline{/-41.4}\,(3.71\underline{/85} - 0.5\underline{/40} \times 4.17\underline{/80.3})}{0.5\underline{/40} + 1}$$

$$= 140\underline{/-54.8} \times 2.38\underline{/53} = 333\underline{/-1.8}$$

This solution gives a value of $\phi$ very close to zero, and may therefore be adopted. It means that $\bar{E}_2$ must be made 333 volts lower than $\bar{E}_1$.

When the high-tension voltage is 31,500 volts, $\bar{E}_1 = \frac{31{,}500}{4.75} = 6640$ volts. Hence at the same time, $\bar{E}_2$ should be $6640 - 333 = 6307$ volts. This means that the ratio of transformation of each transformer in Bank No. 2 should be $\frac{31{,}500}{6307} = 5.00$.

The required ratio of 5.00 on Bank No. 2 can be obtained by placing each transformer on the 33,000—6600-volt taps.

*Check of Correctness*

To check the correctness of the solution, including the possible error due to not using exactly the right value of $\phi$, Equations (7) and (8) may be applied.

The value of $Z_2$ should be changed to accord with the 6600-volt tap to be used on Bank No. 2. The new value will be

$$R_2'' = 0.733 \times \frac{6600}{7000} = 0.691$$

$X_2'' = 4.10 \times 1 = 4.10$

$Z_2'' = 0.691 + j\,4.10 = 4.16 \underline{/80.7}$ ohms referred to low tension.

By Equation (7):

$$I_1 = \frac{200\underline{/-41.3} \times 4.16\underline{/80.7} + 333\underline{/-1.8}}{.375 + j\,3.69 + .691 + j\,4.10}$$

$$= 141\underline{/-54}$$

$$I_2 = 200\underline{/-41.3} - 141\underline{/-54} = 70\underline{/-17}$$

Checking the value of the angle $\phi$ by graphic construction or by calculation, it is found that $\phi = +2$ deg. The error introduced in the solution by taking $\phi = -1.8$ deg. is therefore negligible from a practical standpoint, and hence it is not necessary to make a re-calculation of $I_1$ using the new value of $\phi$.

In checking the size of the angle $\phi$ it is also found that $V_1 = V_2 = 6180$ volts if the impressed high-tension voltage is 31,500 volts. Using this voltage as a basis for kilovolt-ampere calculations, it is found that:

Total kv-a. $= 6180 \times 200 \times 3 = 3700$ kv-a.

Bank No. 1 kv-a. $= 6180 \times 141 \times 3 = 2600$ kv-a.

Bank No. 2 kv-a. $= 6180 \times 70 \times 3 = 1300$ kv-a.

It is seen that the banks divide the kv-a. in proportion to their respective ratings, and that the sum of the kv-a. in the two banks comes to only 200 kv-a. more than the total load. This represents a wasted capacity of only 4.4 per cent of the total rating of the banks. Thus the operating conditions may be regarded as fairly efficient.

Had the two banks been operated with equal ratios of transformation, the kv-a. assumed by Bank No. 2 would have been roughly equal to

$$3700 \times \frac{3.38}{3.38 + 4.16} = 1660 \text{ kv-a.}$$

This exceeds the rating of the bank by 160 kv-a.

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# Progress in the Study of System Stability

BY I. H. SUMMERS* and J. B. McCLURE*

Member, A. I. E. E. Associate, A. I. E. E.

***Synopsis.***—*In the second part of this paper and in the appendices attention is given to simplified methods of treating the problem of system stability. Methods are recorded which have been found useful in making many system studies. These methods have had considerable verification by tests both on a model system and on large operating systems and have been simplified to such an extent that many operating companies are now finding it to their advantage to undertake the work of making careful studies of their own systems, just as they now make short circuit studies which formerly were thought too difficult and too highly theoretical.*

*The first part of the paper gives some comments and conclusions of the authors and their colleagues as a result of many such system studies as well as studies involving more detailed methods, and also as the result of practical experience through contact with various operating companies. Some of these comments are based directly on an example which is given in detail in Appendix I.*

## Introduction

THE literature on Power System Stability is growing rapidly.† It includes papers on theoretical methods of calculating stability, on observations of actual systems, and on methods of improving stability. This paper is intended to give the conclusions of the authors and their colleagues based on many careful system studies and on observations and tests on actual and model systems. Appendix I contains the results of some calculations to compare the theoretical performance of various assumed system connections. The economies of design are not considered as such in this paper. This phase may be readily introduced after the engineering facts have been obtained. Other factors enter in such as geological and local weather conditions. Thus the calculations given here are specifically recognized as being but one item in the problem, an important item nevertheless.

The appendices of the paper include formulas and calculations which have been found useful in making stability studies and which may be helpful in extending the usefulness of the paper.

The conditions under which instability occurs may be classified as:

Case 1. Under steady load conditions due to inadequate synchronizing power.

Case 2. Under steady load conditions due to hunting.

Case 3. During disturbances, particularly those due to short circuits.

*Case 1.* Various criteria have been developed to permit the design of a system which will be stable under these conditions.[1, 18, 21] Continuously vibrating regulators are helpful in increasing the power limit, especially when the machine synchronous reactances are a large percentage of the whole reactance. A power system must be stable under steady load conditions for a reasonable margin above the expected load to allow for some swings and hunting, otherwise the system will be liable to lose synchronism at any time. Therefore no system should be considered practical unless such a margin is established at the outset. Thus in practise, the problem reduces to the consideration of cases 2 and 3.

*Case 2.* This type of instability occurs principally at light loads and when the resistance of the lines involved is high. Continuously vibrating regulators are apparently helpful in eliminating danger from this cause.

*Case 3.* This is the type of instability which demands most attention today. Faults may be conductor-to-ground, conductor-to-conductor, two-conductors-to-ground, or three-conductors-shorted, in the order of their severity. Experience indicates that some systems are largely subjected to one-conductor-to-ground faults, while others are largely subjected to two-conductor-to-ground faults. The character of the fault, whether one-conductor or two-conductor-to-ground, has a decisive influence in the design of systems for stability at all times.

The effect of these faults is suddenly to throw an active and reactive load on the system and to reduce the synchronizing power between machines. As a result the position of the rotors of the machines in the system tends to vary, the variation being in general such as to increase the angular separation between the generators and motors.

An accurate analysis involves a step-by-step calculation of the motion of each machine in the system, the principle factors involved being the line reactances, machine synchronous and transient reactances, time constants of the machine field structures, governor and regulator actions, switching times, and machine inertias. Simplified methods of analysis in certain cases are available.* The examples in Appendix I of this paper have been chosen so that these simplified methods may be used, thereby making it possible to investigate a larger number of cases without unduly increasing the labor involved. Step-by-step calculations are also used extensively and a simple example of this method is given in Appendix IV.

*Both of the Central Station Engineering Dept., General Electric Company, Schenectady, N. Y.

†See Bibliography.

*Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.*

1. For references see Bibliography.

*See Bibliography 1, and Appendices II and VIII.



29-141

## Part I

### The Relation of System Connections and Apparatus to Stability

As a result of many stability studies and also of practical experience the following comments have been prepared.

### Apparatus

(*a*) *Generators*

(*I*) *Short Circuit Ratio.* High short circuit ratio is of benefit in improving the power limit under steady load conditions with hand control. The use of the

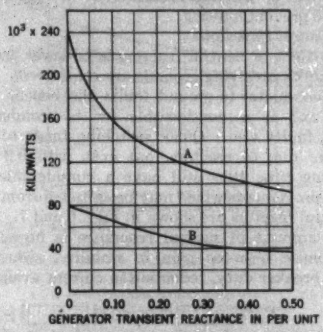



Fig. 1—Power which may be Carried through Fault Conditions outside Generator Transformers *Versus* Generator Transient Reactance when the Fault is Cleared in 1.0 sec.

For set-up see Diagram A Fig. 4
*A*—1 conductor to ground fault
*B*—2 conductor to ground fault

proper kind of voltage regulators and excitation systems extends the power limit both under steady load conditions and under transient conditions† and may largely overcome the disadvantages of low short circuit ratio.

How much dependence should be placed on regulator action is a question which is not yet settled. If no regulator is used or if no reliance is placed on the regulator action the short circuit ratio should be just great enough so that steady state stability is always insured for the most severe load condition anticipated, provided that line charging requirements do not predominate. On this basis it will often be found that a higher short circuit ratio is required than would otherwise be necessary, which results in a greater first cost and lower efficiency. Therefore, it is thought that an alternative basis may be acceptable, namely, that the short circuit ratio be only sufficient for steady stability under normal conditions. A regulator would then be used to maintain stability during short periods of overload such as might occur, for example, owing to the sudden loss of one generator in a system.

†See Figs. 4 and 5 of Bibliography 1.

(*II*) *Transient Reactance.* A low transient reactance is of benefit in improving stability under transient conditions (see Fig. 1) provided that the disturbances which are anticipated are not so severe that there is no possibility of holding in synchronism. Thus, with a given arrangement of lines and transformers, it may be found that there is ample stability for conductor-to-ground faults, but no chance of it under two-conductor-to-ground faults except when the generators happen to be operating at greatly reduced loads. In this case a reduction in transient reactance might be of little value. On the other hand, with a different system layout, a reduction in transient reactance may be necessary for stability even with conductor-to-ground faults or in still another case such a reduction may permit operation through two-conductor-to-ground faults. The proper value of machine transient reactance thus depends markedly on system layout and its determination involves a study of line and transformer as well as generator costs.

(*III*) *Damper Windings.* Damper windings have two effects: the first a damping action, the second an increase in fault current and shock to the system. The

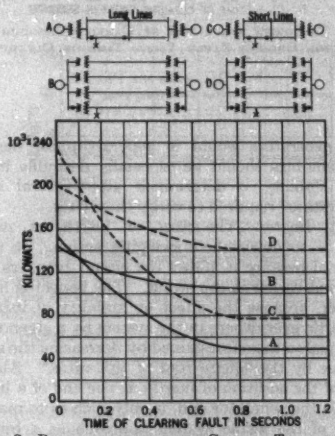



Fig. 2—Power which may be Carried Through a Two-Conductor-to-Ground Fault Outside the Generator Transformers *Versus* Time of Clearing the Fault.

——— Long lines
– – – – Short lines

latter effect is due to the reduction in generator negative phase sequence reactance. If the shock to the system is relatively small a slight increase in shock, because of the reduction in reactance, will not be serious. If the shock is so severe that synchronism will be lost without damper windings, their presence cannot make matters worse. There will be a critical shock which is just great enough to cause instability when no damper

winding is used. Calculations made on typical systems have indicated that with a shock of this magnitude the beneficial effect of damping exceeds the disadvantageous effect of increased shock. Furthermore, the presence of damper windings produces a markedly beneficial effect in extinguishing arcs more quickly due to the reduction in the recovery voltage. Therefore, the use of low resistance damper windings on water

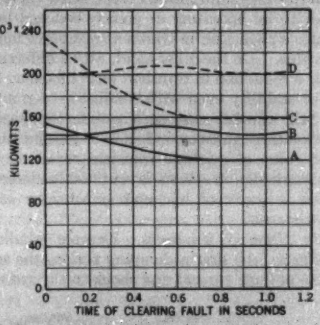



FIG. 3—POWER WHICH MAY BE CARRIED THROUGH A ONE-CONDUCTOR GROUND FAULT *Versus* TIME OF CLEARING THE FAULT

FOR DIAGRAMS SEE FIG. 2

——— Long lines
- - - - - Short lines

wheel generators would in general appear desirable. Such windings should be especially desirable in cases where stability is determined after several swings. Field tests are required to verify these data.

(*IV*) *Inertia.* The effect of inertia of machine rotors is to delay their swinging action. It is thus beneficial because it allows the circuit breakers to act at a point earlier in the swing. The benefit is limited, however, because the effect on stability of increasing the inertia everywhere in the system by a given ratio is only equal to the effect gained by decreasing the switching time by the square root of this ratio.* Also, the effect of the addition of inertia at one end of a line, for example the generator end, is only such as to make the inertia of the whole system approach as a limit the inertia of the other end of the line.† It would appear that inertia can only be economically obtained when it is secured in large quantities by means of interconnection.

(*V*) *Double Windings.* Double windings[17] are often a valuable feature when the interconnection of machines at generated voltage is desired. The principle involved is the use of the inherent reactance of the machines to limit the short circuit current.

*See Appendix VIII.

†Because in this case the equivalent inertia constant

$$M = \frac{M_1 M_2}{M_1 + M_2}$$

(*b*) *Excitation Systems*

It has been definitely shown that regulators which act quickly are effective in improving stability. For example, as stated above in paragraph (*I*) under generators, with proper regulators both steady state and transient power limits may be materially increased. To accomplish this result it is necessary that the excitation systems be fast enough to respond sufficiently. The practical criterion of the speed of response necessary has been investigated and a tentative figure of 200 volts per second determined.[1, 16] Field tests should be made on an actual system to verify this decision.

The use of the appropriate type of regulator also tends to prevent hunting.

(*c*) *Neutral Impedance*

The effect of neutral reactors is to lower the shock when faults involving grounds are considered.

For conductor-to-ground faults the benefit is very great, and it is considerable for two-conductor-to-ground faults also. Quick switching tends to reduce the gain due to reactors, but even with 0.2 second switching time they still have a considerable value. The improvements which may be expected from the use of neutral reactors are shown in Figs. 6 and 7.

The amount of neutral reactance is necessarily a compromise between gain in stability, reduction in circuit breaker duty, reduction in current available for

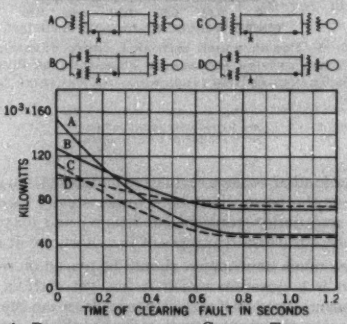



FIG. 4—POWER WHICH MAY BE CARRIED THROUGH A TWO-CONDUCTOR-TO-GROUND FAULT OUTSIDE THE GENERATOR TRANSFORMERS *Versus* THE TIME OF CLEARING THE FAULT

——— Long lines, mid-sectionalizing bus
- - - - - Long lines, no mid-sectionalizing bus
*A* and *C*.....High-voltage Buses
*B* and *D*.....Low-voltage Buses

actuating relays, reduction in telephone interference, and an increase in phase voltage to ground during disturbances.

The latter consideration becomes important in connection with lightning arresters and overvoltage relays. Studies have shown that when ground relays are used a reactor of about 2½ to 3 times the reactance of the transformer is usually correct. In cases of sufficient importance this figure should be checked by special cal-

culation. The neutral reactance so far discussed does not in any way approach the dimensions of a Petersen coil, and therefore does not involve resonance phenomena. The Petersen coil is merely a reactor which permits a reactive fault current equal to the line charging current to ground under fault conditions and this reduces the fault current to a low value.[3, 4] In addition, it operates to cause the voltage across the arc to recover slowly in case the arc is extinguished. When the arc extinguishes, both the voltage across it and the dielectric

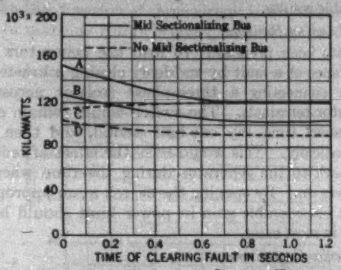



FIG. 5—POWER WHICH MAY BE CARRIED THROUGH A ONE-CONDUCTOR-TO-GROUND FAULT OUTSIDE THE GENERATOR TRANSFORMERS *Versus* TIME OF CLEARING FAULT (SEE FIG. 4 FOR DIAGRAM)

——— Mid sectionalizing bus
- - - - - No mid sectionalizing bus

strength of the arc space begins to increase. The arc will extinguish permanently if the recovery voltage across it is always less than its dielectric strength.[24] Thus the magnitude of recovery voltage is a measure of arc stability. The magnitude of the recovery voltage in the first ¼ cycle depends on the degree of "tuning" and is proportional to the ratio of fault current with the Petersen coil to the fault current without the Petersen coil. Even with only a moderate degree of tuning this ratio is small and experience shows that even on widely distributed systems with large charging currents, the arc is unstable and goes out. Petersen coils are much used abroad, but have so far been little used in this country. Experience abroad would indicate that their use here should be reconsidered.

Neutral resistors may be of two types: current limiting and braking. The former is of relatively high resistance and acts primarily to reduce the shock to the generator and the system having the fault. The latter is of low resistance and is used to load the generator, thus providing a braking action. With this type of resistor the shock to the generator is reduced while the shock to the system is increased.

It has been shown[18] that the current limiting type of resistor causes greater phase to ground voltages than a reactance would for the same gain in stability. Further, the reactor is usually cheaper. Therefore as a current limiting device reactors are in general preferable. Whether or not a braking type of resistor is preferable to a current limiting reactor is a question which is not yet entirely clear. However, for general applications the reactor appears preferable since the choice of braking resistor requires very careful study in each particular case, which is not the case with reactors. Furthermore with a braking resistor there is a greater danger of telephone interference than if either a current limiting resistor or reactor is used.

(*d*) *Synchronous Condensers*

The authors believe that the use of synchronous condensers wholly or principally as an aid to stability is not in general desirable, except perhaps in a few isolated cases. This belief is based on the observation of certain synchronous condensers under transient conditions and also on calculations of the type leading to curves shown in Figs. 24 and 25. These curves show how slight is the gain obtained in the case for which the calculations were made. Thus it appears that normally condensers should only be purchased on the basis of their function in supplying wattless kv-a. In other words, it is thought that in most cases the gain is not sufficient to justify them solely on the basis of their stabilizing effect. In cases where it is desired to in-

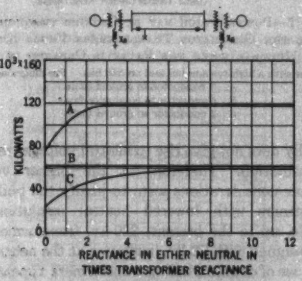



FIG. 6—POWER WHICH MAY BE CARRIED THROUGH FAULTS OUTSIDE THE GENERATOR TRANSFORMERS *Versus* REACTANCE IN EITHER NEUTRAL WHEN THE FAULT IS CLEARED IN 1.0 SEC.

Long lines with high-voltage busses and no mid-bus
*A* One conductor-to-ground fault
*B* Conductor-to-conductor fault
*C* Two conductor-to-ground fault

crease any stabilizing effect which they may accomplish this may be done advantageously by providing a balancing type of regulator and high ceiling exciters. When considering the use of condensers it is important to bear in mind that they may not and apparently usually do not increase the transient limit as much as the steady state limit.

(*e*) *Governors*

From a stability standpoint governors should operate quickly and should possess anti-hunting features tending to reduce swinging after disturbances. Governor operation in direct response to fault indication may prove desirable. Field tests as an aid in improvement of governor characteristics under transient conditions would be very desirable.

Automatic control of frequency is being tried on certain systems. To the extent that each system and each station hold very closely to the exact system frequency, the problem of tie-line loading should be simplified and a corresponding improvement in stability will result.

(*f*) *Transformers*

Present indications are that power transformer neutrals should be insulated sufficiently to permit the use of neutral reactors. The value of neutral reactance which satisfies the requirements previously mentioned

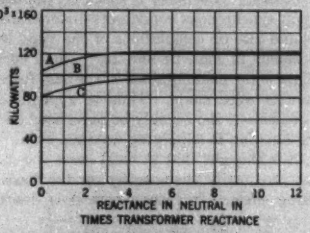



FIG. 7—POWER WHICH MAY BE CARRIED THROUGH FAULTS OUTSIDE THE GENERATOR TRANSFORMERS *Versus* REACTANCE IN THE NEUTRAL WHEN THE FAULT IS CLEARED IN 0.2 SEC.
Long lines with a high-tension bus and no mid bus. For diagrams see Fig. 6
*A* 1 conductor to ground fault
*B* Conductor to conductor fault
*C* 2 conductor to ground fault

generally does not give rise to neutral voltages requiring full insulation. Therefore at the higher voltages, economic considerations seem to justify the building of transformers with lowered neutral insulation. For example, up to the present, 220-kv. transformers have been designed with 73-kv. insulation at the neutral.

The use of double winding transformers appears to be an interesting possibility. In general a higher transformer reactance decreases the fault current and the shock to the generators and system, during the time the fault is on. On the other hand, when the faulty line is cleared, the synchronizing power between generator and system is reduced. The synchronizing power before the fault is also reduced resulting in a greater initial angle between the generator and system linkages behind transient reactance.

With a high-voltage bus arrangement there results a definite advantage in favor of low transformer reactance, from the standpoint of stability. On the other hand with a low voltage bus and split bus discussed later this advantage is less prominent and in fact a high reactance may be found advantageous in these cases. The question of the possible desirability of specifying low transformer reactance involves not only relative transformer costs and the effect on system stability but also the problem of increased circuit breaker duty. This question has not as yet been definitely evaluated and should be given further study.

(*g*) *Lightning Arresters*

The primary function of lightning arresters is to reduce the overvoltage surges to such values that they will not damage terminal apparatus and since their effect is relatively local the reduction in number of line outages attributable to lightning arresters placed only at the ends of the line is not great.

In two instances, lightning arresters have been installed at frequent intervals along the transmission line to prevent the flashover of insulators by lightning, with favorable results.

(*h*) *Loading Resistors*

It has been proposed* to load the generators upon occurrence of a fault by suddenly closing a low-tension switch connecting a three-phase resistor across the generator terminals. The switch would remain closed for a short time, say one-half second, and then open automatically. This would have the effect of reducing the shock to the generator during the time when the fault was on. By opening the switch at an appropriate time a considerable gain in power limit should be obtained in most cases.

(*i*) *Series Capacitors*

The use of series capacitors has been considered as a means for correcting for line reactance. As at

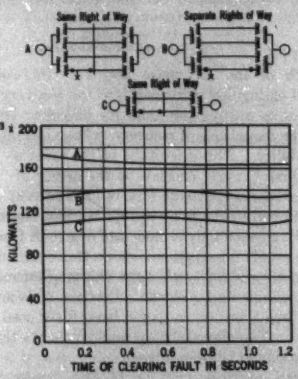



FIG. 8—POWER WHICH MAY BE CARRIED THROUGH ONE CONDUCTOR TO GROUND FAULT OUTSIDE GENERATOR TRANSFORMERS *Versus* SWITCHING TIME

present designed, capacitors are equipped with protective spark gaps and short circuiting switches in order to avoid excessive voltages during short circuit. On this account their value for transient stability would at first appear questionable. It may be shown, however, that this feature can be turned to advantage when a low voltage bus is used at either end of the line, provided the condensers are large enough so that the

*This device was suggested by one of our associates, Mr. W. F. Skeats.

protective gap can be so adjusted that a fault on one line does not short out the capacitors on the remaining line. In this case the capacitors on the affected line short out on the occurrence of a fault and thus increase the total reactance to the fault. The unaffected lines will retain their low reactance. This proposal has great promise but economic considerations will usually prevent its adoption at the present time.

(*f*) *Switches and Relays*

When the duration of short circuit is low, the impulse given to machine rotors is small, and hence stability is

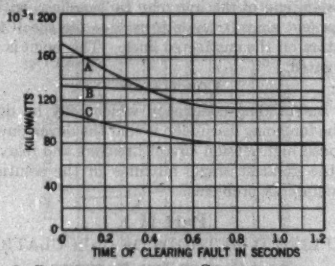



FIG. 9—POWER WHICH MAY BE CARRIED THROUGH A TWO CONDUCTOR TO GROUND FAULT OUTSIDE GENERATOR TRANSFORMER

For conditions see diagrams *A*, *B*, and *C*. Fig. 8

improved. From this standpoint, therefore, high speed in both relays and circuit breakers is very desirable.

TABLE I

| Time of clearing fault in seconds | Power which may be carried through a two-conductor-to-ground fault |
|---|---|
| 0.0 | 100 per cent |
| 0.1 | 83 per cent |
| 0.2 | 68 per cent |
| 0.3 | 56 per cent |
| 0.5 | 42 per cent |
| 0.75 | 33 per cent |

Table I shows the average reduction in power limit over transmission systems involving waterwheel generating capacity due to delayed switching,* with power limit at zero switching time as reference, for two-conductor-to-ground faults.

## LINES

(*a*) *Over Insulation of Lines*

The tendency has been to increase the insulation on lines. For example, the 220-kv. lines of the Southern California Edison Co. were insulated originally with 11 disks. Later, when the 220-kv. lines were built for the Philadelphia Electric Co. Conowingo development, 14 disks were used and lines are now being planned involving the use of 18 disks. It appears that by the use of a suitable number of disks, it should be possible to eliminate arc-overs due to voltages induced by near-by strokes of lightning, but even with ground wires, the possibility of entirely eliminating arc-overs due to direct strokes is questionable.

(*b*) *Ground Wires*

The beneficial effect of ground wires[8] is to lower the voltage induced by lightning in the vicinity. They also are thought to lower the probability of direct strokes on the line wire, but not necessarily to prevent their occurrence. Ground wires are also beneficial in that they attenuate the traveling waves which result from lightning or other causes. Low resistance ground wires lower the zero phase sequence impedance and thus make one-conductor and two-conductor-to-ground faults more severe if sufficient neutral impedance is not used. In addition, the tower footing resistance is equalized and results in a more uniform ground current for relaying. Excessive potential gradients at the tower footings are also reduced by distributing the ground current through several towers.

(*c*) *Horizontal versus Vertical Spacing*

With horizontal spacing there generally results a lower total number of faults due to lightning than with

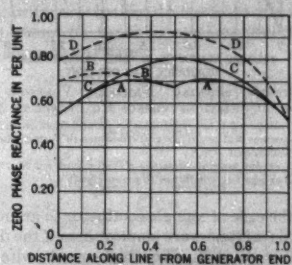



FIG. 10—ZERO PHASE SEQUENCE REACTANCE VIEWED FROM THE POINT OF FAULT VERSUS POSITION OF FAULT FOR SYSTEMS SHOWN IN DIAGRAMS A, B, C, AND D. FIG. 4

Calculations based on

*A-A* High-tension bus and mid bus
*B-B* High-tension bus and no mid bus
*C-C* Lwo-tension bus and mid bus
*D-D* Low-tension bus and no mid bus
NOTE: *D-D* becomes *A-A* at mid bus

vertical spacing. On the other hand, with horizontal spacing most of the faults appear to involve two conductors and ground while with vertical spacing most of the faults involve only one conductor and ground. There is some question as to which of these arrangements results in the lower number of the more severe two-conductor-to-ground type of fault. Field data would be of value in this connection.

(*d*) *Power Arc Suppression Devices*

The use of Petersen coils and lightning arresters in this connection has already been referred to above.

*For high voltage bus arrangement.

The extinction of the power arc following an insulator flashover by means of a fuse at the insulator, rather than by tripping the line, has been tried with some success.

### System Connections

(a) *High-Voltage Bus**

The use of a high-tension bus either at the generator or system end of the line or as a mid bus results in a maximum shock during the occurrence of a fault, but a minimum reduction in synchronizing power after the faulted line has been cleared. If the shock is already small as in the case of a single conductor to ground fault when neutral reactances are employed, or if the duration of the fault is short as when high-speed switches are used, this is a desirable arrangement from a stability standpoint. If these conditions do not exist this type of arrangement may prove unsatisfactory.

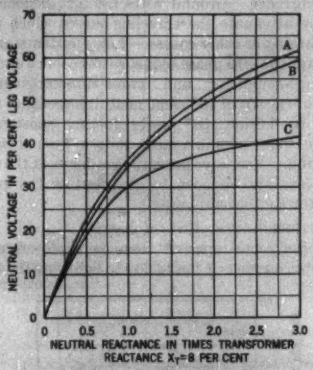



Fig. 11—Curves showing Neutral Voltages under Ground Fault Conditions versus Reactance in Neutral

*A* Neutral voltage with one conductor to ground fault on the high-tension bus at the system end *versus* neutral reactance of system end; neutral reactance of generator end $= 3\ X_T$

*B* Same as *A* except neutral reactance of system end $= 2\ X_T$

*C* Same as *B* except two conductor to ground fault

(b) *Low-Voltage Bus**

A low-tension bus has the advantage over a high-tension bus that the reactance to the fault is increased. On the other hand, when the fault clears the synchronizing power is less than with a high-voltage bus. If there are several lines, say four or more, the low-voltage bus is very advantageous. A further advantage is that high speed switching is not required, provided the faults do not involve more than one conductor.

For long distance transmission this arrangement will usually be uneconomical, but for transmission over relatively short distances it offers great promise. The curves in Fig. 2 show the indicated results with this arrangement.

*Figs. 4 and 5 show the comparison between high- and low-voltage buses.

(c) *Split Bus*

Another solution is to use a low-voltage bus at the system end of the line and to split the lines at the generator end, putting part of the generating capacity on each bus.[5, 6, 7] When this is done it is usually possible for the generators on any one line to ride through the disturbance occasioned by a fault on another. However, for long distance transmission lines even with this arrangement a higher speed of switching than has heretofore been commonly available in the higher voltage switches will be required to insure stability.

It seems possible that high transformer reactance at the system end of the line may be beneficial with this arrangement since it tends to reduce the shock to the generators on the unaffected lines. This point is being investigated.

### Conclusion

One outstanding conclusion which may be derived from the foregoing discussion is that the development of high-speed high-tension circuit breakers and relays will mark the greatest single advance in the solution of present stability problems.

## Part II

## SIMPLIFIED METHODS OF CALCULATION

### Ideal Case of Two Machines

This case neglects governors, damping, decrements, and resistance and has been thoroughly discussed in a previous paper.[1] Appendix VIII of the present paper supplements the previous paper by the addition of more extensive charts for the determination of angular position at any instant after a disturbance and of charts to facilitate the calculation of power limit with quick switching.

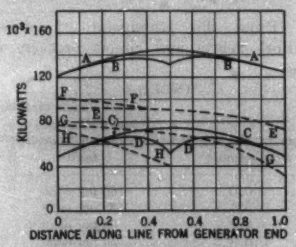



Fig. 12—Power which may be Carried through a Fault with one Second Switching Time

| | |
|---|---|
| *A–A* 1 C G fault, no mid bus | High-tension switching |
| *B–B* 1 C G fault, mid bus | High-tension switching |
| *C–C* 2 C G fault, no mid bus | High-tension switching |
| *D–D* 2 C G fault, mid bus | High-tension switching |
| *E–E* 1 C G fault, no mid bus | Inst. low-tension switching |
| *F–F* 1 C G fault, mid bus | Inst. low-tension switching |
| *G–G* 2 C G fault, no mid bus | Inst. low-tension switching |
| *H–H* 2 C G fault, no mid bus | Inst. low-tension switching |

Note: *F–F* and *H–H* extend only to mid bus, with fault beyond this point, the low-tension switches at generator end are unable to discriminate

The new angle-time curves were obtained on the Integraph at Massachusetts Institute of Technology.

### Ideal Case of Two Machines Including the Effect of Resistance

Methods which previously were confined to the solution of ideal cases have been extended to apply to circuits with resistance. This case is discussed in Appendix II.

### General Case of Two Machines

This case considers the factors neglected in the ideal case. The method of calculation has been discussed before.[1]

### More than Two Machines

The general method of calculation is discussed in general in the same paper referred to above. A specific

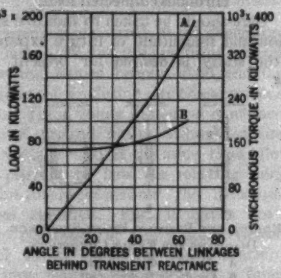



Fig. 13—Auxiliary Curves used in the Transient Stability Investigation of the System shown in Fig. 4

*A* Load on 120,000-kv-a. generating station *versus* angle between linkages behind transient reactances

*B* Maximum torque which would be exerted by excitations corresponding to the steady-state angle of the linkages behind transient reactance

example involving three machines is explained and treated in greater detail in Appendix IV.

### Circuit Diagrams

There are in general four diagrams which are required to permit the full calculation of stability according to present methods. There are:

Synchronous positive phase sequence impedance diagram.

Transient positive phase sequence impedance diagram.

Negative phase sequence impedance diagram.

Zero phase sequence impedance diagram.

The construction of these diagrams is thoroughly described in previous articles.[1, 19] It is important to note that separate diagrams must be made for transient and synchronous impedance even though these are both positive phase sequence impedances. The synchronous impedance can be used in conjunction with the negative and zero phase sequence impedances in a steady state analysis. In a transient analysis the transient positive phase sequence impedance replaces the synchronous, and is also used in conjunction with the negative and zero phase sequence impedances during unbalanced conditions.

### Equivalent Impedance of Open Lines

If one circuit of a three-phase line, connecting two balanced three-phase systems or parts of one system, is opened, the effect is to decrease the positive phase sequence currents. It may be shown that the effect on the positive phase sequence diagram is the same as the insertion of a balanced three-phase impedance equal to the paralleled value of the zero and negative impedances which would be met by a series voltage of the corresponding phase sequence inserted at the point where the circuit is interrupted. Were two lines opened the equivalent series impedance to be inserted would be the series value of the negative and zero phase sequence impedances.

For example, if one phase of one circuit were opened in Fig. 14A the effect from the standpoint of the positive phase sequence impedance would be as shown in Fig. 14B. The negative and zero phase sequence impedance diagrams as met by a series voltage at the point of fault are shown in Figs. 14C and 14D.

In case resistance is considered the same procedure would apply.

### Equivalent Impedance of Fault

It has been shown[1, 28] that single-phase faults may be represented by the equivalent three-phase fault of the appropriate kind. In Fig. 15 is shown the equivalent fault impedance for the three common faults which are liable to occur on a system.

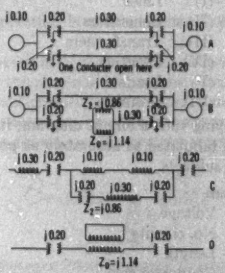



Fig. 14—Equivalent positive Phase Sequence Impedance Diagrams for a Circuit with One Conductor Open

Note: Zero phase sequence impedance of one line assumed equal to three times the positive; the mutual between two lines assumed one-half of this

These results can be obtained from the preceding by regarding a one-conductor-to-ground fault as a three-phase fault with two conductors open, a line-to-line fault as a three-phase fault with one conductor open and no neutral connection, and a two-conductor-to-ground fault as a three-phase fault with one conductor open.

### Choice of Equivalent Machine to Represent a System

Ordinarily a system, if closely linked together, will be represented by a single machine. The four impedances of this machine should be determined

separately on the calculating table using the four corresponding equivalent circuits representing the system, mentioned above.

The inertia constant of the equivalent machine is the sum of the inertia constants of all the machines in the system expressed in terms of a common base power.

When the resistances involved are not too large the d-c. calculating table may be used to advantage in obtaining the reactances of the equivalent machine. This method is discussed in detail in an article by Mr. A. P. Mackerras.[19] In case the resistance is appreciable an a-c. calculating table is essential.

### Zero Phase Sequence Reactances

The zero phase sequence reactance diagram is often more difficult to evaluate because of mutual reactances between lines and between windings in transformers and generators. Special attention has been given to this and formulas are presented in Appendices IV and V.

### Essential Data for a Stability Study

It is considered essential to have the following information submitted, before attempting to make a stability study on a power system.

(a) A single line *circuit diagram* of the system under consideration as well as of adjacent systems which may be connected, giving
  1. Location of, and
  2. Electrical arrangement of
     (I) Lines
     (II) Generators
     (III) Transformers
     (IV) Reactors
     (V) Loads
     (VI) Grounds

Accompanying such a circuit diagram, it is desirable to have data tabulated as accurately as possible under the following subjects.

(b) Lines
  1. Voltage
  2. No. circuits
  3. Length
  4. Conductor size
  5. Number of ground wires and material

(c) Synchronous Machines
  1. Type
     (I) Turbo generators
     (II) Waterwheel generators
     (III) Frequency sets
     (IV) Condensers
  2. Kv-a. capacity of each
  3. Rev. per min.
  4. Short circuit ratio
  5. Type of excitation
     (I) Self excited
     (II) Separately excited
     (III) Main field rheostat
  6. Type of regulator

(d) Transformers
  1. Type
     (I) Two-windings tep-up
     (II) Three-winding transformers
     (III) Auto transformers
     (IV) Y-Y; Y-Delta, etc.
  2. Kv-a. capacity of each
  3. Reactances
  4. Ground points
  5. Neutral impedances

(e) Loads
  1. Kilowatts from each bus
  2. Power factor
  3. Per cent resistance, induction, and synchronous connected load.

Note: Care should be taken to indicate specifically the location and magnitude of future expansions and whether the study is desired for present or future conditions.

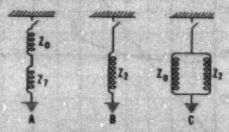



Fig. 15—Equivalent Positive Phase-Sequence Impedance Diagrams for Fault Conditions

*A* Single conductor to ground
*B* Conductor to conductor
*C* Two conductor to ground

### Acknowledgment

The authors gratefully wish to acknowledge the contributions to this article by Mr. R. H. Park. They also wish to thank Miss Edith Clarke and Messrs. E. M. Hunter and Myron Zucker for their assistance in the preparation of the paper.

## Appendix I

### Specific Example

An endeavor has been made to investigate the effects of various bus and apparatus arrangements in a typical transmission system which is required to withstand shocks ensuing from major switching operations and fault conditions.

In Fig. 16 is shown the simplified diagram of such a typical generating station delivering power over high-voltage transmission lines to a large interconnected system which is represented as an equivalent motor. The generating station is assumed to consist entirely of waterwheel generators. The power is to be transmitted over 154-kv. lines. where two circuits are considered and over 110-kv. lines where four circuits are considered. These ratios of voltages and number of circuits are chosen in order that the maximum steady state powers under normal conditions may be equal. The curves in Part I show the results found in this particular study.

*Constants of the Systems.* The generating capacity is assumed to be 120,000 kv-a. and this value is used as

a kv-a. base throughout. Reactances are given in per unit, and inertia constants in seconds. The synchronous, transient, and negative reactances of the generators are assumed to be 0.48,* 0.24, and 0.23 per unit respectively; and the inertia constant, 7.5 seconds. The corresponding constants for the equivalent motor at the receiving end are 0.14 and 0.115 per unit reactance and 105 seconds. The step-up transformers at the generator end have a reactance of 0.08 per unit and the step-down transformers at the receiving end a reactance of 0.10 per unit. The 154-kv. circuits have a reactance of 0.52 per unit each and the 110-kv. circuits 1.04 per unit each. These values are sufficiently large to correspond to long distance transmission and where short lines are considered these values are reduced to 0.19 and 0.38 respectively.

The transformer neutrals at the generator and receiving end have 0.22 and 0.20 per unit reactance respectively which values become 0.66 and 0.60 per unit reactance in the single line zero phase sequence reactance diagram. These values of neutral reactance reduce the severity of ground faults without causing excessive neutral voltages and at the same time allow sufficient ground current to flow for relaying purposes; they are maintained throughout the investigation unless otherwise specified. Fig. 10 gives the zero phase sequence reactance of the system viewed from the point of fault, including lines, transformers, and transformer neutral reactances as a function of the position of fault for two typical bus arrangements. These values were obtained from formulas given in Appendix V -(b)

*Assumptions and Methods of Calculation*

The following assumptions are made to simplify and expedite the calculations.

(a) Resistance and capacitance are neglected.
(b) Reactances in the direct and quadrature axes are assumed to be alike.
(c) Normal voltage is maintained under steady state conditions on the high-tension side of transformers at the generator end.
(d) The power factor at this point is normally 0.98 lag.
(e) Linkages behind transient reactance of the generator and motor remain constant during the first swing.
(f) No damping torques are considered.
(g) Results are based on the first swing only.
(h) Faults are considered only on the high-tension side of the transformers at the generator end unless otherwise specified.
(i) Constant shaft torque, governor action, and load speed characteristics, neglected.
(j) With one exception, the two breakers necessary to clear the fault, whether high tension or low tension, operate simultaneously.

*Allowing for saturation.

The breakers which must open to clear the fault are shown in black on the respective diagrams. The exception referred to is seen in diagrams *B* and *D* (Fig. 4), where the low tension breakers are assumed to open instantly on the occurrence of a fault. The fault was finally cleared in this case by the opening of the high-tension breaker marked black. The time of this

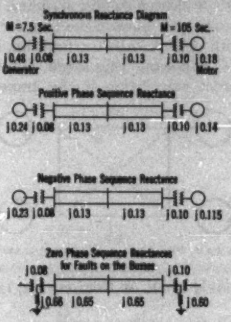



FIG. 16—DIAGRAM SHOWING DISTRIBUTION OF REACTANCES IN A SAMPLE SYSTEM WHICH HAS BEEN USED TO DEMONSTRATE THE EFFECT OF BUS ARRANGEMENTS. WHEN LOW-TENSION BUS ARRANGEMENTS ARE CONSIDERED, THE REACTANCES ARE SIMILAR

Reactance base 120,000 kv-a., 154 kv.
Generator capacity 120,000 kv-a.

breaker operation is the independent variable in this case.

*Brief Review of Methods of Calculations.* In order to determine the power which may be transferred through a fault condition with zero switching time two constants only are necessary, *viz.*, the transfer reactance under normal conditions and the transfer reactance when the

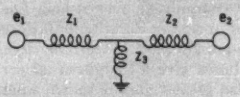



FIG. 17—POSITIVE PHASE-SEQUENCE DIAGRAM USED IN DEMONSTRATING PRINCIPLE OF SUPERPOSITION IN APPENDIX III

fault has been cleared. From the ratio of these two reactances the initial angle at which the machines can operate with stability, is determined. Curve *A*, Fig. 13, gives the load on the generator as a function of the initial angle and Curve *B* gives the maximum torque which would be exerted as a function of the initial angle.

In a similar way the power which may be carried through the first swing of the machines, with a fault which remains on the system, is obtained from the ratio of the transfer reactance under normal conditions to the transfer reactance with the fault on. From this ratio the initial angle of the machines for stable operation is determined and the corresponding load is found from

Curve *A*, Fig. 13. These two values give two points on curves showing power which may be passed through a fault *versus* switching time. Generally no gain is obtained with switching times of 0.75 second or 1.0 second.

Intermediate points on the curves are obtained by assuming an initial load and finding the angle at which the fault must be cleared to give stability. To find this angle it is necessary to know three transfer impedances: before the fault occurs, with the fault on, and with the fault cleared. Knowing this angle, time is obtained either by direct calculation if the travel along this

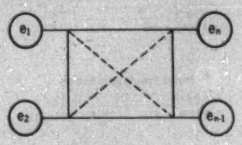



Fig. 18—Diagram Showing a Representative Network

curve is relatively small, or from curves, (see Appendix VIII).

## Discussion of Curves

(a) The interesting feature shown in the curves of Fig. 2 is that for switching times of the order of 0.75 second, multiple circuit lines with low-tension buses show a decided gain over two circuit lines with high-tension buses. If high-tension buses are used, however, switching times of 0.1 second or less must be obtained to produce stability comparable with that obtained using low-tension buses.

A slight additional advantage would be shown for multiple circuit lines were the transformer capacity per circuit increased by one-third, so as to allow full load to be transmitted over three circuits.

Referring to Fig. 3 it is seen that full load of 120,000 kw. may be transmitted over a long line with high-tension buses and fault duration of 0.75 second with a conductor-to-ground fault. Multiple circuit lines with low-tension buses give a margin of 20 per cent above this and a still greater gain is shown when short lines are considered.

It would thus seem desirable to employ multiple circuit lines with low-voltage buses where the transmission distance is sufficiently short to justify their use economically.

(b) Fig. 4 shows that with fault durations of 0.75 second or greater only 50,000 kw. can be carried through a two-conductor-to-ground fault with high-tension buses throughout. Introducing low-tension buses at one end gives an increase over this of approximately 50 per cent. For fault durations as long as this a mid bus shows no advantage. However, as the fault duration is decreased a mid bus shows an increasing gain because only half a line is switched out to clear the fault. Finally, for very fast switching, a high-tension bus with a mid bus is desirable. This is because the fault is not left on the system long enough to cause much disturbance and when it is cleared, all the transformer capacity is operative and only one section of line is out. Similar curves are shown in Fig. 5 for a single-conductor-to-ground fault. These show a margin of 10 per cent in favor of a mid bus with a low tension bus arrangement at one end.

The effect of a low tension bus at the system end was not investigated. However, it is evident that with only two circuits the use of high-speed switches together with high-voltage buses is essential if a power limit approaching the full generator capacity is desired.

(c) In Fig. 6 it is seen that only relatively small amounts of power can be passed over a solidly grounded system under either a two-conductor-to-ground or one-conductor-to-ground fault condition with fault durations of 1.0 second. If reactance is added to the neutrals an appreciable gain is obtained. When 3 times the transformer reactance has been added to either neutral the increase in power for a two-conductor-to-ground fault is 70 per cent (for a single-conductor-to-ground fault practically 100 per cent) of the gain which could be obtained by completely isolating the neutrals.

Somewhere between two and three times transformer reactance seems to be the desirable limit of neutral reactance, considering telephone interference problems, relaying, and neutral voltages. These values give practically all the gain for stability purposes that would be obtained by isolating the neutrals.

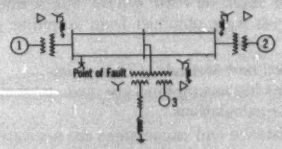



Fig. 19—System Set-up From Which Swing Curve On Fig. 24 was Calculated

For impedance see Fig. 20

With three times the transformer reactance in the neutrals and 1.0 second switching time, only 50,000 kw. can be carried through a double-conductor-to-ground and 62,000 kw. through a single-conductor-to-ground fault. From Fig. 7 these values are increased to 94,000 and 100,000 when the fault duration is reduced to 0.2 second. These are gains of 47 and 38 per cent, respectively. The gain due to fast switching is even greater with solid neutrals.

(d) Fig. 1 shows that for 1.0 second switching a slight gain is indicated when the generator transient reactance is reduced.

(e) Fig. 11 shows the increase in neutral voltages during ground fault conditions, as the neutral reactance is increased. Curve *C* is for a two-conductor-to-ground fault and it is seen that the neutral voltage is less in this case than for a single-conductor-to-ground fault. This will always be the case if $Z_1 \leqq \sqrt{Z_1 Z_0}$ at

the fault; a condition which usually obtains. The subscripts refer respectively to negative, positive, and zero phase sequence.

Approximately 60 per cent normal leg voltage is obtained with three times the transformer reactance in the neutrals in this example.

In the investigation of multiple circuit lines it is well to bear in mind that building each line on a separate right of way would substantially decrease the probability of simultaneous outage of two circuits due to lightning disturbances. If neutral reactors were not employed this isolation of circuits would increase the

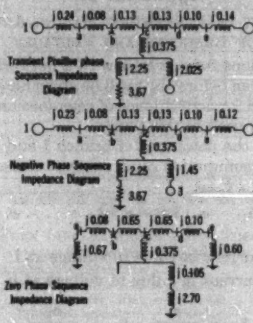



FIG. 20—EQUIVALENT IMPEDANCE DIAGRAMS FOR THE SYSTEM SHOWN ON FIG. 19 WITHOUT FAULT

severity of faults near buses since the zero phase sequence reactance is less.

Throughout this discussion the beneficial effect of high-speed switching has been more and more apparent. The curves all tell the same story, namely that one of the largest items affecting improvement in system stability is probably the introduction of high-speed, high-tension circuit breakers with high-speed relays.

## Appendix II

### EQUAL AREA METHOD OF CALCULATING STABILITY WHEN RESISTANCE IS INVOLVED

The equal area method has been extensively used for calculating the stability of a generator feeding a synchronous load over a line of negligible resistance.[1]

However, the same general method may be used when line resistance is included, and when there is impedance as well as synchronous load.

Specifically, the driving point and transfer impedances are found as explained in Appendix III. This method supplants the methods previously used where the impedances of the load at each end of the line were combined with that of the machines.

The torque angle curves for each equivalent machine may then be found. (For salient pole machines, formulas (52) and (25) of Doherty and Nickle's *Synchronous Machines II* are available.)

The differential equations of motion are

$$M_1' \, p^2 \, \delta_1 = f_1 \, (\delta_1 - \delta_2) \qquad (1)$$

$$M_2' \, p^2 \, \delta_2 = f_2 \, (\delta_1 - \delta_2) \qquad (2)$$

where

$M_1$ = inertia constant of machine 1 in seconds

$M_1' = \dfrac{M_1}{2 \, \pi \, f}$ and $f$ = normal frequency.

$f_1 \, (\delta_1 - \delta_2)$ = synchronizing power of machine 1 also

$M_2'$ and $f_2 \, (\delta_1 - \delta_2)$ are similar quantities for machine 2.

Then there is

$$p^2 \, \delta = \frac{f_1 \, (\delta)}{M_1'} - \frac{f_2 \, (\delta)}{M_2'} \qquad (3)$$

where

$$\delta = \delta_1 - \delta_2$$

$$p = \frac{d}{d \, t}$$

That is, the acceleration of $\delta$ is proportional to

$$\frac{f_1 \, (\delta)}{M_1'} - \frac{f_2 \, (\delta)}{M_2'} \qquad (4)$$

consequently, the rate of change of $\delta$ will be zero if

$$\int_{\delta_0}^{\delta} \left[ \frac{f_1 \, (u)}{M_1'} - \frac{f_2 \, (u)}{M_2'} \right] d \, u = 0 \qquad (5)$$

which is the equal area criterion of stability that is sought and was derived by Mr. R. H. Park. This

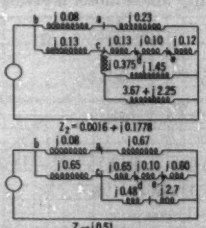



FIG. 21—NEGATIVE AND ZERO PHASE-SEQUENCE IMPEDANCE DIAGRAMS AS VIEWED FROM POINT OF FAULT SHOWN ON FIG. 19 ASSUMING A TWO-CONDUCTOR TO GROUND FAULT, THE THREE-PHASE FAULT

$$\text{Impedance is } Z_F = \frac{Z_0 \, Z_2}{Z_0 + Z_2} = 0.0010 + j \, 0.1318$$

method is general and may be employed to determine stability either when the fault remains on indefinitely or when it is cleared at some definite time. If switching is involved the functions $f_1$ and $f_2$ will of course change discontinuously during the process of integration.

In the following a detailed formula is developed*

*This formula was developed by Mr. M. Zucker.

which applies to the particular case of two synchronous machines with either long delayed or instantaneous switching. The equal area criterion that has been established is equivalent to the statement that the machines have come to rest with respect to each other before the acceleration becomes finally zero. In order to find $\delta_f$ (the angle for zero acceleration) we have, referring to Appendix III and to Appendix IV, paragraphs 6 and 7 for definition of terms.

$$\frac{T_1 - T_{11} - K_{12} \sin(\delta_f - \alpha)}{M_1'} = \frac{T_2 - T_{22} + K_{12} \sin(\delta_f + \alpha)}{M_2'} \tag{6}$$

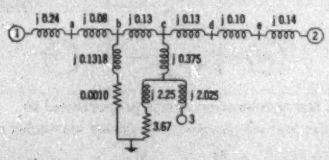



FIG. 22—EQUIVALENT POSITIVE PHASE-SEQUENCE IMPEDANCE NETWORK FOR SYSTEM SHOWN ON FIG. 19 WITH TWO-CONDUCTOR-TO-GROUND FAULT

where

$T_1$ is torque acting on generator from prime mover

$T_2$ is torque acting on motor from load (this is a negative quantity unless motor is acting as a generator).

Let $$\frac{M_2'}{M_1'} = R$$

This reduces to

$$\frac{R(T_1 - T_{11}) - T_2 + T_{22}}{K_{12}} = (R+1)(\cos\alpha \sin\delta_f) - (R-1)(\sin\alpha \cos\delta_f) \tag{7}$$

Let $$(R-1)\sin\alpha = m$$
$$(R+1)\cos\alpha = n$$
$$\frac{R(T_1 - T_{11}) + T_{22} - T_2}{K_{12}} = F$$

Then $$F = n \sin\delta_f - m \cos\delta_f \tag{8}$$

which can be solved as

$$\sin\delta_f = \frac{nF + m\sqrt{m^2 + n^2 - F^2}}{m^2 + n^2} \tag{9}$$

This determines the limiting angle. The area sought is

$$A = \frac{1}{M_1'} \int_{\delta_0}^{\delta_f} \left[ T_1 - T_{11} - K_{12} \sin(\delta - \alpha) \right] d\delta - \frac{1}{M_2'} \int_{\delta_0}^{\delta_f} \left[ T_2 - T_{22} + K_{12} \sin(\delta + \alpha) \right] d\delta \tag{10}$$

which becomes

$$\frac{M_2'}{K_{12}} A = \frac{\pi F}{180} (\delta_f - \delta_o) + m(\sin\delta_f - \sin\delta_o) + n(\cos\delta_f - \cos\delta_o) \tag{11}$$

when angles are expressed in degrees.

Thus the criterion for stability is that

$$\frac{\pi F}{180}(\delta_f - \delta_o) + m(\sin\delta_f - \sin\delta_o) + n(\cos\delta_f - \cos\delta_o) \gtrless 0 \tag{12}$$

## Appendix III

### POWER FLOW IN A NETWORK HAVING ANY NUMBER OF BRANCHES AND VOLTAGES

The equations for power flow in a network (Fig. 18) have been given before[22] but will be given here in slightly different form for convenience of reference and to define certain terms used in this paper.

Let $P_{1E}$ be the power out of branch 1 and

$\mathbf{I}_1$ be the summation of all currents out of branch 1.

$$P_{1E} = \mathbf{e}_1 \cdot \mathbf{I}_1 \text{ or} \tag{13}$$

$$P_{1E} = \mathbf{e}_1 \cdot \mathbf{i}_{11} - \mathbf{e}_1 \cdot \mathbf{i}_{21} - \mathbf{e}_1 \cdot \mathbf{i}_{31} - \ldots \mathbf{e}_1 \cdot \mathbf{i}_{n1} \tag{14}$$

where

$\mathbf{i}_{11}$ is current in 1 due to voltage at 1.

$\mathbf{i}_{n1}$ is current in 1 due to voltage at $n$

$$\mathbf{i}_{11} = \frac{\mathbf{e}_1}{\mathbf{Z}_{11}} \quad \mathbf{i}_{n1} = \frac{\mathbf{e}_n}{\mathbf{Z}_{n1}} \tag{15}$$

$$P_{1E} = \mathbf{e}_1 \cdot \frac{\mathbf{e}_1}{\mathbf{Z}_{11}} - \mathbf{e}_1 \cdot \frac{\mathbf{e}_2}{\mathbf{Z}_{21}} - \ldots \mathbf{e}_1 \cdot \frac{\mathbf{e}_n}{\mathbf{Z}_{n1}} \tag{16}$$

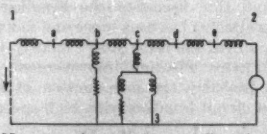



FIG. 23—NETWORK ARRANGEMENT OF FIG. 22, TO MEASURE TRANSFER IMPEDANCE BETWEEN 1 AND 2 AND DRIVING POINT IMPEDANCE AT 2

Going to scalars, since $Z_{1n} = Z_{n1}$ and $\theta_{1n} = \theta_{n1}$

$$P_{1E} = \frac{E_1^2}{Z_{11}} \cos\theta_{11} - \frac{E_1 E_2}{Z_{12}} \cos(\delta_{12} + \theta_{12}) \ldots\ldots - \frac{E_1 E_n}{Z_{1n}} \cos(\delta_{1n} + \theta_{1n}) \tag{17}$$

where $\theta_{1n}$ is angle of $\mathbf{Z}_{1n}$

$\delta_n$ is angle of $\mathbf{e}_n$

$\delta_{1n} = \delta_1 - \delta_n$

and $\mathbf{Z}_{11}$ is the driving point impedance at 1 and $\mathbf{Z}_{12}$ is the transfer impedance between 1 and 2

Write $\theta_{1n} = 90° - \alpha_{1n}$

or $\alpha = 90° -$ power factor angle

Then (17) may be rewritten in the alternative form

$$P_{1R} = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \ldots\ldots$$

$$\ldots\ldots\ldots + \frac{E_1 E_n}{Z_{1n}} \sin (\delta_{1n} - \alpha_{1n}) \qquad (18)$$

which is often found more convenient

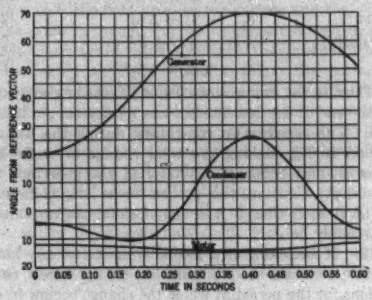



FIG. 24—FLUX LINKAGE ANGLE *Versus* TIME FOR A TWO-CONDUCTOR FAULT AT GENERATOR END OF LINE. RESISTANCE LOAD AND CONDENSER AT MID BUS

Initial generator load = 95,000 kw
Initial motor load = 70,000 kw.
Initial condenser load = 25,000 kv-a.
Initial shunt load = 25,000 kw.

Example:—See Fig. 17

$$P_{1R} = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \qquad (19)$$

where $$Z_{11} = Z_1 + \frac{Z_2 Z_3}{Z_2 + Z_3}$$

$$Z_{12} = \frac{Z_1 Z_2 + Z_1 Z_3 + Z_2 Z_3}{Z_3}$$

## Appendix IV

### SAMPLE SWING CURVE CALCULATION

Assuming that the original circuit has been resolved into one that properly represents the actual conditions, the steps in calculating a swing curve may be outlined as follows:

1. Draw the positive, negative, and zero-phase sequence impedance diagrams. Fig. 20 shows the component diagrams corresponding to the simplified circuit of Fig. 19.

2. Find the negative and zero-phase sequence driving point impedances at the point of fault and determine the equivalent impedance of the fault. These are illustrated in Fig. 21.

3. Draw the diagram of the system for fault conditions. This is illustrated in Fig. 22 which corresponds to a two-conductor-to-ground fault.

4. From initial load conditions, find the magnitude and phase angle of the vectors representing machine linkages, which are represented by voltages behind transient reactance (Table III gives values for numerical example). In this example unit voltage was held at points *b*, *c*, and Fig. 20,—point *c* being considered the reference vector.

5. Find the "angular acceleration constant"

$$k = \frac{360 f (\Delta t)^2}{M} \qquad (20)$$

where

$f$ is normal frequency
$\Delta t$ is time interval selected
$M$ is inertia constant

for each machine. A time interval of 1/20 of a second is recommended for most cases. Values for these are shown in the table.

6. Calculate driving point and transfer impedances (only the latter need be found if there is no resistance). Referring to Fig. 23, $Z_{11}$ is the driving point impedance measuring the voltage at 1 when unit current flows there. $Z_{12}$ is the transfer impedance measuring the voltage at 1 causing unit current to flow at 2, all other voltages being zero.

7. Find the power as the transient begins, by adding the components for each machine. The driving point power output is

$$P_{11} = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} \qquad (21)$$

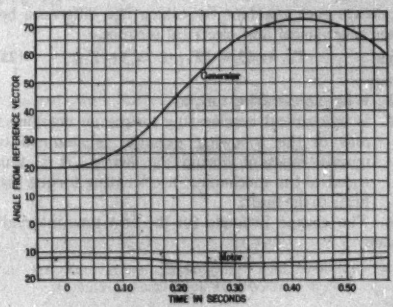



FIG. 25—FLUX LINKAGE ANGLE *Versus* TIME FOR A TWO LINE TO GROUND FAULT AT THE GENERATOR END OF LINE. RESISTANCE LOAD AT MID BUS

Initial generator load = 95,000 kw.
Initial motor load = 70,000 kw.
Initial shunt load = 25,000 kw.

(If there is no resistance this term becomes zero.) The transfer power component indicating power flowing at 1 toward 2 is

$$P_{12} = \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \qquad (22)$$

In case normal regulators are acting we may assume the linkages to remain constant over the period of the swing. Then $\frac{E_1 E_2}{Z_{12}}$ is constant. This assumption is not essential but should be made where justifiable, as it greatly simplifies the calculations. In this case we may define $K_{11} = \frac{E_1^2}{Z_{11}}$, $K_{12} = \frac{E_1 E_2}{Z_{12}}$ etc.

Considered as per unit values it is convenient to note that these expressions for power may be taken as torque by writing $T$ instead of $P$.

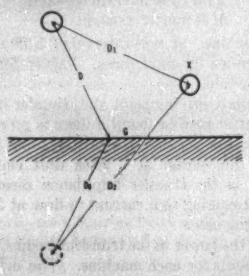



Fig. 26—Diagram for Illustrating the Formula for Flux Linkages at X with a Transmission Line Conductor and its Assumed Image

8. Find the torque available to accelerate or decelerate each machine by taking the difference between mechanical and electrical torques.

Thus $$T_{a1} = T_1 - (T_{11} + T_{12} + T_{13}) \qquad (23)$$

Where

$T_{a1}$ is net accelerating torque

$T_1$ is mechanical accelerating torque on machine 1 and in the following example is assumed to remain constant during the swing. It is thus equal to the mechanical accelerating torque just prior to the fault.

9. The change in angle for the first time interval* is then

$$\Delta \delta_1 = \frac{k T_a}{2}$$

for each machine, where the subscripts from here on, to and including Equation (27), refer to the instant at the end of the successive time intervals instead of to the particular machines. This should result in values of the order of 1 to 2 degrees for the machines that move most. (In the example, for instance, this term is 1.7° for 1 and 1.1° for 3.) If considerably greater values are obtained, it indicates that the time interval chosen is too great.

10. The change in angle for the first period should be added, with due regard to sign, to the initial angle. This gives the angle between machines at the end of the first period. That is

$$\delta_1 = \delta_o + \Delta \delta_1$$

11. Repeat the process of finding torques for the second period. Find the change in angle, during the second period as:

$$\Delta \delta_2 = \Delta \delta_1 + k T_1 \qquad (24)$$

Then: $$\delta_2 = \delta_1 + \Delta \delta_2 \qquad (25)$$

similarly $$\Delta \delta_3 = \Delta \delta_2 + k T_2 \qquad (26)$$

$$\delta_3 = \delta_2 + \Delta \delta_3 \text{ etc.} \qquad (27)$$

Thus, in the example, see Table IV, the angle change at the end of the first interval was 1.7 degrees per interval. The acceleration component during the second period is 3.2, making the total change in angle 4.9 degrees, and bringing the angle of the generator to 26.6 deg. Continue this process for as long as desired or until such time as the assumptions can no longer reasonably hold.

12. If switching or a second transient of any kind occurs, compute the $T$'s under the first transient conditions for the period at which the change occurs (*i. e.*, $T_{a1}$ for 0.2 second would be 0.277 if nothing changed in the example). Then compute the $T$'s for the same period under the new conditions ($T_{a1}$ for 0.2 second would be − 0.274 if the new conditions held throughout the period).

Average them (0.0016) and, using this for the $T$, proceed as before. The curve has been plotted in Fig. 24. A similar calculation, made for the case with the condenser omitted, led to the curve of Fig. 25.

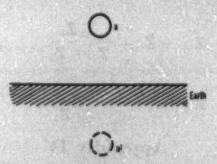



Fig. 27—Equivalent Conductor Arrangement of a Single-Circuit Line

## Appendix V

### Zero Phase Sequence Impedance of Lines with Connected Apparatus

#### Part A Theoretical Basis

In order to find the zero phase sequence impedance of a transmission line it is strictly necessary to consider the proximity effect of the line and the earth and determine the actual current path throughout the earth. Rüdenberg and Carson have studied this effect. However it is probably greatly variable due to different soil conditions and thus a simplified method is in order.

Two assumptions might be made as limiting conditions. (a) The resistivity is high so that the current

*Appendix XII of Bibliography 1.

penetrates indefinitely depthwise in the earth, and (b) the resistivity is zero so that all the alternating current is confined to an infinitesimally thin lamina at the surface.

Actually conditions are intermediate between these extremes. Thus we may choose case *b* for calculation and empirically revise the answer in the direction of an intermediate value.

In case *b*, the field between the surface and the wire is the same as though the return current flowed in an image conductor having the radius of the line conductor and situated an equal distance below the surface. This follows because no alternating flux can penetrate a perfect conductor. The boundary condition at the surface is that of a flux line everywhere parallel to the surface. This is the same as would be produced by the line conductor with its image, which thus correctly represents the assumed condition. The empirical modification consists in receding the image to a location where the calculations check test, in a specific instance, then using this same image depth in other cases where the soil conditions are thought to be the

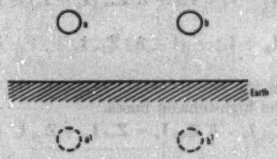



Fig. 28—Equivalent Conductor Arrangement of a Double-Circuit Line

same, or where it is desired to calculate the mutual effect of parallel lines.

Thus a simple and approximately correct engineering method is obtained.

In Fig. 26 the linkages per unit length of line* are

$$\Psi = 2\,\mathbf{I}\log\frac{D_g}{D_1} - 2\,\mathbf{I}\log\frac{D_g}{D_2} = 2\,\mathbf{I}\log\frac{D_2}{D_1}$$

*A much more satisfactory way of viewing this problem (though perhaps not so familiar to most engineers) is to identify the linkages per unit length of line with the vector magnetic potential. Thus

$$\Psi = \int \frac{\mathbf{i}\,dv}{r}$$

where $\mathbf{i}$ is vector current density
$r$ is distance between $\Psi$ and $\mathbf{i}$
$dv$ is a volume element.

This integral need only be taken over the volume of the conductors. By forming it over the volume of a pair of parallel line wires making up a circuit the potential is found at any point, specifically on a neighboring conductor and the formula given above for linkages is obtained. The linkages per unit length are thus related to magnetomotive force by means of the relation

$$\mathbf{H} = \text{Curl}\,\Psi$$

The product of permeability by the time derivative of $\Psi$ thus gives volts per unit length of line induced on the neighboring conductor by the circuit considered, which is the quantity sought.

between $x$ and any point on the ground plane, where

$\mathbf{I}$ is current in conductor

$D_1$, $D_2$ are geometric mean distances as given in figure.

This involves the assumption that an average $\Psi$ is obtained, thereby neglecting any parasitic currents which may be induced.

A three-phase line with three wires in parallel and transposed so that the current is equal in each (for zero phase sequence calculations) is often considered as a

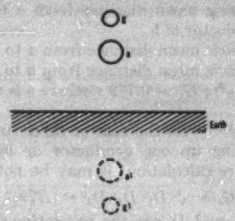



Fig. 29—Equivalent Conductor Arrangement of a Single-Circuit Line with Ground Wires

single equivalent conductor by making it of proper size and position. Zero phase sequence impedance is defined as the ratio of the voltage drop along the three wires to the current in one wire. The factor 3 thus appears.

Finally for a twin circuit line with return circuits assumed below the ground there is obtained, referring to Fig. 28

$$\mathbf{E}_o = \mathbf{I}_{ao}\,\mathbf{Z}_{aa} + \mathbf{I}_{bo}\,\mathbf{Z}_{ab}$$

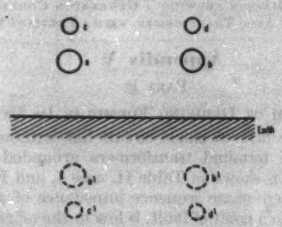



Fig. 30—Equivalent Conductor Arrangement of a Double-Circuit Line with Ground Wires

where

$\mathbf{E}_o$ is the zero phase sequence voltage induced along conductor $a$

$\mathbf{I}_{ao}$ is the zero phase sequence current in $a$

$\mathbf{I}_{bo}$ is the zero phase sequence current in $b$

$$\mathbf{Z}_{aa} = j\,6\,\omega\,L\log\frac{a\,a'}{G_s}$$

$$\mathbf{Z}_{ab} = j\,6\,\omega\,L\log\frac{a\,b'}{a\,b}$$

$$\omega = 2\,\pi \times \text{frequency}$$

In practical units

$$Z_{aa} = j\,0.014\,f\,L \log_{10} \frac{a\,a'}{G_s} \text{ ohms, etc.}$$

where $f$ = frequency in cycles per second
$L$ = length of line in miles
$L$ = length of line
$a\,a'$ = geometric mean distance from $a$ to its assumed return conductor
$a\,b'$ = geometric mean distance from $a$ to the return conductor of $b$
$a\,b$ = geometric mean distance from $a$ to $b$
$G_s$ = geometric mean distance from $a$ to itself.

For a round wire $G_s = 0.779\,r$ where $r$ is radius of the round wire.

To find $G_s$[12,13,14] for the case of three round wires in parallel making up one conductor or line (for zero phase sequence calculation) it may be noted that

$$G_s = \sqrt[9]{D_1^2\,D_2^2\,D_3^2\,r^3\,(.779)^3}$$

where $D_1$, $D_2$, and $D_3$ are the respective distances between the centers of the three wires.

The geometric mean distance between two such conductors is the $n^2$ root of the product of $n^2$ terms consisting of all the distances from the wires of one conductor to the wires of the other.

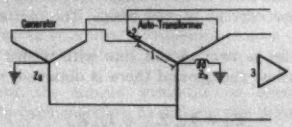



FIG. 31—DIAGRAM SHOWING A GENERATOR CONNECTED TO A STEP-UP AUTO TRANSFORMER, WITH A TERTIARY WINDING

## Appendix V

### PART B

### METHOD OF DERIVING FORMULAS IN TABLE

Example (a). A single circuit line without ground wires with terminal transformers grounded through impedance is shown in Table II, case I, and Fig. 27.

As the zero-phase sequence impedance of a system, viewed from a point of fault, is low in the neighborhood of any grounded neutral transformer, the magnitude of the ground current will depend upon the location of the fault along the line. Referring to case (1) the fault is located at a distance $K$ from the generator transformer and assuming that the ground current divides as shown, the two equations for the zero-phase sequence voltage may be written as follows:

$$\mathbf{V}_o = \mathbf{I}_a\,[(1-K)\,\mathbf{Z}_{aa} + \mathbf{Z}_{tb} + 3\,\mathbf{Z}_{nb}] = \mathbf{I}_a\,\mathbf{A} \tag{28}$$

$$\mathbf{V}_o = (\mathbf{I}_g - \mathbf{I}_a)\,[K\,\mathbf{Z}_{aa} + \mathbf{Z}_{ta} + 3\,\mathbf{Z}_{na}] = (\mathbf{I}_g - \mathbf{I}_a)\,\mathbf{B} \tag{29}$$

solving for $\mathbf{I}_a$ and substituting in Equation (28)

$$\mathbf{V}_o = \mathbf{I}_g \frac{\mathbf{A}\,\mathbf{B}}{\mathbf{A}+\mathbf{B}} \tag{30}$$

and

$$\mathbf{Z}_o = \frac{\mathbf{V}_o}{\mathbf{I}_g} = \frac{\mathbf{A}\,\mathbf{B}}{\mathbf{A}+\mathbf{B}} \tag{31}$$

Example (b). A double circuit line without ground wires, with high-tension buses and terminal transformers grounded through impedance is shown in Case II and Fig. 28.

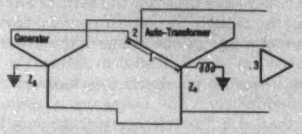



FIG. 32—DIAGRAM OF A GENERATOR CONNECTED TO A STEP-DOWN AUTO-TRANSFORMER, WITH A TERTIARY WINDING

As in example (a), the zero-phase sequence impedance varies with the position of the fault along the line. Equations for the zero-phase sequence voltage from the point of fault to ground may be written as follows:

$$\mathbf{V}_o = \mathbf{Z}_a\,(\mathbf{I}_g - \mathbf{I}_a - \mathbf{I}_b) + K\,\mathbf{Z}_{aa}\,(\mathbf{I}_g - \mathbf{I}_a) - K\,\mathbf{Z}_{ab}\,\mathbf{I}_b \tag{32}$$

$$\mathbf{V}_o = \mathbf{Z}_b\,(\mathbf{I}_a + \mathbf{I}_b) + (1-K)\,\mathbf{Z}_{aa}\,\mathbf{I}_a + (1-K)\,\mathbf{Z}_{ab}\,\mathbf{I}_b \tag{33}$$

Equating the zero-phase voltages over the two paths between the high-tension buses.

$$\mathbf{Z}_{aa}\,\mathbf{I}_a + \mathbf{Z}_{ab}\,\mathbf{I}_b - K\,\mathbf{Z}_{aa}\,\mathbf{I}_g = \mathbf{Z}_{ab}\,\mathbf{I}_a + \mathbf{Z}_{aa}\,\mathbf{I}_b + K\,\mathbf{Z}_{ab}\,\mathbf{I}_g$$

and

$$\mathbf{I}_o = \mathbf{I}_a - K\,\mathbf{I}_g \tag{34}$$

Substituting Equation (34) in Equations (32) and (33) and collecting terms

$$\mathbf{V}_o = \mathbf{C}\,\mathbf{I}_a + \mathbf{D}\,\mathbf{I}_g \tag{35}$$

$$\mathbf{V}_o = \mathbf{E}\,\mathbf{I}_a + \mathbf{F}\,\mathbf{I}_g \tag{36}$$

where

$$\mathbf{C} = -[2\,\mathbf{Z}_a + K\,(\mathbf{Z}_{aa} + \mathbf{Z}_{ab})] \tag{37}$$

$$\mathbf{D} = [\mathbf{Z}_a\,(1+K) + K\,(\mathbf{Z}_{aa} + K\,\mathbf{Z}_{ab})] \tag{38}$$

$$\mathbf{E} = [2\,\mathbf{Z}_b + (1-K)\,(\mathbf{Z}_{aa} + \mathbf{Z}_{ab})] \tag{39}$$

$$\mathbf{F} = -[K\,\mathbf{Z}_b + (1-K)\,K\,\mathbf{Z}_{ab}] \tag{40}$$

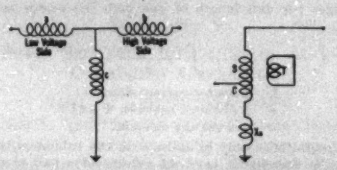



FIG. 32A—THE EQUIVALENT CIRCUIT FOR THE ZERO-PHASE IMPEDANCE OF AN AUTO-TRANSFORMER

Subtracting Equation (35) from (36)

$$\mathbf{I}_a = \frac{\mathbf{F}-\mathbf{D}}{\mathbf{C}-\mathbf{E}}\,\mathbf{I}_g \tag{41}$$

Substituting (41) in (35)

$$V_e = \frac{CF - DE}{C - E} I_g$$

Therefore

$$Z_e = \frac{V_e}{I_g} = \frac{CF - DE}{C - E} \qquad (42)$$

Example (c). Impedance of transmission lines, with ground wires.

The preceding examples have been presented for circuits without ground wires. The same formulas apply for circuits with ground wires if the coefficients $Z_{aa}$, $Z_{ab}$, etc., are respectively replaced by $Z_{aa}'$, $Z_{ab}'$, etc., which account for the change in flux linkages due to the current.

A *single circuit line*, equipped with ground wires, is shown in Fig. 29. The three conductors and ground wires have been reduced to an equivalent conductor and ground wire. The return conductors are indicated by primed letters.

TABLE II

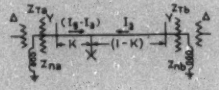
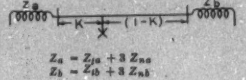
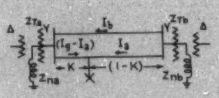
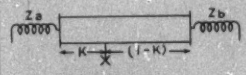
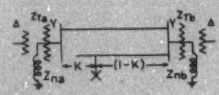
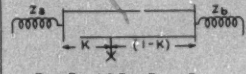
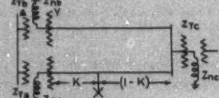
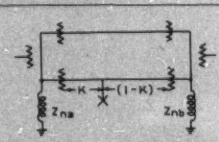
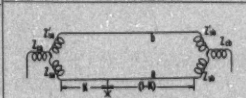
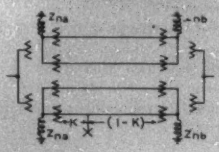
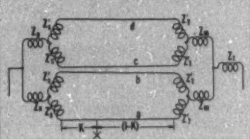
| Case No. | Apparatus connections in single line diagram | Simplified zero phase sequence reactance diagram | Zero phase sequence reactance viewed from the point of fault |
|---|---|---|---|
| 1 |  |  $Z_a = Z_{ja} + 3\,Z_{na}$<br>$Z_b = Z_{jb} + 3\,Z_{nb}$ | $Z_e = \frac{A\,B}{A + B}$ where<br>$A = Z_a + K\,Z_{aa}$<br>$B = Z_b + (1 - K)\,Z_{aa}$ |
| 2 |  |  $Z_a = Z_{Ta} + 3\,Z_{na};\ Z_{aa} = Z_{bb}$<br>$Z_b = T_{Tb} + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$ | $Z_e = \frac{C\,F - D\,E}{C - E}$ where<br>$C = -[2\,Z_a + K\,(Z_{aa} + Z_{ab})]$<br>$D = (1 + K)\,Z_a + K\,(Z_{aa} + K\,Z_{ab})$<br>$E = (2\,Z_b + (1 - K)\,(Z_{aa} + Z_{ab})$<br>$F = -[K\,Z_b + (1 - K)\,K\,Z_{ab}]$ |
| 3 |  |  $Z_a = Z_{Ta} + 3\,Z_{na};\ Z_{aa} = Z_{bb}$<br>$Z_b = Z_{Tb} + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$ | $Z_e = \frac{G\,J - H\,I}{G - I}$ where<br>$G = Z_b + (1 - K)\,Z_{ab}$<br>$H = Z_b + (1 - K)\,Z_{aa}$<br>$I = -[Z_a + Z_{aa} - (1 - K)\,Z_{ab}]$<br>$J = (1 - K)\,(Z_{aa} - Z_{ab})$ |
| 4 |  | $Z_a = Z_{Ta} + 3\,Z_{na};\ Z_{aa} = Z_{bb}$<br>$Z_b = Z_{Tb} + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$<br>$Z_c = Z_{Tc} + 3\,Z_{nc}$ | $Z_e = \frac{Q\,N - L\,M}{Q - M}$ where<br>$Q = Z_a + K\,(Z_{aa} - P\,Z_{ab})$<br>$L = Z_a + K\,(Z_{aa} - O\,Z_{ab})$<br>$M = (1 - K)(Z_{aa} - P\,Z_{ab}) + (1 - P)\,Z_c$<br>$N = (1 - K)\,O\,Z_{ab} + O\,Z_c$<br>$O = \frac{K\,(Z_{ab} - Z_{aa}) - Z_a}{Z_b + Z_{aa} - Z_{ab}}$<br>$P = \frac{Z_{ab} - Z_{aa} - Z_a}{Z_b + Z_{aa} - Z_{ab}}$ |
| 5 |  <br>Note: Resolve double winding transformers into<br> <br>where $Z_s$ is usually negative. |  $Z_{ca} = Z_c + 3\,Z_{na};\ Z_{aa} = Z_{bb}$<br>$Z_{cb} = Z_c + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$<br>$Z_{aa}'$ is distinguished from $Z_{aa}$ to allow for any lumped constants which might exist and destroy the symmetry. | $Z_e = \frac{R\,U - S\,T}{R - T}$ where<br>$R = -[Z_{ca} + Z_{sa} + K\,(Z_{aa} + W\,Z_{ab}) + W\,Z_{sa}]$<br>$S = Z_{ca} + Z_{sa} + K\,(Z_{aa} + Y\,Z_{ab}) + Y\,Z_{ca}$<br>$T = Z_{cb} + Z_{sb} + (1 - K)\,(Z_{aa} + W\,Z_{ab}) + W\,Z_{sb}$<br>$U = -[Y\,Z_{cb} + (1 - K)\,Y\,Z_{ab}]$<br>$V = Z_{sb}' + Z_{aa} + Z_{sa}' - Z_{ab}$<br>$W = \frac{Z_{sb} + Z_{aa} + Z_{sa} - Z_{ab}}{V}$<br>$Y = \frac{Z_{aa} + K\,(Z_{aa} - Z_{ab})}{V}$ |

TABLE II—*Continued*

| Case No. | Apparatus connections in single line diagram | Simplified zero phase sequence reactance diagram | Zero phase sequence reactance viewed from the point of fault |
|---|---|---|---|
| 6 |  <br>Note: Double winding transformers reduced as in (5).<br>Two double circuit lines considered. |  <br>$Z_n = Z_T + 3\,Z_{na}$<br>$Z_m = Z_T + 3\,Z_{nb}$<br>$Z_{aa} = Z_{bb} = Z_{cc} = Z_{dd}$<br>$Z_{ab} = Z_{bd} = Z_{cd} = Z_{dc}$<br>$Z_{ac} = Z_{bd} = Z_{ca} = Z_{db}$<br>$Z_s'$ and $Z_T'$ are distinguished from $Z_s$ and $Z_T$ to allow for any lumped constants which might exist and destroy the symmetry. $Z_r$ is added for flexibility. | $Z_0 = \dfrac{\begin{vmatrix} a & -a & c & d & q \\ e & f & -f & -e & r \\ -d & -c & a & s & x \\ g & h & i & j & t \\ l & m & n & p & o \end{vmatrix}}{\begin{vmatrix} a & -a & c & d \\ e & f & -f & e \\ -d & -c & a & s \\ g & h & i & j \end{vmatrix}}$<br>Where<br>$a = Z_s' + Z_{aa} + Z_T' - Z_{ab}$<br>$c = Z_{ac} - Z_{bc}$<br>$d = Z_{ad} + Z_{bd}$<br>$e = Z_n + Z_m + Z_{ab} - Z_{ac}$<br>$f = Z_n + Z_s' + Z_{aa} + Z_T' + Z_m - Z_{bc}$<br>$g = Z_{ad} + Z_r$<br>$h = Z_{ac} + Z_r$<br>$i = Z_n + Z_m + Z_{ab} + Z_r$<br>$j = Z_n + Z_m + Z_s + Z_T + Z_r + Z_{aa}$<br>$l = (1 - K)\,Z_{ad} + Z_r$<br>$m = (1 - K)\,Z_{ac} + Z_r$<br>$n = (1 - K)\,Z_{ab} + Z_m + Z_r$<br>$o =$ Zero<br>$p = (1 - K)\,Z_{aa} + Z_T + Z_m + Z_r$<br>$q = K\,Z_{bd} - K\,Z_{ad}$<br>$r = Z_n + K\,Z_{ab} - K\,Z_{ac}$<br>$s = Z_s + K\,Z_{aa} - K\,Z_{ab}$<br>$t = -Z_n - Z_s - K\,Z_{aa}$<br>$x = Z_{ab} - Z_s - Z_{aa} - Z_T$ |
| 7 | Same as (1) but with ground wires. | Same as (1) | $Z_0 = \dfrac{A'\,B'}{A' + B'}$ where<br>$A' = Z_a + K\,(Z_{aa}')^2$<br>$B' = Z_b + (1 - K)\,Z_{aa}$<br>and<br>$Z_{aa}' = \dfrac{Z_{aa}\,Z_{gg} - (Z_{ga})^2}{Z_{gg}}$ |
| 8 | Same as (2) but with ground wires over each circuit. | Same as (2) | $Z_0 = \dfrac{C'\,F' - D'\,E'}{C' - E'}$ where<br>$C' = -[2\,Z_a + K\,(Z_{aa}'' + Z_{ab}'')]$<br>$D' = Z_a\,(1 + K) + K\,(Z_{aa}'' + K\,Z_{ab}'')$<br>$E' = 2\,Z_b + (1 - K)\,(Z_{aa}'' + K\,Z_{ab}'')$<br>$F' = -[K\,Z_b + (1 - K)\,K\,Z_{ab}'']$<br>See Appendix V part B for Evaluation of $Z_{aa}''$ and $Z_{bb}''$ |

Writing simultaneous zero-phase sequence voltage equations

$$\mathbf{V}_{aa} = \mathbf{Z}_{ag}\,\mathbf{I}_g + \mathbf{Z}_{aa}\,\mathbf{I}_a \tag{43}$$

$$\mathbf{V}_{ag} = \mathbf{Z}_{gg}\,\mathbf{I}_g + \mathbf{Z}_{ga}\,\mathbf{I}_a \tag{44}$$

but

$$\mathbf{Z}_{ag} = \mathbf{Z}_{ga}$$

$$\mathbf{V}_{gg} = 0$$

solving

$$\mathbf{I}_a = \frac{-\mathbf{V}_{aa}\,\mathbf{Z}_{gg}}{(\mathbf{Z}_{ga})^2 - \mathbf{Z}_{aa}\,\mathbf{Z}_{gg}} \tag{45}$$

This gives

$$\mathbf{V}_{aa} = \mathbf{I}_a\,\mathbf{Z}_{aa}'$$

where

$$\mathbf{Z}_{aa}' = \frac{\mathbf{Z}_{aa}\,\mathbf{Z}_{gg} - (\mathbf{Z}_{ga})^2}{\mathbf{Z}_{gg}} \tag{46}$$

When $\mathbf{Z}_{aa}'$ is substituted in formulas (28) and (29) the correct coefficients for a single circuit line with ground wires are obtained.

A *double circuit line* equipped with ground wires is shown in Fig. 30. The three conductors and ground wires of each line have been reduced to equivalent conductors and ground wires. The return conductors are indicated by primed letters.

The resulting modified coefficients are

$$\mathbf{Z}_{aa}'' = \mathbf{Z}_{aa} - \mathbf{Z}_{ac}\,\mathbf{J}_{ac} - \mathbf{Z}_{ac}\,\mathbf{J}_{bc} \tag{47}$$

$$\mathbf{Z}_{ab}'' = \mathbf{Z}_{ab} - \mathbf{Z}_{ac}\,\mathbf{J}_{bc} - \mathbf{Z}_{ad}\,\mathbf{Z}_{ac} \tag{48}$$

where

$$\mathbf{J}_{ac} = \frac{\mathbf{Z}_{ac}\,\mathbf{Z}_{cc} - \mathbf{Z}_{ad}\,\mathbf{Z}_{cd}}{\mathbf{Z}_{cc}^2 - \mathbf{Z}_{cd}^2} \tag{49}$$

$$\mathbf{J}_{bc} = \frac{\mathbf{Z}_{ad}\,\mathbf{Z}_{cc} - \mathbf{Z}_{cd}\,\mathbf{Z}_{ac}}{\mathbf{Z}_{cc}^2 - \mathbf{Z}_{cd}^2} \tag{50}$$

Equations (47), (48), (49), and (50) have been developed in Park and Bancker's paper.[1] When $\mathbf{Z}_{aa}''$ and $\mathbf{Z}_{ab}''$ are substituted for $\mathbf{Z}_{aa}$ and $\mathbf{Z}_{ab}$ in formulas (37)-(40) they give coefficients which are correct for a double circuit line with ground wires.

TABLE III

CONSTANTS FOR STEP-BY-STEP CALCULATIONS

Driving Point Impedances

| Machine | $M$ | $k$ | $E$ | $\delta_0$ | During fault $Z$ | During fault $\theta$ | After fault $Z$ | After fault $\theta$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 7.50 | 7.20 | 1.045 | 19.98° | 0.4215 | 89.83° | 0.890 | 89.19° |
| 2 | 105.0 | 0.514 | 1.015 | −12.29° | 0.5703 | 89.44° | 0.816 | 88.16° |
| 3 | 0.625 | 86.4 | 1.437 | − 4.37° | 2.504 | 88.95° | 2.578 | 88.64° |

Transfer impedances

| Impedance | During fault $Z$ | During fault $\theta$ | After fault $Z$ | After fault $\theta$ |
|---|---|---|---|---|
| $Z_{12}$ | 2.178 | 91.21° | 1.050 | 91.50° |
| $Z_{13}$ | 14.68 | 94.67° | 7.15 | 94.97° |
| $Z_{23}$ | 7.10 | 94.50° | 4.56 | 94.95° |

Torque components

| | Total before fault | During fault | After fault |
|---|---|---|---|
| $T_{11}$ | 0.7917 | $2.59 \sin 0.17° = 0.0077$ | $1.227 \sin 0.81° = .0174$ |
| $T_{12}$ | | $0.487 \sin (\delta_{12} + 1.21°)$ | $1.002 \sin (\delta_{12} + 1.50°)$ |
| $T_{13}$ | | $0.1023 \sin (\delta_{13} + 4.67°)$ | $0.210 \sin (\delta_{13} + 4.97°)$ |
| $T_{22}$ | −0.5833 | $1.806 \sin 0.56° = 0.0177$ | $1.263 \sin 1.84° = .0406$ |
| $T_{21}$ | | $-0.487 \sin (\delta_{12} - 1.21°)$ | $-1.002 \sin (\delta_{12} - 1.50°)$ |
| $T_{23}$ | | $-0.2054 \sin (\delta_{23} - 4.50°)$ | $-0.320 \sin (\delta_{23} - 4.95°)$ |
| $T_{33}$ | 0.0 | $0.825 \sin 1.05° = .0151$ | $0.802 \sin 1.36° = .0190$ |
| $T_{31}$ | | $-0.1023 \sin (\delta_{13} - 4.67°)$ | $-0.210 \sin (\delta_{13} - 4.97°)$ |
| $T_{32}$ | | $0.205 \sin (\delta_{23} + 4.50°)$ | $0.320 \sin (\delta_{23} + 4.95°)$ |

## Appendix VI

### The Zero-Phase Sequence Impedance of an Auto-Transformer

In making stability studies on a large system the zero-phase sequence network plays an important part in the equivalent circuit if ground faults are encountered.

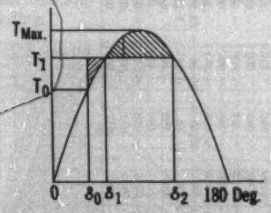



Fig. 33—Torque-Angle Diagram showing Effect of a Suddenly Applied Load

Zero-phase sequence networks often involve auto-transformers which prove troublesome to evaluate correctly. This appendix derives a formula for the zero-phase sequence impedance of a three-phase bank of auto-transformers as viewed from the load side, with the neutral grounded through an impedance and a generator connected to the other side. The generator may also be grounded through an impedance. See Figs. 31 and 32.

The following equations may be written.[22]

$$\left.\begin{aligned} \mathbf{v}_1 &= \mathbf{z}_{11}\,\mathbf{i}_1 + \mathbf{z}_{12}\,\mathbf{i}_2 + \mathbf{z}_{13}\,\mathbf{i}_3 + \mathbf{E} \\ \mathbf{v}_2 &= \mathbf{z}_{21}\,\mathbf{i}_1 + \mathbf{z}_{22}\,\mathbf{i}_2 + \mathbf{z}_{23}\,\mathbf{i}_3 + \mathbf{E} \\ \mathbf{v}_3 &= \mathbf{z}_{31}\,\mathbf{i}_1 + \mathbf{z}_{32}\,\mathbf{i}_2 + \mathbf{z}_{33}\,\mathbf{i}_3 + \mathbf{E} \end{aligned}\right\} \qquad (51)$$

$$\mathbf{i}_1 + \mathbf{i}_2 + \mathbf{i}_3 = 0$$

In these equations the quantities are expressed as per unit quantities all on a common kv-a. base and on their own voltage base, as is common in transformer practise. The impedance $\mathbf{z}_{11}$ is the self impedance of winding 1 and $\mathbf{z}_{12}$ is the mutual impedance from winding 1 to winding 2. Each of these quantities considers

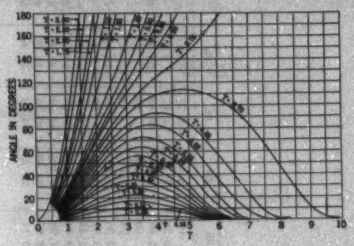



Fig. 34—Angle-Time Curves for $\frac{T_o}{T_m} = 0.00$

only the flux in the air. $\mathbf{E}$ is a per-unit quantity representing the voltage induced in each winding by the flux in the iron.

To eliminate $\mathbf{E}$ subtract and the result is

$$\left.\begin{aligned} \mathbf{v}_1 - \mathbf{v}_2 &= \mathbf{z}_1\,\mathbf{i}_1 - \mathbf{z}_2\,\mathbf{i}_2 \\ \mathbf{v}_2 - \mathbf{v}_3 &= \mathbf{z}_2\,\mathbf{i}_2 - \mathbf{z}_3\,\mathbf{i}_3 \\ \mathbf{v}_3 - \mathbf{v}_1 &= \mathbf{z}_3\,\mathbf{i}_3 - \mathbf{z}_1\,\mathbf{i}_1 \end{aligned}\right\} \qquad (52)$$

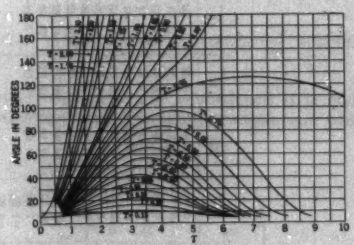



Fig. 35—Angle-Time Curves for $\frac{T_o}{T_m} = 0.10$

where

$$\left.\begin{aligned} \mathbf{z}_1 &= \mathbf{z}_{11} - \mathbf{z}_{12} - \mathbf{z}_{13} + \mathbf{z}_{23} \\ \mathbf{z}_2 &= \mathbf{z}_{22} - \mathbf{z}_{12} - \mathbf{z}_{23} + \mathbf{z}_{13} \\ \mathbf{z}_3 &= \mathbf{z}_{33} - \mathbf{z}_{13} - \mathbf{z}_{23} + \mathbf{z}_{12} \end{aligned}\right\} \qquad (53)$$

The measured impedances in a transformer are $\mathbf{z}_{1-2}$, $\mathbf{z}_{1-3}$, and $\mathbf{z}_{2-3}$ where $\mathbf{z}_{1-2}$ for example is the per-unit impedance found by short circuiting winding 2 and measuring current and volts at winding 1.

TABLE IV

| $t$ | 0 | .05 | .10 | .15 | .20 | | .20 | .25 | .30 | .35 | .40 | .45 | .50 | .55 | .60 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $k_1 T_{a1} = 7.20\ T_{a1}$ | 0 | 1.68 | 3.23 | 2.90 | 2.46 | | | .01 | −2.54 | −2.77 | −2.77 | −2.75 | −2.80 | −2.85 | −2.70 |
| $\Delta\ \delta_1$ | 0 | 1.68 | 4.91 | 7.81 | 10.27 | | 10.27 | 10.28 | 7.74 | 4.97 | 2.20 | −.55 | −3.35 | −6.20 | −8.90 |
| $\delta_1$ | 19.98 | 21.66 | 26.57 | 34.38 | 44.65 | | 44.65 | 54.93 | 62.67 | 67.64 | 69.84 | 69.29 | 65.94 | 59.74 | 50.84 |
| $k_2 T_{a2} = .514\ T_{a2}$ | 0 | −.09 | −.17 | −.15 | −.13 | | | .002 | .16 | .23 | .27 | .28 | .27 | .23 | .18 |
| $\Delta\ \delta_2$ | 0 | −.09 | −.26 | −.41 | −.54 | | −.54 | −.54 | −.38 | −.15 | .12 | .40 | .67 | .90 | 1.08 |
| $\delta_2$ | −12.29 | −12.38 | −12.64 | −13.05 | −13.59 | | −13.59 | −13.05 | −13.43 | −13.58 | −13.46 | −13.06 | −12.39 | −11.49 | −10.41 |
| $k_3 T_{a3} = 86.4\ T_{a3}$ | 0 | −1.07 | −1.45 | .26 | 2.10 | | | 6.60 | 6.30 | −.60 | −7.14 | −9.57 | −6.82 | −.22 | 6.42 |
| $\Delta\ \delta_3$ | 0 | −1.07 | −2.52 | −2.26 | −.16 | | −.16 | 6.44 | 12.74 | 12.14 | 5.00 | −4.57 | −11.39 | −11.61 | −5.19 |
| $\delta_3$ | −4.37 | −5.44 | −7.96 | −10.22 | −10.38 | | −10.38 | −3.94 | 8.80 | 20.94 | 25.94 | 21.37 | 9.96 | −1.65 | −6.84 |
| $\delta_1 - \delta_2 = \delta_{12}$ | 32.27 | 34.04 | 39.21 | 47.43 | 58.24 | | 58.24 | 67.98 | 76.10 | 81.22 | 83.30 | 82.35 | 78.33 | 71.23 | |
| $\delta_1 - \delta_3 = \delta_{13}$ | 24.35 | 27.10 | 34.53 | 44.60 | 55.03 | | 55.03 | 58.87 | 53.87 | 46.70 | 43.90 | 47.92 | 55.98 | 61.39 | |
| $\delta_2 - \delta_3 = \delta_{23}$ | 7.92 | 6.94 | 4.68 | 2.83 | 3.21 | | 3.21 | 9.11 | 22.23 | 34.52 | 39.40 | 34.43 | 22.35 | 9.84 | |
| Constant $\alpha_{12}$ | −1.21 | | | | | | −1.50 | | | | | | | | |
| Constant $\alpha_{13}$ | −4.67 | | | | | | −4.97 | | | | | | | | |
| Constant $\alpha_{23}$ | −4.50 | | | | | | −4.95 | | | | | | | | |
| $\delta_{12} - \alpha_{12}$ | 33.48 | 35.25 | 40.42 | 48.64 | 59.45 | | 59.74 | 69.48 | 77.60 | 82.72 | 84.80 | 83.85 | 79.83 | 72.73 | |
| $\delta_{13} - \alpha_{13}$ | 29.02 | 31.77 | 39.20 | 49.27 | 59.70 | | 60.00 | 63.84 | 58.84 | 51.67 | 48.87 | 52.89 | 60.95 | 66.36 | |
| $\sin(\delta_{12} - \alpha_{12})$ | .5517 | .577 | .648 | .751 | .861 | | .864 | .937 | .977 | .992 | .996 | .994 | .984 | .955 | |
| $\sin(\delta_{13} - \alpha_{13})$ | .4851 | .526 | .632 | .758 | .863 | .277 | .866 | .898 | .856 | .784 | .753 | .798 | .874 | .916 | |
| $T_{12} = K_{12} \sin(\delta_{12} - \alpha_{12})$ | .2687 | .281 | .316 | .366 | .419 | −.274 | .866 | .939 | .970 | .994 | .998 | .996 | .987 | .957 | |
| $T_{13} = K_{13} \sin(\delta_{13} - \alpha_{13})$ | .0496 | .054 | .065 | .078 | .088 | 2/.003 | .182 | .188 | .180 | .165 | .158 | .168 | .184 | .192 | |
| $T_{a1} = T_1 - T_{11} - T_{12} - T_{13}$ | .4657 | .449 | .404 | .341 | .277 | .0016 | −.274 | −.353 | −.384 | −.384 | −.382 | −.390 | −.396 | −.375 | |
| $\delta_{12} + \alpha_{12}$ | 31.06 | 32.83 | 38.00 | 46.22 | 57.03 | | 56.74 | 66.48 | 74.60 | 79.72 | 81.80 | 80.85 | 76.83 | 69.73 | |
| $\delta_{23} + \alpha_{23}$ | 3.42 | 2.44 | .18 | −1.67 | −1.29 | | −1.74 | 4.16 | 17.28 | 29.57 | 34.45 | 29.48 | 17.40 | 4.89 | |
| $\sin(\delta_{12} + \alpha_{12})$ | .5159 | .542 | .616 | .722 | .839 | | .836 | .917 | .964 | .984 | .990 | .987 | .974 | .938 | |
| $\sin(\delta_{23} + \alpha_{23})$ | .0597 | .043 | .003 | −.029 | −.022 | .204 | −.030 | .072 | .297 | .494 | .566 | .492 | .299 | .085 | |
| $T_{21} = -K_{12} \sin(\delta_{12} + \alpha_{12})$ | −.2512 | −.264 | −.300 | −.352 | −.408 | −.197 | −.838 | −.919 | −.966 | −.986 | −.992 | −.990 | −.976 | −.941 | |
| $T_{23} = -K_{23} \sin(\delta_{23} + \alpha_{23})$ | −.0123 | −.009 | −.001 | .006 | .005 | 2/.007 | .010 | −.023 | −.095 | −.158 | −.181 | −.158 | −.096 | −.027 | |
| $T_{a2} = T_2 - T_{22} - T_{21} - T_{23}$ | −.3375 | −.328 | −.301 | −.255 | −.197 | .0036 | .204 | .318 | .438 | .520 | .549 | .524 | .448 | .344 | |
| $\delta_{13} + \alpha_{13}$ | 19.68 | 22.43 | 29.86 | 39.93 | 50.36 | | 50.06 | 53.90 | 48.90 | 41.73 | 38.93 | 42.95 | 51.01 | 56.42 | |
| $\delta_{23} - \alpha_{23}$ | 12.42 | 11.44 | 9.18 | 7.33 | 7.71 | | 8.16 | 14.06 | 27.18 | 39.47 | 44.35 | 39.38 | 27.30 | 14.79 | |
| $\sin(\delta_{13} + \alpha_{13})$ | .3368 | .382 | .498 | .642 | .770 | | .767 | .808 | .754 | .666 | .628 | .681 | .777 | .833 | |
| $\sin(\delta_{23} - \alpha_{23})$ | .2151 | .198 | .160 | .128 | .134 | .046 | .142 | .243 | .457 | .636 | .699 | .634 | .459 | .255 | |
| $T_{31} = -K_{13} \sin(\delta_{13} + \alpha_{13})$ | −.0345 | −.039 | −.051 | −.066 | −.079 | .107 | −.161 | −.170 | −.158 | −.140 | −.132 | −.143 | −.163 | −.175 | |
| $T_{33} = K_{23} \sin(\delta_{23} - \alpha_{23})$ | .0442 | .041 | .033 | .026 | .018 | 2/.153 | .045 | .078 | .146 | .203 | .224 | .203 | .147 | .082 | |
| $T_{a3} = T_3 - T_{33} - T_{31} - T_{32}$ | −.0248 | −.017 | .003 | .024 | .046 | .076 | .107 | .073 | −.007 | −.083 | −.111 | −.079 | −.003 | .074 | |

The succeeding relations follow from combining Equations (53) with the equations representing these short circuited connections.

$$\left.\begin{aligned} \mathbf{z}_1 &= \frac{\mathbf{z}_{1-2} + \mathbf{z}_{1-3} - \mathbf{z}_{2-3}}{2} \\ \mathbf{z}_2 &= \frac{\mathbf{z}_{1-2} + \mathbf{z}_{2-3} - \mathbf{z}_{1-3}}{2} \\ \mathbf{z}_3 &= \frac{\mathbf{z}_{1-3} + \mathbf{z}_{2-3} - \mathbf{z}_{1-2}}{2} \end{aligned}\right\} \tag{54}$$

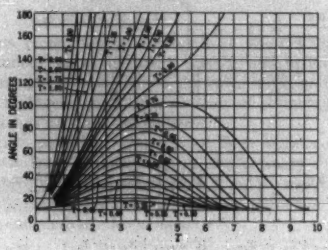



FIG. 36—ANGLE-TIME CURVES FOR $\frac{T_e}{T_m} = 0.20$

For zero-phase sequence calculations the equations may be written

$$\left.\begin{aligned} \mathbf{v}_{10} &= \mathbf{z}_{11}\,\mathbf{i}_{10} + \mathbf{z}_{12}\,\mathbf{i}_{20} + \mathbf{z}_{13}\,\mathbf{i}_{30} + E_0 \\ \mathbf{v}_{20} &= \mathbf{z}_{21}\,\mathbf{i}_{10} + \mathbf{z}_{22}\,\mathbf{i}_{20} + \mathbf{z}_{23}\,\mathbf{i}_{30} + E_0 \\ \mathbf{v}_{30} &= \mathbf{z}_{31}\,\mathbf{i}_{10} + \mathbf{z}_{32}\,\mathbf{i}_{20} + \mathbf{z}_{33}\,\mathbf{i}_{30} + E_0 \\ \mathbf{i}_{10} &+ \mathbf{i}_{20} + \mathbf{i}_{30} = 0 \\ \mathbf{v}_{30} &= 0 \end{aligned}\right\} \tag{55}$$

The latter relation is introduced because of the tertiary winding.

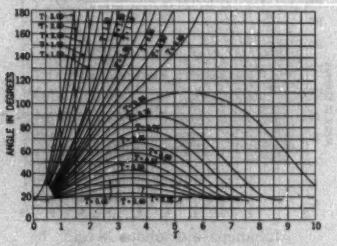



FIG. 37—ANGLE-TIME CURVES FOR $\frac{T_e}{T_m} = 0.30$

The result of simplifying is

$$\left.\begin{aligned} \mathbf{v}_{10} &= (\mathbf{z}_1 + \mathbf{z}_3)\,\mathbf{i}_{10} + \mathbf{z}_3\,\mathbf{i}_{20} \\ \mathbf{v}_{20} &= \mathbf{z}_3\,\mathbf{i}_{10} + (\mathbf{z}_2 + \mathbf{z}_3)\,\mathbf{i}_{20} \end{aligned}\right\} \tag{56}$$

To find the voltage across both windings 1 and 2 it is necessary to introduce the voltage ratio in order that the voltages may be expressed on a common voltage base before adding.

Let $K$ be the ratio of the voltage in the winding between neutral and the generator to that in the winding between neutral and the load, at no load.

There is obtained the following set of relations, where the capital letters signify that the quantities have been expressed on a common voltage base, that of the load.

$$\left.\begin{aligned} \mathbf{V}_{eo} &= \mathbf{V}_{10} + \mathbf{V}_{20} \\ \mathbf{v}_{20} &= \frac{1}{1-K}\,\mathbf{V}_{20} \\ \mathbf{v}_{10} &= \frac{1}{K}\,\mathbf{V}_{10} \\ \mathbf{i}_{20} &= (1-K)\,\mathbf{I}_{10} \\ \mathbf{i}_{10} &= K\,\mathbf{I}_{10} \end{aligned}\right\} \tag{57}$$

Combining:

$$\left.\begin{aligned} \mathbf{V}_{eo} &= K^2\left(\mathbf{z}_1 + \frac{1}{K}\,\mathbf{z}_3\right)\mathbf{I}_{10} \\ &\quad + (1-K)\,[(1-K)\,\mathbf{z}_2 + \mathbf{z}_3]\,\mathbf{I}_{20} \\ \mathbf{V}_{10} &= K^2\,(\mathbf{z}_1 + \mathbf{z}_3)\,\mathbf{I}_{10} + K\,(1-K)\,\mathbf{z}_3\,\mathbf{I}_{20} \end{aligned}\right\} \tag{58}$$

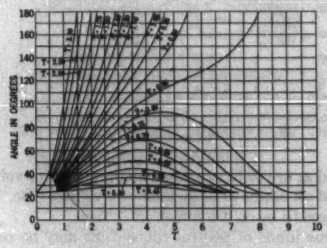



FIG. 38—ANGLE TIME CURVES FOR $\frac{T_e}{T_m} = 0.40$

Another relation is now needed and it is obtained by writing the drops through the transformer windings

$$\mathbf{z}_e = \frac{\mathbf{V}_{eo} + \mathbf{I}_{10}\,K^2\,\mathbf{z}_n}{\mathbf{I}_{20}} \tag{59}$$

This gives

$$\mathbf{z}_e = K\,(1-K)\left[\frac{1-K}{K}\,\mathbf{z}_2 + \frac{\mathbf{z}_3}{K}\right] + \frac{\mathbf{I}_{10}}{\mathbf{I}_{20}}\,K^2\left[\mathbf{z}_1 + \frac{1}{K}\,\mathbf{z}_3 + \mathbf{z}_n\right] \tag{60}$$

Still another relation is now needed to find the current division and this is obtained by writing the drops through the neutral connections.

$$K^2\,(\mathbf{I}_{20} - \mathbf{I}_{10})\,\mathbf{z}_e - \mathbf{V}_{10} - \mathbf{I}_{10}\,K^2\,\mathbf{z}_n = 0 \tag{61}$$

The factor $K^2$ is introduced into (59) and (61) to allow for $\mathbf{Z}_e$ and $\mathbf{Z}_n$ being expressed on the generator voltage base instead of the load voltage base.

This gives

$$\frac{\mathbf{I}_{10}}{\mathbf{I}_{20}} = \frac{\mathbf{z}_g - \dfrac{(1-K)}{K}\mathbf{z}_3}{\mathbf{z}_g + \mathbf{z}_1 + \mathbf{z}_3 + \mathbf{z}_n} \tag{62}$$

Substituting (**62**) in (**60**) gives the final formula

$$\mathbf{z}_o = (1-K)^2\,\mathbf{z}_2 + \frac{\mathbf{z}_3\,[\mathbf{z}_g + (1-K)^2(\mathbf{z}_1 + \mathbf{z}_n)] + K^2\,\mathbf{z}_g\,[\mathbf{z}_n + \mathbf{z}_1]}{\mathbf{z}_g + \mathbf{z}_1 + \mathbf{z}_3 + \mathbf{z}_n} \tag{63}$$

In case the "series-common to common" impedance is given it may be made use of by means of the relation

$$\mathbf{z}_{1-2} = \mathbf{z}_{sc-c}\,\frac{1}{(1-K)^2}$$

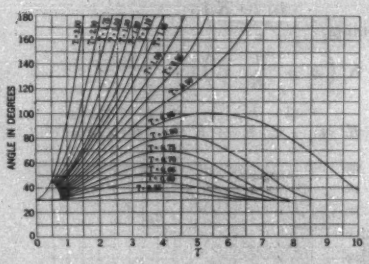



FIG. 39—ANGLE-TIME CURVES FOR $\dfrac{T_o}{T_m} = 0.50$

$\mathbf{z}_n$ and $\mathbf{z}_g$ are to be expressed on the generator voltage base and all others to be on their own voltage base. All reactances to be on a common kv-a. base.

Various kinds of neutral connections may be represented by letting $\mathbf{z}_g$ and $\mathbf{z}_n$ be finite, zero, or infinite as the case may be. In case there is no tertiary, $\mathbf{z}_3$ is infinite and substitution of this gives the correct solution. In case the neutrals are connected together and then grounded through a common impedance this impedance may be considered to be in the load circuit by expressing it on the load voltage base and adding it to the impedance found by neglecting it. It may be noted that $\mathbf{z}_n$ naturally associates itself with $\mathbf{z}_1$ in formula (**63**). Thus if $\mathbf{z}_1'$ be taken to include $\mathbf{z}_n$ and $\mathbf{z}_1$ the following simple form occurs

$$\mathbf{z}_o = (1-K)^2\,\mathbf{z}_2 + \frac{\mathbf{z}_3\,[\mathbf{z}_g + (1-K)^2\,\mathbf{z}_1'] + K^2\,\mathbf{z}_g\,\mathbf{z}_1'}{\mathbf{z}_1' + \mathbf{z}_3 + \mathbf{z}_g} \tag{64}$$

These results apply to step-down as well as step-up auto-transformers.

In cases where the auto transformers become part of a complicated network it is a practical necessity to have an equivalent circuit for the zero-phase sequence impedance of the auto transformer. The formula derived above may be reduced to an equivalent network by means of a method suggested by R. H. Park. This consists first in establishing the validity of the process by showing that the necessary criterion that such an equivalent circuit can be constructed in terms of per unit quantities is merely that the impedances be expressed on a common kv-a. base. Then, referring to Fig. 32A, four relations are obtained by considering each of the two branches of the equivalent circuit in Fig. 32A first open, then grounded.

Thus

$$a + c = x_{c-t} + x_n \tag{65}$$

$$b + c = x_{sc-t} + K_c^2\,x_n \tag{66}$$

$$b + \frac{a\,c}{a+c} = (1-K_c)^2\left[\frac{x_{s-c} + x_{s-t} - x_{c-t}}{2} + \frac{\left[\dfrac{x_{c-t} + x_{s-t} - x_{s-c}}{2}\right]\left[\dfrac{x_{s-c} + x_{c-t} - x_{s-t}}{2} + x_n\right]}{x_n + x_{c-t}}\right] \tag{67}$$

$$a + \frac{b\,c}{b+c} = \left(1 - \frac{1}{K_c}\right)^2\left[\frac{x_{sc-s} + x_{s-t} - x_{sc-t}}{2} + \frac{\left[\dfrac{x_{sc-t} + x_{s-t} - x_{sc-s}}{2}\right]\left[\dfrac{x_{sc-s} + x_{sc-t} - x_{s-t}}{2} + K_c^2\,x_n\right]}{K_c^2\,x_n + x_{sc-t}}\right] \tag{68}$$

Also there is

$$x_{s-c} = x_{sc-c}\left(\frac{1}{1-K_c}\right)^2 \tag{69}$$

$$x_{sc-s} = x_{sc-c}\left(\frac{K_c}{1-K_c}\right)^2 \tag{70}$$

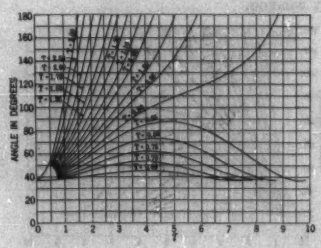



FIG. 40—ANGLE-TIME CURVES FOR $\dfrac{T_o}{T_m} = 0.60$

Where $K_c$ is voltage in the common winding divided by voltage in the series plus common windings and $x_n$ is expressed on the low-voltage base. The subscripts on the various reactances refer to the series, common, series common, and tertiary windings. The first two equations are written by inspection, and the second two from Formula (**63**).

These relations combined result in the following relation between the reactances

$$x_{s-t} = \frac{1}{1-K_c}\left[x_{sc-t} - K_c x_{c-t} + \frac{K_c}{1-K_c} x_{sc-c}\right] \quad (71)$$

Formula (71) combined with numbers (65), (66), and (67), (69), and (70) results in the following values for the branches of the equivalent circuit.*

$$c = \frac{x_{sc-t} + x_{c-t} - x_{sc-c}}{2} + K_c x_n \quad (72)$$

$$b = x_{sc-t} + K_c^2 x_n - c \quad (73)$$

$$a = x_{c-t} + x_n - c \quad (74)$$

This gives an equivalent circuit whereby per unit reactances may be used directly and external impedances may be added to the two branches, on their own voltage base, in any amount of complexity and treated as an ordinary network.

These equations could have been obtained more directly from a knowledge of the ordinary formulas for three circuit transformers[25, 26] but it was thought best to include the full derivation in order to obtain a more complete set of relations.

## Appendix VII

The following detailed data submitted for a stability study on a system would practically eliminate the necessity of making any assumptions.

(a) A single line, circuit diagram of the system under consideration as well as of adjacent systems which may be connected, giving

1. Location of, and
2. Electrical arrangement of
   - (i) Lines
   - (ii) Generators
   - (iii) Transformers
   - (iv) Reactors
   - (v) Loads
   - (vi) Grounds
   - (vii) Delta-Y grounded banks

(b) Map showing the geographical location and topography of the area which the lines traverse.

(c) Lines
1. Voltage
2. Number of circuits
3. Spacing
4. Length
5. Size of conductors—material
6. Ground wires:—number, size, material, location
7. Soil conditions, tower footings

(d) Synchronous Machines
1. Type
   - (i) Turbo generators
   - (ii) Waterwheel generators
   - (iii) Frequency sets
   - (iv) Condensers
   - (v) Synchronous motors
2. Location
3. Kv-a. capacity
4. Frequency
5. Speed
6. Short circuit ratio
7. "Potier" reactance*
8. Synchronous reactance
9. Direct and quadrature transient reactance
10. Negative phase sequence reactance
11. Zero phase sequence reactance (if grounded)
12. Single or double winding; connections
13. Normal load in operation
14. Type of excitation used
    - (i) Self excited
    - (ii) Separately excited; size, rev. per min. of exciters
    - (iii) Main field rheostats
15. Governor regulation of prime movers
16. $WR^2$ including prime movers
17. Type of regulator used

(e) Transformers
1. Kv-a. rating
2. Location
3. Number of windings
4. Step up or auto transformers
5. Arrangement of windings, Y-Y, etc.
6. Reactances, particularly auto-transformers
7. Neutral impedances
8. Grounding transformers

(f) Loads
1. Actual load on each bus
2. Connected load on each bus
3. Location of load centers
4. Nature of loads if possible
5. Peak load
6. Load factor
7. Location of load grounds
8. Per cent resistance, induction and synchronous connected load

(g) Bus Arrangements
1. High-voltage buses
2. Low-voltage buses
3. Generators on each bus
4. Load on each bus
5. Bus reactors
6. Voltage normally maintained on the various buses
7. Interconnections with other systems

(h) Relaying
1. For fault conditions what time of breaker opening is expected

*These results were first obtained by Mr. H. C. Verwoert.

*The reactance determined by the Potier method, *i. e.*, the reactance used in calculating regulation. This was formerly referred to as "the reactance" or the leakage reactance.

2. What normal switching operations are likely to occur
3. Overload relay settings

(i) Fault conditions

Information as to the type of faults encountered and the behavior of the system under fault conditions would be useful in directing the stability study in the proper channel.

1. 1-conductor-to-ground fault
2. 2-conductor-to-ground fault
3. Conductor-to-conductor fault
4. Three-phase fault
5. Major switching operations
6. Frequency of small oscillations

## Appendix VIII

### Simplified Methods in the Ideal Case

The fundamental equation for rotor motion in an ideal case has been given,[1] referring to Fig. 33, as

$$\frac{M}{2\pi f}\frac{d^2\delta}{dt^2} = T_1 - T_m \sin\delta \qquad (75)$$

$$T_m = \frac{\Psi_a \Psi_b}{x} \qquad (76)$$

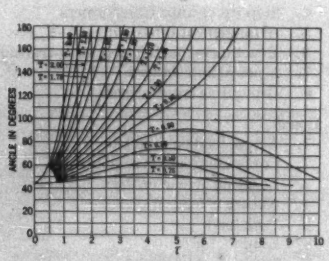



Fig. 41—Angle-Time Curves for $\frac{T_o}{T_m} = 0.70$

$\Psi_a, \Psi_b$ = Per unit linkages in the two machines
$x$ = Per unit reactance between the linkages
$T_1$ = New per unit total torque
$M$ = Time to come to rest with normal torque applied
$\delta$ = Electrical angle between machine linkages
$f$ = Normal frequency
$t$ = Time

This equation results from substituting

$$M = \frac{I\,\omega^2}{\omega\, T_n} \qquad (77)$$

where $I$ is moment of inertia
$\omega$ is normal speed of rotor
$T_n$ is normal torque

in the relation that torque equals the product of moment of inertia and angular acceleration, taking due account of the relation between mechanical and electrical angle.

Curves for the solution of this equation have been given but it has been thought desirable to make new ones in greater detail so as to simplify the interpolation.

In order to do this the Integraph[20] at the Massachusetts Institute of Technology was used.

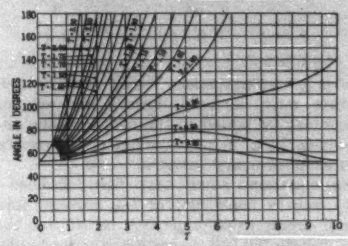



Fig. 42—Angle-Time Curves for $\frac{T_o}{T_m} = 0.80$

Let $$\tau = t\sqrt{\frac{2\pi f}{M}\,T_m} \qquad (78)$$

and $$T = T_1/T_m \qquad (79)$$

This gives

$$\frac{d^2\delta}{d\tau^2} + \sin\delta = T \qquad (80)$$

Equation (80) is in form for direct solution on the integraph and the curves shown in Fig. 34 to Fig. 43 were

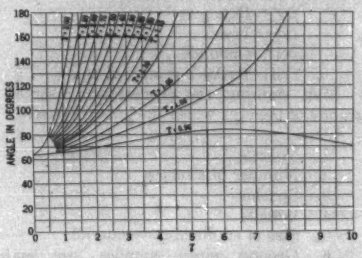



Fig. 43—Angle-Time Curves for $\frac{T_o}{T_m} = 0.90$

obtained, where $\delta_0$ is the initial angle, $T_0$ the initial torque and

$$\sin\delta_0 = \frac{T_0}{T_m}$$

For small excursions along the torque angle curves Equation (80) may be written

$$p^2 \Delta \delta + m^2 \Delta \delta = \Delta T \, 1 \tag{81}$$

where

$$p = \frac{d}{d(\Delta \tau)}$$

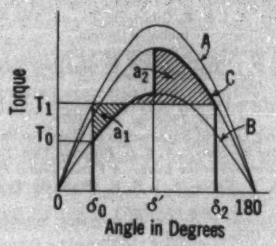



FIG. 44—TORQUE-ANGLE DIAGRAMS SHOWING THE EFFECT OF CLEARING A FAULT BY OPENING A PARALLEL LINE

$m^2$ = slope of curve at some average point in the excursion but may be taken at $\delta_o$ in the absence of other information. Making this assumption in the ideal case $m^2 = \cos \delta_o$.

$\Delta \delta$ = Increase in angle from $\delta_o$.

$$\Delta \tau = \Delta t \sqrt{\frac{2 \pi f}{M} T_m} \tag{78a}$$

$$\Delta T = T - \frac{T_o}{T_m} = T - \sin \delta.$$

$\Delta t$ = time of travel from $\delta_o$.

$\delta_o$ is angle of rotor at beginning of excursion, corresponding to a torque of $T_o$.

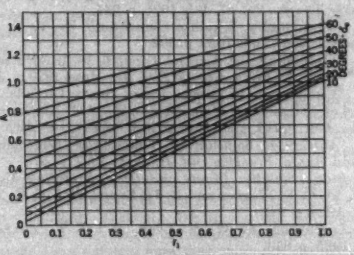



FIG. 45—CURVES USED IN DETERMINING THE ANGLE AT WHICH SWITCHING MUST OCCUR TO MAINTAIN STABILITY. PART I

Solving

$$\Delta \delta = \frac{\Delta T}{m^2} \frac{1}{\left(\frac{p}{m}\right)^2 + 1} 1 \tag{82}$$

which gives

$$\Delta \delta = \frac{\Delta T}{m^2} [1 - \cos m \, \Delta \tau] \tag{83}$$

and

$$\Delta \tau = \frac{1}{m} \cos^{-1}\left(1 - \frac{m^2 \Delta \delta}{\Delta T}\right) \tag{84}$$

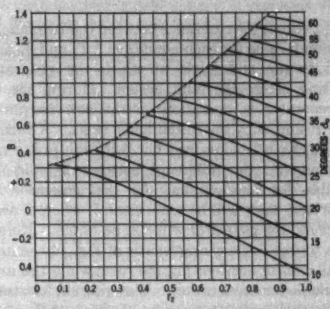



FIG. 46—CURVES USED IN DETERMINING THE ANGLE AT WHICH SWITCHING MUST OCCUR TO MAINTAIN STABILITY. PART II

In case $m = 0$ this reduces to

$$\Delta \delta = \Delta T \frac{(\Delta \tau)^2}{2} \tag{85}$$

$$\Delta \tau = \sqrt{\frac{2 \Delta \delta}{\Delta T}} \tag{86}$$

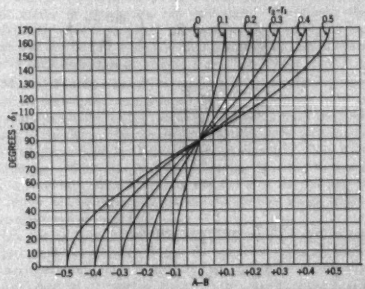



FIG. 47—CURVES USED IN DETERMINING THE ANGLE AT WHICH SWITCHING MUST OCCUR TO MAINTAIN STABILITY. PART III

Time may be obtained from Equations (84) and (86) by applying Equation (78) or (78a)

### The Angle at Which Switching of the Fault Must Occur for a Given Initial Torque and Angle to Achieve Stability

Consider the ideal case of a generator delivering power to a motor over two or more interconnecting lines. The torque-angle characteristics are shown on Fig. 44, the equations of which are

$$T = \frac{\Psi_a \Psi_b}{x} \sin \delta$$

where $x$ equals the reactance between the two machines, a different value for each condition. $T_1$ and $\delta_o$ are the initial torque and angle at which the generator is operating before the fault occurs. During the fault, the generator is operating on the new torque-angle curve $B$ and with the initial angle of $\delta_o$. A torque of only $T_o$ can be maintained but, with the prime mover delivering $T_1$, the difference between $T_1$ and $T_o$ is available for acceleration. As the generator rotor accelerates, there will be some angle $\delta'$ where if switching occurs, the generator will just be stable. Referring to the torque angle characteristic of Fig. 44 the area $a_1$ is available for accelerating the rotor while the area $a_2$ is available for deceleration. The criterion for stability limit is that switching occurs at $\delta'$ so that $a_2 = a_1$. The maximum angle $\delta'$ may be obtained from the equation[1]

$$\cos \delta' = \frac{\sin \delta_o (\delta_2 - \delta_o) - r_1 \cos \delta_o + r_2 \cos \delta_2}{r_2 - r_1} \qquad (87)$$

where

$$r_1 = \text{ratio } \frac{B_{max}}{A_{max}}$$

$$r_2 = \text{ratio } \frac{C_{max}}{A_{max}}$$

$$\delta_2 = \pi - \sin^{-1}\left(\frac{\sin \delta_o}{r_2}\right)$$

Also

$$T = \frac{\sin \delta_0}{r_1}$$

$$T_1 = \frac{T_0}{r_1}$$

$$\Delta T = \frac{1 - r_1}{r_1} \sin \delta_0$$

$$T_m = B_{max}$$

This equation has been expressed* in the form of three curves in Figs. 45, 46, and 47, whereby knowing $r_1$, $r_2$, and $\delta_o$, $\delta'$ may be obtained directly. For example, from Fig. 45 for a given $r_1$ and $\delta_o$, a value of $A$ may be found; from Fig. 46 for a given $r_2$ and $\delta_o$, a value $B$ may be found. Then, knowing these, the angle $\delta'$ may be found from Fig. 47.

*By Mr. E. M. Hunter.

For a given set of conditions, the amount of power that can be carried through a fault with instantaneous switching and again with very slow† switching may be found directly.[1] For intermediate fault durations, the angle $\delta'$ may be determined from Figs. 45, 46, and 47, the time for the rotor travel from $\delta_o$ to $\delta'$ may then be determined from the curves in Figs. 34 to 43.

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†About 0.75 second.

## Discussion

**W. S. Peterson:** In order to form a judgment of the general problem of stability, a great many portions of the problem are handled by solving a two-machine problem with generators at one end and synchronous machines, steam plants, synchronous condensers, or synchronous motors, at the receiving end. By the study of such a simple system, it is possible to form better judgments of what is happening. This brings up the point Mr. Summers mentioned of "boiling down" the system. He didn't mention it in his presentation of the paper, but in one of the appendices he refers to the method which was first presented by Miss Clarke, in which a portion of a system is represented by an equivalent machine at the end of the line. In a long transmission line there are the capacity effects of the line, a load on that line, both of which are shunt paths considered with relation to the synchronous machines at each end of the line.

At that time the device was originated of paralleling the impedance of the machine with the impedance of the shunt paths and the formulas devised by Miss Clarke are suitable to that purpose.

I have taken a little different attack on that problem, and suggest another method in which the machine is used with its original reactances, values of $W r^2$, and excitation voltages.

Assume there is a synchronous machine at one end of a transmission line, and another synchronous machine at the other end. Then when it comes to combining line capacitance and loads of any kind on the receiving bus, to form an equivalent machine, which is different from the machine being considered, it is preferable to bring into use the general circuit constants in which the loads and other shunt circuits are combined with the transmission line.

Evans, Sels, and Wagner, have shown ways of combining admittances and impedances, such as are found in connection with transmission circuits to form a new general circuit with constants, $A$, $B$, $C$, and $D$. Almost any sort of network between the two points can be represented by general circuit constants. The machines are then separated merely by a simple circuit expressed with these constants. It is possible to use the same power relationships, and formulas would be used in an ordinary transmission-line calculation, except that instead of the relationships being between the ends of the line, the relationships are expressed between the internal voltages of the synchronous machines. By this method it is possible to calculate the power angle diagrams, such as Mr. Summers has mentioned in his paper.

In general, it is this type of diagram, where power is plotted against angle, or torque against angle, which is the fundamental thing that is used in following the angular movements of the machines.

In using this method it is found that there is a considerable shift of the curve with respect to the axes, depending on the constants, loads, etc., assumed but I have suggested the method because it is the simplest way of handling the two-machine problem. It is exactly in line with the use of the driving-point impedance and the transfer impedance used in more complicated circuits.

In addition to that point I want to say that I think that one of the best aids to stability in addition to quick circuit breakers, is quick excitation. I should like to see the regulators and excitation systems developed to the point where the manufacturers would be absolutely sure that those devices can be depended upon. Otherwise, the stability of a line is too much decreased from the values we can obtain if we have absolutely good regulators. I think there should be much development in that particular branch of the work.

**V. B. Wilfley:** With reference to the section on the excitation systems, it would have been interesting to have had a more complete discussion of the exciter part of this system itself, that is, apart from the regulator.

To my mind, if you have a regulator which operates to close its contacts instantly on drop of positive sequence voltage, keeps them closed until the voltage is restored to normal, and has anti-hunting characteristics, you can ask no more of it. Then it is up to the excitation system proper. And to my mind most of the work on the quick-response excitation system must be done with reference to the exciter in conjunction with the generator field.

There seems to be considerable disagreement in the results obtained by factory tests as to just what is the best exciter response. This paper mentions 200 volts per second. That doesn't mean anything in itself unless it is considered with the rest of the system, but we have found in general that speeds of say 400 to 600 volts per second are in general more desirable and the expense involved in securing these speeds is very little, if any, more than that required to obtain 200 volts per second.

The matter of fast relaying and switching is certainly of importance and deserves emphasis.

I anticipate that there will be considerable improvement in circuit-breaker design and in system relaying within the next two or three years because that particular line has been lagging.

With regard to intermediate synchronous condensers and stability, I cannot agree with the author's statements. To my mind the intermediate synchronous condenser is to be largely instrumental in bringing about the transmission of large amounts of power over very long distances at high voltages.

It should be remembered that very fast relaying and breaker operation impose heavier duties on the system breakers. It is possible that you may go from one type of system trouble to another. That is, you may alleviate certain stability troubles and increase circuit-breaker troubles. That is something that should be kept in mind when making any changes on the system.

Mr. Peterson brought out the point that the manufacturing companies should arrive at a more solid basis regarding their guarantees on quick-response excitation systems. I think most engineers realize the difficulty involved. The benefit to be derived from quick-response excitation is very intangible and it is very hard to place an actual kilowatt value on it as compared with the added cost. Extensive studies on the systems involved are necessary in order to arrive at any idea as to what quick-response excitation will mean in the way of value. It is a matter of whether you can afford to stand certain outages or whether you want to spend some money and possibly eliminate them.

**L. R. Gamble:** On a recent development of the Chelan power site on the Washington Water Power system, an investigation was made of quick-response excitation. We found that it practically does us no good. We are praying for a circuit breaker that will do the job, a breaker that is extremely fast in operation under fault conditions.

**Mabel Macferran:** There appear to be two sides to the question of high-speed excitation. On the favorable side is the increase in synchronizing torque which results from the strengthening of the fields. On the unfavorable side is the virtual elimination of decrement in the short-circuit current. This increases the energy fed into the fault and so causes the rotors to slow down more suddenly, thus increasing the shock to the system. Such an effect will be especially marked on systems where faults contain appreciable resistance.

On the system of the company with which I am connected, it has often been observed that the synchronous condensers slow down markedly when a ground fault occurs. Apparently the rotors feed their inertial energy very rapidly into the fault, with the result that the speed sometimes drops as low as half normal value. This phenomenon suggests that one should proceed with some caution when applying high-speed excitation to condensers.

**J. P. Jollyman:** I agree with the conclusion of the authors that more speed is desirable in oil circuit breakers.

The question of system stability would be very largely solved if we could get trouble off the system in a very short time. A

very short time means under half a second and as much under as physically possible.

Excitation systems should have fairly high speed both for building up voltage and for lowering voltage. The first is needed when a decrease in transmission capacity occurs due to trouble or to the loss of a circuit. The second is needed when a generator or synchronous condenser is left on a long extra high-voltage line that has been suddenly disconnected from its load. Under these conditions the speed of a water-wheel-driven generator will increase from 10 per cent to 35 per cent which makes a quick decrease of excitation desirable, especially in the case of direct-connected exciters.

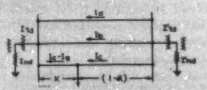

FIG. 1—APPARATUS CONNECTIONS IN SINGLE-LINE DIAGRAM FOR A HIGH-TENSION BUS AND TERMINAL APPARATUS

**J. B. McClure and E. M. Hunter:** (communicated after adjournment) Zero-phase sequence impedance of transmission lines has been given in Table II of the paper for several combinations of terminal connections including one, two, and four lines in parallel. To extend the usefulness of the paper and to make this table more complete, the zero-phase-sequence impedance of three transmission lines in parallel and connected terminal apparatus is presented here.

Letting,

$$Z_d = Z_{Td} + 3\,Z_{nd}$$
$$Z_d' = Z_{Td}' + 3\,Z_{nd}'$$
$$Z_a = Z_{Ta} + 3\,Z_{na} \qquad \text{etc.}$$

the general solution for the diagram shown on Fig. 3 is

$$Z_0 = -\frac{\begin{vmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{vmatrix}}{\begin{vmatrix} e & f & g \\ i & j & k \\ m & n & o \end{vmatrix}}$$

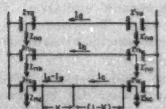

FIG. 2—APPARATUS CONNECTIONS IN SINGLE-LINE DIAGRAM FOR A LOW-TENSION BUS AND TERMINAL APPARATUS

where,

$$a = -[Z_d + K\,Z_{ac}]$$
$$b = -[Z_d + K\,Z_{bc}]$$
$$c = -[Z_d + K\,Z_{cc} + Z_3]$$
$$d = [Z_d + K\,Z_{cc} + Z_c]$$
$$e = [Z_a + Z_a' + Z_{aa} - Z_{ab}]$$
$$f = [Z_{ab} - Z_b - Z_b' - Z_{bb}]$$
$$g = [Z_{ac} - Z_{bc}]$$
$$h = [K\,Z_{bc} - K\,Z_{ac}]$$
$$i = [Z_{ab} - Z_{ac}]$$
$$j = [Z_b + Z_b' + Z_{bb} - Z_{bc}]$$
$$k = [Z_{bc} - Z_c - Z_c' - Z_{cc}]$$
$$l = [K\,Z_{cc} + Z_c - K\,Z_{bc}]$$
$$m = [Z_d + Z_a + Z_a' + Z_{aa}]$$
$$n = [Z_d + Z_d' + Z_{ab}]$$
$$o = [Z_d + Z_d' + Z_{ac}]$$
$$p = [Z_d - K\,Z_{ac}]$$

This general solution can be used to determine the zero-phase-sequence impedance of the following arrangements shown in Figs. 1 and 2.

(a) 3 circuits, high-tension bus, all switches closed; where $Z_a, Z_a' \ldots\ldots Z_c' = 0$

(b) 3 circuits, low-tension bus, all switches closed; where $Z_d$ and $Z_d' = 0$

(c) 3 circuits, low-tension bus, any low-tension switches open. Same as (b).

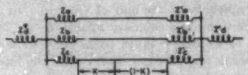

FIG. 3—SIMPLIFIED ZERO-PHASE-SEQUENCE IMPEDANCE DIAGRAM FOR FIG. 1

(d) 3 circuits alone ($Z_0'$), viewed from high-tension bus where $Z_a, Z_a' \ldots\ldots Z_c', K$, and $Z_d' = 0$; $Z_d$ is any arbitrary value assumed for convenience.

$$Z_0' = -\frac{Z_0\,Z_d}{Z_0 - Z_d}$$

Relay operation often gives cascading of breaker opening and hence, it is often desired to know the zero-phase-sequence impedance for the arrangement shown in Fig. 4.

The general equation for the zero-phase-sequence impedance of this set-up is

$$Z_0 = \frac{\begin{vmatrix} q & r & s \\ t & u & v \\ w & x & y \end{vmatrix}}{\begin{vmatrix} t & u \\ w & x \end{vmatrix}}$$

where,

$$q = [Z_d' + (1 - k)\,Z_{ac}]$$
$$r = [Z_d' + (1 - k)\,Z_{bc}]$$
$$s = [Z_d' + (1 - k)\,Z_{cc} + Z_c']$$

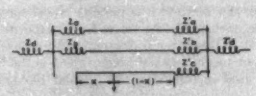

FIG. 4—SIMPLIFIED ZERO-PHASE-SEQUENCE IMPEDANCE DIAGRAM FOR FIG. 2

$$t = [Z_{aa} - Z_{ab} + Z_a + Z_a']$$
$$u = [Z_{ab} - Z_{bb} - Z_b - Z_b']$$
$$v = [(1 - k)\,(Z_{ac} - Z_{bc})]$$
$$w = [Z_d + Z_d' + Z_a + Z_a' + Z_{aa}]$$
$$x = [Z_d + Z_d' + Z_{ab}]$$
$$y = [Z_d' + (1 - k)\,Z_{ac}]$$

This general solution may be used to determine the zero-phase-sequence impedance of the following arrangements

(a) 3 circuits, high-tension bus, one high-tension switch open, where $Z_a, Z_a' \ldots Z_c' = 0$

(b) 3 circuits, low-tension bus, one high-tension switch open where $Z_d$ and $Z_d' = 0$

**I. H. Summers:** Mr. Peterson's suggestion of using general circuit constants is a good one. It is probably a matter of preference which method to use and the method of circuit analysis with driving point and transfer impedances used in our paper is exactly equivalent.

Mr. Wilfley's remarks indicate that he believes that the

intermediate synchronous condenser is something to be mainly instrumental in bringing about the transmission of large blocks of power over very large distances. He does not give any data in support of this belief but we can refer to the discussion presented by Miss Macferran which indicates that in certain cases at least, synchronous condensers are somewhat detrimental to stability. The curves in Figs. 24 and 25 in our paper also fail to show any appreciable gain from the condensers under consideration. Further study and experience are needed on this point but it should be pointed out that at least the evidence seems to be lacking which would establish the great benefits which Mr. Wilfley claims for intermediate synchronous condensers when transient conditions are considered.

The question which Mr. Wilfley has raised in regard to the relative efficacy of different types of regulators is one which was rather thoroughly thrashed out after the St. Louis Regional Meeting in March 1928. The final outcome of the discussion which developed at that time was an agreement on the part of all of the parties who presented discussions, including several of Mr. Wilfley's associates, that the ability of regulators to improve the stability of synchronous apparatus can, in general, vary widely even though the conditions mentioned by Mr. Wilfley are fulfilled. That is, it was generally agreed that other factors can be important in regulator design besides those listed by Mr. Wilfley.

Unless Mr. Wilfley has some new thoughts or data which show that the results previously found were incorrect, it would seem unfortunate to raise this same question again.

It is gratifying to note the general agreement in regard to the benefits to be expected from quick switching. It would seem that breakers which will open the circuit in 0.2 second time are desirable and it is interesting to note that 230-kv. breakers which open the circuit in less than 0.2 second have actually been built and tested.

# Series Synchronous Condensers
## for Generation of Voltage Consumed by Line Inductance

BY THEODORE H. MORGAN*
Associate, A. I. E. E.

*Synopsis.—The factors determining the power-carrying capacity of a transmission system are briefly discussed in this paper. The principal effects obtained by the operation of synchronous condensers used to compensate for the system consumption of lagging reactive kv-a. are pointed out. This method of compensation is contrasted with the direct method of supplying the reactive kv-a. to the line in the manner in which it is consumed, i. e., by the series method.*

*A plan for obtaining direct or series reactive kv-a. compensation by a method employing electric machinery is described. This includes a description of a method for producing the required voltage and inserting it into the system.*

*Some of the characteristics of operation and advantages to be gained by the use of the described method are given.*

* * * * *

### Principles and Practise

A COMPLETE investigation of the transmission line power-limit problem shows that in the final analysis the limit of the amount of power which can be transmitted over a given system at a fixed maximum voltage and load power factor is determined by the total series inductive reactance of the system. The combined inductive reactance effects of the circuit, from the point of generation of the internal e. m. f. in the alternator to the point of voltage drop due to the e. m. f. of the load end machinery, determine the maximum amount of power that can be transmitted from the rotor of the generator to the rotors of the load machines.

The inductive reactive kv-a. of the load has its influence in limiting the maximum power which a system can transmit. An understanding of this principle, combined with the necessity of maintaining constant voltage at the load, has led to the practise of operating synchronous condensers at the load end of the line. These condensers may be considered as a source of inductive reactive kv-a. capable of compensating totally for load power factor, but only partially for line consumption of reactive kv-a. Such a method of compensation gives load end voltage control while increasing the system power limit. In fact, voltage control and reactive kv-a. compensation are interrelated, one action accompanying the other. The ultimate power limit is reached with the limit of compensation. The important fact related to synchronous condenser operation at the load end of the line is that complete compensation for line effects becomes impossible with increasing load, and the load and generator machinery finally fall out of step because of the inability of the system to transmit the load required of it.

About a year and a half ago, in an attempt to test out a new practise, an installation of series capacitors was placed in operation on a transmission line.[1] Such capacitors provide a method of series inductive compensation which is direct and inherently automatic. They produce a voltage across them which is opposite in phase angle to the voltage caused by the inductive reactance of the line. By proper choice of the capacitor size these two voltages may be made to entirely counteract each other, thus compensating for the inductive effects of the system. The line effects are completely eliminated and the amount of power which it is possible to transmit is very materially increased.

*General Methods.* It may be said that there are in general two methods by which reactive kv-a. may be supplied to a transmission system. First, it may be furnished indirectly by apparatus connected across the line in a manner similar to an ordinary load; or second, it may be added in a direct manner through apparatus connected in series relation to the line conductors. Each method gives compensating effects which are different in character and results obtained.

The first method changes the phase angle of the line current with respect to its voltage and in this way produces a line drop at such an angle that the load end voltage is held constant at a required value which may be equal to that of the generator end. This is shown in a simple case by the vector diagram of Fig. 1, in which the line charging current and resistance drop are omitted. With increase of line current, the angle between the generator-end voltage and the load current increases and the compensating reactive power supplied must increase with the load in order that the load voltage may be maintained. The maintenance of synchronism between generator and load is dependent entirely upon this principle when the phase angle between load current and generator-end voltage becomes large. This is because the power represented by these two quantities considered by themselves becomes diminishing under these conditions.

In the second method, the compensation is obtained by the addition of a series voltage to the system. This plan does not alter the line current, but the reactive kv-a. is produced by the inserted voltage acting with this current. The compensation is direct and the reactive kv-a. is supplied in the same manner that it is

*Assistant Professor of Electrical Engineering, Stanford University, Palo Alto, Calif.

1. See Bibliography 2 and 3.

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29-135

consumed. Referring to Fig. 2, $E_L$, the voltage produced by line inductance is counteracted by the voltage $E_C$, equal to it and opposite in phase angle. In this case the line effects have been completely compensated for, and the load end voltage becomes identically equal in magnitude and phase to that of the generator end.

## A New Method

The problem at its present status would seem to demand that all possibilities and options should again

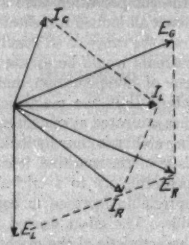


Fig. 1—Vector Diatram showing Compensation with Synchronous Condenser

$E_G$ is generator end voltage
$I_R$ is load current
$I_C$ is correcting current
$I_L$ is line current
$E_L$ is voltage produced by line inductive reactance
$E_R$ is load end voltage

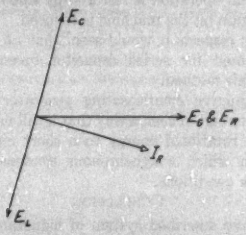


Fig. 2—Vector Diagram showing Direct Compensation

$E_G$ and $E_R$ are generator end and load end voltages
$I_R$ is load current
$E_L$ is voltage produced by line inductance
$E_C$ is voltage supplied by correcting apparatus

be investigated. With the belief that the direct or second method is preferable to the one now commonly used, an attempt has been made to develop a plan by which the desired results may be obtained by the use of electrical machinery. It was realized that if a voltage identical both in magnitude and phase to that produced by series capacitors be generated and applied in series to the circuit, effects similar in general character to those realized by capacitors may be obtained. The following system of machine operation has been devised for this purpose.

*Description.* The general plan of arrangement is shown by the wiring diagram of Fig. 3. The reactive kv-a. required for compensation is supplied by a machine similar in construction to a synchronous condenser, which for want of a better name will be called the "inductive compensating generator." This machine is driven at synchronous speed by a synchronous motor, operated in the ordinary way from a bank of transformers connected across the line.

The voltage to be supplied to the line by the driven machine should be proportional to the line current since its purpose is to compensate for a voltage caused by this current flowing through the line inductive reactance. With the iron of the magnetic circuit of the machine below the point of saturation, this would require an exciting current which is at all times proportional to the alternating current of the line. This immediately suggests using the line current for machine

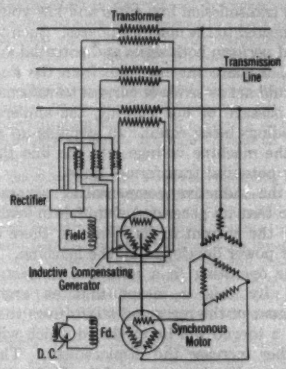


Fig. 3—Wiring Diagram of Arrangement of Apparatus

excitation purposes. This current may be passed through current transformers to obtain a suitable magnitude, then rectified with a polyphase mercury arc or other rectifier, and passed through the field circuit of the machine. Special current transformers with sufficient iron in the core would produce voltage impulses on sudden changes of line current, thus providing rapid response in machine excitation.

The requirements of frequency and magnitude having been met, there is the question of maintenance of proper phase relation for the compensating voltage. Due to its inherent characteristic, the driving synchronous motor would hold the rotor of the inductive compensating generator to an approximately constant phase position with respect to the line voltage. If it were possible to maintain constant power factor on the line, this is all that would be required, once the original setting of the angle between the two rotors had been correctly adjusted. However, since there is a

possibility of change of line power factor angle with change of load, it would seem that provision should be made to meet this contingency. The machine should normally operate with the voltage which it produces in leading quadrature relation to the current through it. By arranging the stator of either the driving motor or the inductive compensating generator so that it can be moved in such a way as to alter the relative phase angle between their armature windings, the required condition can be maintained. The real power output will always be zero and the stator position could be automatically controlled to produce this condition for all phase positions of the line current.

In cases where compensation is to be made on relatively low-voltage lines, the separate phase windings of the machine could be connected directly in series with the line wires. When used on high-voltage lines transformers would be necessary. These transformers would have their high-voltage windings placed in series with the transmission line wires and low-voltage windings connected to the machine phases. Such transformers would perform both series and potential duty and in addition, insulate the machine from the line voltage. They would act as series or current transformers in permitting passage of line current, the ampere-turns of both windings being equal. In stepping-up and introducing the machine voltage into the line they would be doing potential transformer duty.

With the inductive compensating generator being driven so that its generated e. m. f. is in leading quadrature to the current in its windings, there will be no torque or power developed by the machine. However, it will be operating in a condition of unstable equilibrium. By this is meant that on any relative displacement of the rotor and stator from the required position, a torque will be produced which will tend to still further increase the displacement. This torque will increase with the amount of the displacement up to the 90 electrical degree angle in either direction. The position of 180 electrical degrees from the required operating position is the stable one, and the rotor would seek this position if allowed to do so. In order to maintain the desired operation it is necessary that the driving motor be designed to produce more torque for small angles of displacement than that produced by the driven machine. Under normal operation the load on the driving motor would be very small as it would only be required to supply the rotation losses of the compensating machine. Thus for the driving machine, there would be required a relatively small motor with special characteristics.

*Characteristics and Advantages.* When this plan of compensation is applied to very long lines it might be desirable to insert a number of compensating units at intervals along the line, so that the supplied voltage would not be excessive at any single unit. This would also aid in keeping the line voltage more uniform throughout the entire length. For all cases of complete compensation, irrespective of the number or location of the units, the total reactive kv-a. supplied would be equal to the inductive reactive kv-a. consumed by the line if the line charging kv-a. be neglected. Also complete compensation by compounding the line inductance voltage would eliminate, in every case, its detrimental effects on voltage regulation and power-carrying capacity, leaving only the factor of line resistance.

The one operating benefit derived from line inductance is its effectiveness in limiting short-circuit currents. If the compensation were sufficiently complete to counteract all inductance effects of the line and transformers over the range of all possible currents, the short-circuit currents would be excessively high. The machine system of compensation, however, has the decided advantage that the magnetic circuit of the machine becomes saturated at certain currents and that its compensating ability is thus limited. As a result of this characteristic of the machine, it is possible to obtain full compensation up to a critical current, after which any appreciable increase in compensation becomes impossible. The effect desired is obtained by the inherent characteristic of the machine without any supplementary control. In this respect, compensation by machinery is far superior to that obtained with a series capacitor, which must be short-circuited on heavy currents with the resulting system disturbance upon its subsequent return to the circuit. With machine compensation, on the disappearance of the heavy line current, normal operation is restored by smooth action as the excitation on the machine is reduced.

In other respects it would seem that all the advantages claimed for series capacitor operation would apply to this method.

The inductive compensating generator is connected to the circuit in such a way that it will not supply its storage of rotational energy to a short circuit in the manner in which a synchronous condenser operates under such conditions.

## Conclusion

The above described system of inductance compensation has been devised with the hope that it may in some small way point toward the solution of a vital problem in power transmission. No claim is made that the general plan is finally or completely worked out in all its details. On the basis of conformity to present practise, it will have no advocates. Because of its departure from methods now employed, many matters realized only through operating experience are as yet undetermined. However, granted that the general plan is fundamentally sound, its success must be inseparably linked with the ability to maintain complete, dependable, automatic machine control. In this regard it may be said that the rapid advance which is being made in the art of electrical controls is positive proof that this phase of the problem can be satisfactorily solved when the demand arises.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the faculty of the Electrical Engineering Department of Stanford University for many helpful suggestions, and particularly to Dr. Harris J. Ryan for his inimitable encouragement and assistance in the development of this plan.

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## Discussion

**J. A. Koontz:** We know that in some cases the series capacitor has apparently been put into use with success on relatively low-voltage lines. It may be that some method as suggested by Professor Morgan might be worked out for high-voltage lines. It has been suggested that the synchronous condenser requires additional interrupting capacity in switchgear. By such a method some of this interrupting capacity would be eliminated. I do not believe that Professor Morgan thought the series generator, as proposed, would entirely eliminate the condenser as the condenser has a certain function of improving power factor, but it would take care of a portion of the additional condenser capacity that we utilize on our long lines for regulation purposes and as such might be of advantage if carefully worked out.

**E. C. Starr:** Would it be possible to apply this scheme on the low-voltage side of the transformers supplying the transmission line? If so the cost would be considerably less than if applied to the high-voltage side.

**W. S. Peterson:** There is one point I think we might bring out in this paper, and in presenting it I do not present it as a point of criticism. I merely offer it as a point of investigation for further improvement of the method.

It will be observed, from the suggested method of excitation involving the use of a series current transformer and a rectifier, that only the magnitude of the field current is controlled. There is no way of obtaining a change in the phase angle. This was brought out by Professor Morgan when he indicated the necessity for changing the rotor position for different power factors or different angles of load. During sudden or transient conditions there would be a very rapid change in the power-factor angle of the current. That is, the short-circuit current has a different power factor from the normal load current, and this sudden change will cause a considerable change in load on the motor, as brought out by Professor Morgan. These things will involve transient torque, which makes this problem the same complicated stability problem that we now have. This phase of it should be investigated in order to verify the workability of the system.

**T. H. Morgan:** I take pleasure in confirming the assumption made by Mr. Koontz that this new system has not been suggested as a complete substitute for the synchronous condenser in most cases. The synchronous condenser performs a duty in the correction of load power factor in a manner which it is very difficult to equal by any other method.

Mr. Starr's suggestion of operating the proposed correcting apparatus on the low-tension side of the system would be quite feasible and satisfactory in many cases. It appears to me that the answer to this question would depend to a very large extent upon the physical characteristics of the transmission system under consideration. It must be remembered that this is a series method, and as such, correction must be made at such a point that it will be in series with the total load on the line. On a long transmission line a number of correcting units might be placed at intervals along the line. Of course, in such a case it would be necessary to handle the high voltage on the transformer primary.

I believe the remarks of Mr. Peterson concerning difficulties under transient conditions are perfectly justified. Much investigation must be done before we can be in a position to state the exact and complete operation under transient conditions. The important information required in such an investigation is an accurate determination of the magnitude and phase angle of the line current under such conditions. The diversity of the many factors to be considered in this problem make it practically a separate one for each individual transmission system.

# Recent Developments in Toll Telephone Service

BY W. H. HARRISON[1]

Associate, A. I. E. E.

*Synopsis:—This paper deals principally with the physical and technical phases of the development in recent years of "toll" telephone service in this country, with particular emphasis on the longer haul or "long distance" traffic. The very rapid growth in toll telephone business has required a rapid extension of toll plant including outside plant, buildings, and switchboard and other equipment. The most striking developments in the outside plant are very great growth in toll cable networks and the rapid extension of the carrier telephone systems. The factors involved in the relative use of these various types of plant are discussed. An outline is given of the advance planning and study necessary to insure that these annual programs are properly engineered so that, as closely as possible, they will effectively anticipate future requirements and extensions in a most suitable and practicable manner. The more important limitations affecting the design of toll plant from the standpoints of the efficiency, quality, speed, and length of telephone transmission and the specific treatments of each are generally discussed in the paper. These include such matters as the use of loading coils, vacuum tube repeaters, equalizers for attenuation and phase distortion, and means for reducing the effects of echoes and time lag or delay in the circuits. Mention is also made of modifications of the open wire plant to effect material reductions in crosstalk and to thereby permit a substantial increase in the use of carrier telephone facilities.*

*The paper discusses the extension of toll service to include connection with the telephone networks in other countries including Canada, Mexico, Europe, Cuba, and South America.*

* * * * *

THE term "toll" is applied broadly to telephone service between different localities as contrasted with "local" service which is, in general, within one municipality or center of population. From the early days of the telephone business the growth in toll service has always been rapid. This growth has, however, been particularly marked during the last few years.

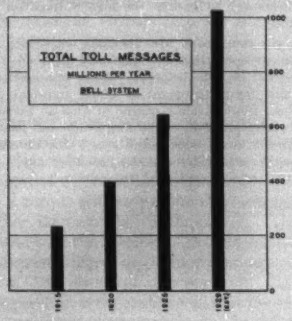


FIG. 1

It is the purpose of this paper to outline briefly some of the plant design and other engineering problems associated with the present rapid growth of this service.

## MAGNITUDE OF GROWTH

The growth of toll telephone business is illustrated by Fig. 1, which shows the telephone toll messages per year in the Bell System for a number of years. This growth is perhaps more strikingly shown by Fig. 2 which shows in terms of cost the gross additions to toll plant per year for the last few years and the estimated expenditures for 1929. It is to be noted that not only is the per cent increase very rapid in comparison with that of past years, but it is expected to continue at a very rapid rate.

A remarkable feature of the increase in the toll business is the fact that the largest increases are being felt in the very long distance business, particularly on the transcontinental routes and the routes between the largest cities in the various parts of the country. Figs. 3 and 4, for example, illustrate respectively the growth in toll messages over a period of years between Chicago and New York, and between Chicago and Los Angeles,

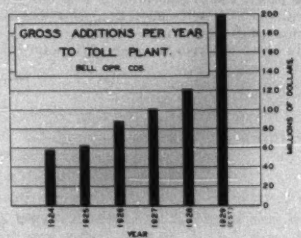


FIG. 2

which routes are typical examples of this growth. Fig. 5 shows the growth in messages for the combined toll business over the transcontinental routes between Chicago and New York and Los Angeles and San Francisco over the same period. It will be noted that while the toll business in the system as a whole has increased 34 per cent over the last 3 years, the toll messages between Chicago and New York have increased about 115 per cent, the toll messages between Chicago and Los Angeles 157 per cent, and the combined transcontinental business 226 per cent. These increases

1. Plant Engineer, American Telephone & Telegraph Company, New York, N. Y.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.*



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in toll messages have required considerable enlargement of the size of the circuit groups between distant points and have contributed largely to the major construction problems in the design and layout of the plant.

The reasons for the recent rapid growth in the toll business are many. The growth has no doubt been influenced by the good level of general business in all parts of the country. There has also been an increasing

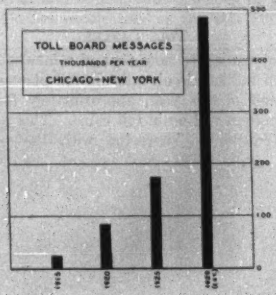



Fig. 3

public appreciation of the extent to which telephone toll service is of value in both business and social life and of the variety of uses to which it can be put. This is evidenced by the increasing number of by-product

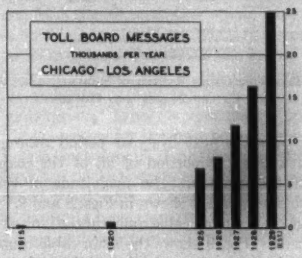



Fig. 4

uses and services which the toll user is constantly requiring. The continued development of economies in plant design, tending to limit increases in telephone rates to a much lower percentage than the general level of prices and which has made possible several recent rate reductions, is without doubt another important influence.

Considerable added stimulation to the growth of the toll business has undoubtedly resulted through improvements in the quality of the service given. Possibly the most important improvement in this respect is the increase in the speed of the service, that is, the decrease in the time which elapses between the placing of a call and its completion. This is shown in Fig. 6. The improvement is greater for the long distance calls than for the toll service as a whole, the average speed

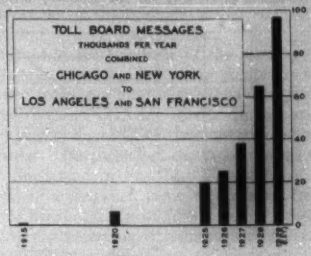



Fig. 5

for the toll board traffic being about 2½ minutes in 1928 as compared with almost 7 minutes in 1925.

The increase in the speed of handling toll service has been largely brought about by the introduction of improved operating practises and facilities which have permitted the use of simplified methods of operation similar to those employed for local business. An increasing amount of the shorter haul toll business is handled directly by the local operator who first answers the subscriber's call. The speed of the large part of the longer haul business which must be handled by toll board operators has been greatly increased by arrangements whereby the toll operator first receiving

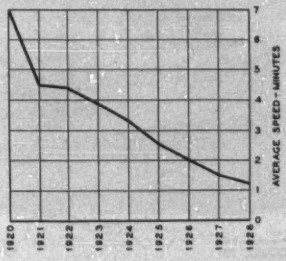



Fig. 6—Average Speed of Toll Service

the call is enabled to do both the recording work and the switching necessary to complete the call. The result of the materially faster service has been that over 95 per cent of the total toll messages are completed or reported upon while the subscriber remains at the telephone, without requiring him to hang up and be called again.

Another important improvement in the quality of

service has been brought about both through large increases in the volume of sound delivered at the end of the toll circuits and by improvements in the design of circuits, resulting in the greater distinctness and naturalness of the messages. This has included the use of methods providing for the efficient transmission

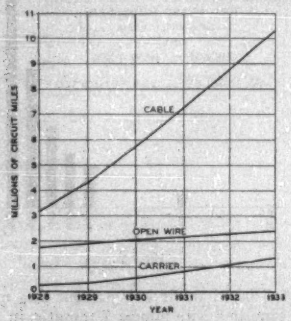



Fig. 7—Estimated Toll Circuit Miles in Plant Bell Operating Companies

of a much larger proportion of the component frequencies which make up speech. These improvements have largely reduced the percentage of messages in which the clearness of transmission is judged to be unsatisfactory, at the present time this being about 1 per cent for the total toll traffic.

Other improvements in service have led to greater freedom from the possibility of interruption of the service and to its improvement in other respects.

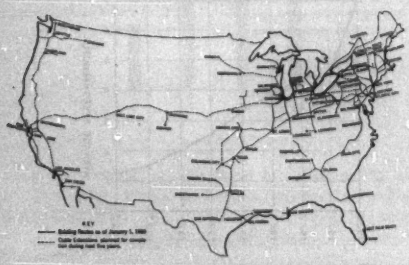


Fig. 8—Main Toll Cable Routes of the United States

While much remains to be done in the further perfection of the toll service, it is believed that material progress has been made in fitting it to the needs of the customer and this has, no doubt, been one of the outstanding reasons for the rapid growth.

## Additions to Plants

The rapid growth in the toll business has required a great expansion of the toll plant and has been accompanied by material changes in the character of the plant and in the nature of the engineering problems. This expansion has been particularly marked in the case of the toll cable plant, additions to which have been experienced in practically all parts of the country. An interesting illustration of this expansion is given in Fig. 7, which shows the relative proportions of the three important types of toll plants at the end of 1928 and the estimated trend for this year and the immediate years following.

## Toll Cables

It is interesting to note that of somewhat over six and a half million circuit miles in toll plant estimated for the end of this year, approximately four and a quarter million will be in toll cable. This percentage will be constantly increasing with the immediate following years. The extension of the toll cable

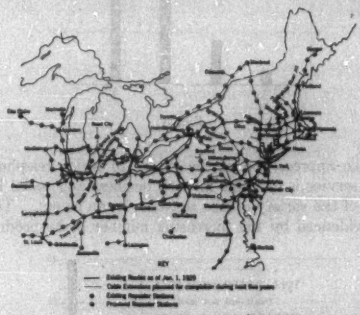


Fig. 9—Main Toll Cable Routes in Northeastern Section of United States and Canada

program over the next five-year period contemplates cable on a large proportion of all of the major toll routes of the country. The magnitude of the proposed cable networks is shown in Figs. 8 and 9. Fig. 8 illustrates the main toll cable routes of the United States and Canada. Fig. 9 shows the main cable routes and extensions in the northeastern area of the United States and Canada, the development in this area being considerably more dense than in any other section of the country. It will be seen that in accordance with these proposed five-year plans toll cable will extend entirely across the continent and up and down the length of both the Atlantic and Pacific coasts, as well as practically from Canada to Mexico in the central part of the country. With the completion of this large toll cable program, it is apparent that some of the toll messages will be routed within the five-year period through more than 4000 miles of cable.

The toll cable which will be installed in the Bell System this year will amount to nearly 5000 miles.

This amount will be increased to between 6000 and 7000 miles for next year, and it is expected that the yearly additions will continue at that rate or even higher for the next few years thereafter. The estimated construction expenditures for the toll cable additions during 1929, including the supporting structures, conduit runs, and repeater and terminal equipments, will be in the order of about $100,000,000.

### Types of Cable Construction

Both aerial and underground methods of toll cable construction are widely used in the Bell System, the

Fig. 10—Aerial Type of Toll Cable Construction

construction at the present time being about equally divided between these two general types. The greater part of the present longer haul toll cables are of the aerial type. In the aerial construction, the cable is suspended from a steel messenger strand supported on poles, as illustrated in Fig. 10. The aerial type of construction is, in general, limited to two cables per pole line and is, of course, used in the places where the growth is moderate.

The underground type of construction up to the present has consisted for the most part of cables drawn into multiple duct, usually of vitrified tile, although in certain sections of the country some use has been made of creosoted wood duct. The underground construction has naturally been employed in cities and metropolitan areas and in heavy and rapidly growing cable routes as between the cities of the Atlantic seaboard and between Chicago and New York, where the provision of facilities for placing a number of cables within a reasonable period of time is important. One of the first toll conduit and cable installations was made in 1908 between Chicago and Milwaukee.

During the past year trial installations have been made of two new types of underground construction designed to meet conditions where one or two cables will handle the requirements for a considerable number of years. One of these consists of a lead sheath cable pulled into a single fiber duct. In the other, a specially protected cable is buried directly in the ground without the use of ducts. The protection, known as tape armor, is applied over a lead covered cable of conventional design, the armoring consisting of coverings of impregnated paper, jute, and steel tapes which safeguard the lead sheath from soil corrosion and mechanical damage. In both of these types of construction, manholes are built only at loading points and thus about 90 per cent of the manholes employed in the more usual conduit structure are omitted.

The splices at the junctions of the sections of tape armored cable between the loading points are encased in split cast iron cases filled with asphaltum compound to prevent contact with the earth. Splices at similar locations in fiber duct installations are covered by large fiber sleeves. The placing of the tape armored type of cable is illustrated in Fig. 11. This type of buried construction appears to have advantages for some conditions where the rate of growth is not rapid. One interesting characteristic is reduced susceptiveness to inductive influences due to the shielding effect of the armor.

Both of these two types of construction have given satisfactory results in trial installations and it seems probable that they will find a considerable field of use in the Bell System.

### Toll Cable Construction and Maintenance

The large annual additions to the toll cable plant necessitate the utmost care and precaution in planning and carrying out the construction and maintenance of this plant. The selection of the route for a toll cable is a matter of great importance, involving consideration not only of first cost and annual charges but freedom

Fig. 11—Placing Tape Armored Type Toll Cable

from inductive disturbances, permanency of routes, accessibility, and good coordination with existing telephone plant. The assurance of relative freedom from interruptions to service of the toll cable plant requires also very careful consideration of suitable maintenance practises. Preventive measures are continually being developed and applied to the cable plant to aid this work. Interesting in this connection is the application of continuous gas pressure and associated alarm gages for the detection of cable sheath failures.

Other measures have been taken to minimize maintenance troubles on the toll cables. For example, much study has been given to the matter of securing the proper tension in the aerial cable suspension strand and a proper relation between the strand and cable tensions in order to obviate buckling of the cable due to temperature changes. Also, in placing cables in the usual multiple tile conduit before the cables enter the manholes, they are brought into a parallel formation, one

Fig. 12—Transporting Poles Up Steep Grades on Tractors and Trailers over Private Right-of-Way

above the other, by splaying the ducts at these points. By the use of this construction, the cables can be placed in the manholes free of bends.

There is also the necessity for very fast installation work in connection with the large toll projects, involving the desirability of making the fullest possible use of automotive and labor-saving equipment especially adapted for handling the pole, wire, cable, and conduit

Fig. 13—Heavy Duty Trenching Machine

construction. This special automotive and construction apparatus includes such units as: four-wheel drive trucks, some of which are equipped with earth-boring machines; six-wheel heavy delivery trucks, several kinds of power derricks, trenching machines, back fillers, tampers, tractors, and several varieties of trailers. On private rights-of-way, as for instance over plowed fields, the ordinary wheel type trucks and trailers cannot be satisfactorily used so specially equipped caterpillar tractors and trailers with caterpillar tracks are employed. Some of the more important applications of labor-saving machinery in construction work are illustrated in Figs. 12, 13, and 14.

## Aerial Wire and Carrier

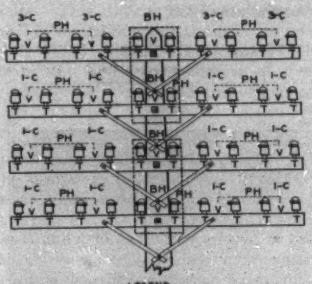
In spite of the magnitude of the toll cable program, it is expected that it will be necessary, in order to meet the demand for additional toll circuit facilities, to string this year about 180,000 conductor miles of open-wire facilities and to install about 200,000 channel miles of carrier telephone facilities. The majority of this wire stringing will, of course, take place on existing open-wire lines not closely paralleled by toll cables. The increased use of carrier telephone facilities has materially favored the further extension of the open-wire along the long toll routes. The open-wire and carrier circuits now being designed are high grade facilities and their service characteristics and economies

Fig. 14—Earth Boring Machine and Derrick on Four-Wheel Drive Truck

are such that a considerable portion of the open-wire and carrier facilities will be retained after they are paralleled by new toll cables.

Major problems presented by the open-wire and carrier construction have been those of crosstalk in the carrier circuits and noise in the very long voice-frequency circuits. In general, the magnitude of the crosstalk problems may be more fully appreciated when it is considered that carrier operation at present involves frequencies about twenty times higher than those important in causing crosstalk in voice operation and wavelengths about one-twentieth as long. Furthermore, the influence of surrounding wires, in parallel with the earth, gives rise to "second order effects" which become very marked within the carrier frequency range. Consequently, the inductive coupling per unit length between circuits is increased about in proportion

to the increase in frequency, a greater number of transpositions within each wavelength is required, the carrier facilities must be balanced with respect to second order effects as well as directly to each other, and the effects of irregularities in construction must be minimized to the greatest practicable extent. It has, therefore, been necessary to give careful consideration to transposition methods and wire arrangements which




LEGEND

| SYMBOL | FACILITY | TOTAL CIRCUITS | |
|---|---|---|---|
| V | VOICE FREQUENCY-PHYSICAL | 20 | |
| PH | VOICE FREQUENCY-PHANTOM | 10 | |
| 3-C | CARRIER SYSTEM FURNISHING 3 TELEPHONE CIRCUITS | 12 | |
| 1-C | CARRIER SYSTEM FURNISHING 1 TELEPHONE CIRCUIT | 12 | |
| T | D-C TELEGRAPH | 40 | |
| BH | CARRIER TELEGRAPH (10 CHANNEL) | 40 | |
| | TOTAL TELEPHONE | | 54 |
| | TOTAL TELEGRAPH | | 80 |

FIG. 15—POLE LINE CONFIGURATION. PHANTOMED CONSTRUCTION

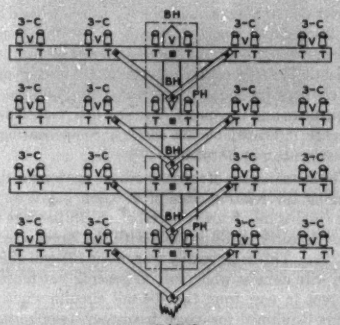
12-in. spacing between wires of non-pole pairs

would provide satisfactory crosstalk reductions and at the same time allow a maximum use of carrier facilities so that the large economies involved in superposing carrier telephone facilities on the open-wire plant may be obtained.

This has resulted in trying out in the plant an entirely new form of open-wire construction. The new method involves abandoning the phantoms on the open-wire pairs on which the carrier facilities are to be superposed, reducing the spacing between the wires of these pairs to 8 in., and widening the spacing between the wires of adjacent pairs to 16 in. The pairs to be used with carrier facilities are transposed in accordance with transposition systems which are especially designed to reduce adequately the coupling between the pairs at the higher carrier frequencies. The experience obtained to date with this type of open-wire construction, while not conclusive, has indicated very favorable crosstalk results. The reduction in the spacing of the open-wire pairs has also resulted in material improvements in the noise on the voice frequency circuits. Where a large proportion of the required circuits are for long haul use, that is to say in excess of about 100 miles, the new construction methods will make it possible to obtain 70 circuits on a 40-wire pole line, 22 voice frequency and 48 carrier circuits. With this arrangement, four carrier telephone systems can be employed per crossarm. The pole pair groups are not normally used for carrier telephone purposes and may therefore remain on a phantomed basis. Figs. 15 and 16 illustrate respectively the pole line configurations of the standard phantomed construction and the newer non-phantomed 8-in. spaced construction.

For routes involving a large proportion of short haul facilities, other transposition arrangements have been developed which make it possible to obtain economically 54 circuits on a 40-wire pole line. In this case the phantoms are retained and the wires are spaced on the normal 12-in. spacing owing to the fact that the carrier frequencies involved do not exceed about 10 kilocycles for the short haul facilities.

The field of use of carrier telephone facilities has been greatly increased with economies and improvements in two types of carrier telephone systems developed within the past few years. One type of system employs a frequency range of 5 to 30 kilocycles and provides three additional telephone channels normally used for long




LEGEND

| SYMBOL | FACILITY | TOTAL CIRCUITS | |
|---|---|---|---|
| V | VOICE FREQUENCY-PHYSICAL | 20 | |
| PH | VOICE FREQUENCY-PHANTOM | 2 | |
| 3-C | CARRIER TELEPHONE | 48 | |
| T | D-C TELEGRAPH | 40 | |
| BH | CARRIER TELEGRAPH (10 CHANNELS) | 40 | |
| | TOTAL TELEPHONE | | 70 |
| | TOTAL TELEGRAPH | | 80 |

FIG. 16—POLE LINE CONFIGURATION. NON-PHANTOMED CONSTRUCTION

8-in. spacing between wires of non-pole pairs

haul circuits from about 125 miles upward. Suitable intermediate repeaters are available for use with this system so as to greatly extend the range of its practical application. The longest systems of this type now in service are between Davenport, Iowa and Sacramento, California, a distance of almost 2150 miles.

The other system, employing a frequency range from about 4 to 10 kilocycles, provides a single additional telephone channel normally employed to provide

short haul facilities, ranging from about 75 to 125 miles. No intermediate repeaters are used with this system. Under special conditions this system can be extended to operate over approximately 200 miles, by the addition of extra terminal amplifier equipment.

Other considerations in the use of long haul carrier telephone systems have been those of reducing the transmission losses at carrier frequencies and thus extending the range of the system, the lessening in the spread of the transmission loss variations under varying weather conditions, and also, the maintenance of the over-all transmission equivalents of the carrier channels within satisfactory limits.

Investigation indicated that leakage effects are the predominating causes of transmission loss variations at carrier frequencies. This led to the development of improved glass insulators which materially reduce the attenuation at carrier frequencies and substantially limit the variations in attenuation between wet and dry weather conditions. Suitable transmission regulation of the over-all circuit has been realized through the use of pilot channels, by which the levels at all points in the carrier systems are maintained within established limits. Rectification at repeaters and terminals of transmitted high-frequency control currents permits the visual indication of the relative levels on calibrated meters. As changes in line equivalents affect both the pilot frequencies and the speech channels in a related manner and are indicated on the meters, compensating gain adjustments may be made.

The increased use of carrier facilities has tended toward bringing the relative costs of different gages of open-wire circuits more closely together, chiefly because of the wider repeater spans possible with the larger gage conductors. This is especially true of the 128-mil diameter open wire circuits which are, in general, not materially different in cost from the 104-mil circuits when completely equipped for voice frequency telephone, d-c. telegraph, and carrier telephone facilities. This has helped make economical the increased use of the larger 128-mil and 165-mil facilities throughout the open-wire plant, which is very advantageous in lessening the service interruptions due to wire breaks.

## Toll Equipment Program

The rapid extension of the outside toll plant facilities has, of course, resulted in a very much increased toll equipment program. This has involved much engineering work in providing suitable switchboard and equipment arrangements, adequate building space, and improved methods of equipment assembly and office cabling. The extremely long distance circuits require numerous telephone repeaters, and the rapid expansion of the toll cable program, requiring repeater stations approximately every 50 miles, has materially increased the building and space requirements as well as the needs for additional repeaters, ringing and compositing apparatus, and adequate battery supply arrangements. As the present full size toll cables provide as many as 325 circuits, it is apparent that with many paralleling cables, building space frequently must be made available at one locality for several thousand telephone repeaters and associated apparatus. The following table, illustrating the increase in the use of telephone repeaters and carrier systems, shows the total number of telephone repeaters and carrier systems installed in the Bell System plant during 1925 and the estimated additions for the year 1930.

ESTIMATED ADDITIONS TO BELL SYSTEM PLANT

| Year | Telephone repeaters | Carrier systems |
|---|---|---|
| 1925 | 2,400 | 11 |
| 1930 | 36,000 | 400 |
| Ratio | 15 | 36 |

Simplified equipment arrangements have been developed which involve mounting apparatus on panels assembled on channel iron or I beam racks, thus bringing about substantial reductions in the space required as compared to the former types of mountings. The panel mounted arrangements have also considerably simplified the cabling arrangements between the various units of the toll circuit equipment required within a given office. Also, in order to simplify the layout and installation of the toll circuit equipment, arrangements have been developed whereby certain equipment is now shipped direct from the factory on completely assembled bays. Fig. 17 shows a bay of voice frequency telephone repeaters arranged in accordance with the latest methods of assembly and cabling. The simplification of the equipment arrangements is further shown in Fig. 18, which illustrates the complete assembly of two long haul carrier terminals with their associated testing apparatus, on standard bay arrangements.

The improved equipment arrangements have materially aided the repeater station building problem and floor plan layouts. The repeater station buildings which are being constructed throughout the country to house toll circuit equipment are, in general, fireproof buildings so designed that they may be extended vertically or laterally, depending upon the particular land conditions or other requirements involved. Fig. 19 shows a typical telephone repeater station on one of the major cable routes. This building now contains about 1000 repeaters. Telephone repeater station buildings are being constructed in several parts of the country which are designed to have an ultimate capacity of 10,000 repeaters.

## Electrical Design Features

The development of very long toll telephone circuits has involved working out a succession of very interesting design features in order to obtain suitable electrical characteristics for the clear transmission of speech over these long circuits. These problems have, in general, been particularly great for very long toll cable circuits. They have been discussed in detail in a

number of papers presented before the Institute. A brief review of the general nature of some of these problems and the method of solution adopted for toll cable circuits will be sufficient here.

In the early extensions of toll cables, difficulty was experienced because of the much higher losses of energy for the high-frequency components of speech than for the low-frequency components due to the large variation in attenuation of the cable for currents of different frequencies. This difficulty was met by the use of "loading," by means of which the attenuation was made much more nearly constant over the band of frequencies most important for the transmission of speech. The loading also greatly increased the efficiency of cable

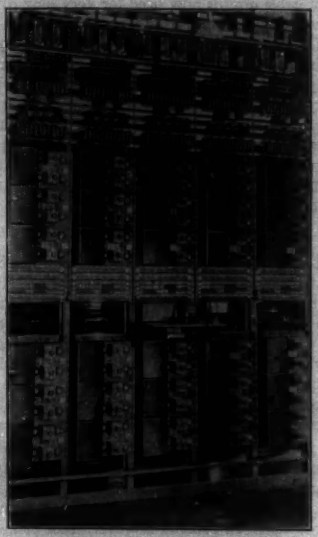


Fig. 17—Installation of Voice-Frequency Telephone Repeaters and Associated Apparatus

transmission by increasing the impedance of the circuit so that for a given power higher voltages and lower currents are used on a loaded circuit than on a circuit without loading. This made possible such cables as the early Chicago-Milwaukee cable, previously mentioned, and, by using as large gages of conductors as seemed practicable, provided satisfactory service through cables between New York and Washington and New York and Boston, distances of about 250 miles. These cables were completed in 1914.

Further extension of the range of cable transmission was limited by the difficulty of obtaining satisfactory over-all efficiency in cable on circuits of 200 or 300 miles in length. This difficulty was largely solved by the perfection of telephone repeaters, particularly those using vacuum tubes. In the design of long telephone

Fig. 18—Assembly of Long Haul Carrier Telephone System Terminals

circuits, even those in cable, it is now practicable to renew the energy of the telephone currents repeatedly without material distortion to a practically unlimited extent.

With the resulting extension of toll cable circuits to

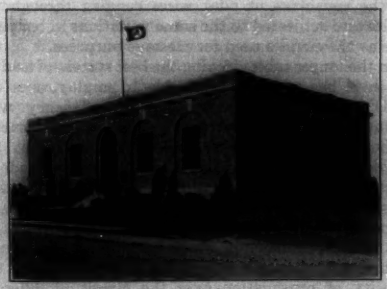


Fig. 19—Typical Repeater Station Building

relatively great distances, as between Chicago and New York, another phenomenon became of importance. At the ends of a telephone circuit the telephone currents are in part delivered to the terminal apparatus and in

part reflected back over the line due to the difference in the impedance of the line and the terminal apparatus. This effect also takes place in a minor degree at intermediate points in the line where discontinuities in electrical characteristics occur. When the time of transmission is very short, these reflected currents do not cause interference with speech unless they are relatively great in magnitude. When the time of transmission is appreciable, however, the reflected currents are heard in the telephone receivers both by the talker and by the listener as echoes. These echoes may have a serious effect in impairing the clearness of speech, the effect being progressively greater as the time lag of the echo current increases.

A first remedy for these effects was an increase in the velocity with which telephone currents were transmitted over the loaded cable circuits. This was done by a change in the design of the loading which also had other important benefits. With further increases in distance and in the efficiency of circuits, however, additional means were required to take care of these echo effects. This has been done by the development and use of means for suppressing the echoes by destroying the efficiency of the return path, that is, the transmission of speech currents in one direction over the circuit acts to prevent the transmission of echo currents in the opposite direction.

One important problem in the longer circuits has been the prevention of changes in efficiency with variations in the temperature of the circuit. The importance of this is illustrated by the fact that the energy loss in a Chicago-New York toll cable circuit may be as much as $10^9$ times as great when the circuit is hot as when it is cold. The daily and even the hourly variations are sufficient to cause large variations in efficiency if not compensated. This compensation is done by the automatic change in the gain of amplifiers which is controlled by the resistance of pilot wires running through the cables and subjected to the same variations in temperature as the circuits used for message purposes.

In the longer cable circuits, the best system of loading which it has seemed practicable to employ, does not sufficiently eliminate variations in efficiency with frequency to permit the transmission of speech currents without serious distortion unless further means are provided. In such circuits, therefore, use is made of so-called "attenuation equalizers," inserted periodically along the circuit, to compensate for the variations in efficiency of the line and associated apparatus.

Another phenomenon which becomes of importance with increased length of circuit is the variation in the velocity of propagation over the circuit of different components of speech. The components of moderate frequency (about 1000 cycles) tend to arrive at the distant end first, those of higher and lower frequencies trailing in later. This produces an additional type of distortion. Some of this distortion can be minimized by improvements in the design of the apparatus. The use of corrective networks which insert in the circuit a distortion in velocity of transmission which compensates that caused by the cable circuit characteristics is also being studied to take care of this situation.

With all of these progressive difficulties removed, it appears, looking to the future, that the limit of transmission over telephone cable circuits may be influenced by the operation of another and still more fundamental factor, namely the time required for the transmission of electric currents over these very long circuits. With the development of toll cable networks covering this country and Europe and with the completion of telephone cables across the Atlantic, total distances of transmission over toll cable circuits as great as 10,000 miles will probably be involved in the future. The types of cable circuit now used for very long distances have a velocity of propagation of about 20,000 miles a second. The time lag in a 10,000-mile cable circuit would be about half a second for transmission in each direction. A delay of this magnitude would interfere with the ordinary methods of conversation involving frequent acknowledgment, interruption, and interchange of question and answer. Looking forward to improving such conditions, research work is now under way to determine the best means of providing cable circuits of still higher velocities.

## International Connections

The toll system of the United States now has connection with telephones in 21 other countries. By this means the users of this service are offered connection with 65 per cent of all of the telephones in other countries of the world or 85 per cent of all the telephones in the world including those in this country. Additional extensions are made from time to time. These extensions to other countries involve many unusual plant arrangements and a brief mention of these is desirable.

Due to our very close relations with Canada, the Bell System connects with Canadian telephone systems at a large number of points. All of the larger cities and a large percentage of the smaller places are available for connection. In general, however, these connections involve no unusual problems, the ordinary types of construction standard in this country being extended in Canada where closely similar standards of construction are in use. Similarly, a connection made in 1927 to Mexico City and other important cities in Mexico by the extension of open wire toll lines involves no new technical features.

The connection of this country with Cuba was accomplished in 1921 by three submarine cables, of very unusual construction. These cables, 115 miles in length, cross the Florida Straits which have a maximum depth of about 6000 feet. Because of the great depth, the type of construction used for transoceanic telegraph cables was necessary for mechanical reasons and this made necessary a novel electrical design of the cables to provide adequate transmission efficiency. The

cables have proved very satisfactory and the availability of these circuits has resulted in the gradual development of a large telephone business between points in the United States and Cuba.

In 1927 the first commercial service was opened between the United States and Europe by a circuit from New York to London. This has since been supplemented by two additional circuits and other additional circuits now under construction and planned will raise this group to six by the end of 1932. The first circuit includes for the transatlantic link a long wave radio system transmitting from points near New York and London to receiving stations in the eastern central part of Scotland and northern part of Maine, respectively. The other two circuits are short wave radio circuits, both transmitting and receiving stations being near the New York and London terminals.

These circuits, both the long wave and short wave, are of pioneer character. The effort has been to obtain as good a degree of continuity of service as transmission conditions will permit and consistent with requirements for satisfactory commercial services. In working to obtain this result one is, of course, faced with the very large variations in efficiency of transmission under various conditions and also in the magnitude of the interfering atmospherics which tend to interfere with good reception.

With the long wave transmission (5000 meters), practically no degree of directivity of the transmitting antenna has been employed, although at the receiving antenna an improvement in the ratio of signal power to static power of about 400 to 1 is obtained by construction giving directive effects. In this connection, it might be noted that the northern location of both receiving stations is also an important factor in reducing noise. Relatively high powers are necessarily transmitted, the transmitting set power for long waves being about 200 kw. The power received by the receiving antenna is a small fraction of a micro-watt, sometimes being as small as $10^{-12}$ watt. It is interesting to note that this power is equivalent to that received from the North star on 10 sq. in. of the earth's surface.

With the short wave transmission using wavelengths between about 15 and 45 meters, it is possible to obtain a high degree of directivity of both transmitting and receiving antennas. The gains from the antennas used during the most important hours as compared with undirected transmission and reception represent equivalent power advantages of about 70 to 1 and 30 to 1, respectively. The transmitting powers used are somewhat lower than with the long wave, being about 15 kw. The short wave channels are, in general, less affected than the long wave by high atmospheric disturbances, but are much more affected at times of magnetic storms when large variations in the field strength of the signal at the receiving antenna often occur. Fortunately these two types of disturbances seldom appear at the same time and the two types of radio channel admirably supplement each other in the maintenance of uninterrupted service.

Work is now proceeding in the design of a transatlantic telephone cable which will provide a third type of circuit between New York and London. For this cable, transmission will probably be overland from New York to Nova Scotia, thence by submarine cable to Newfoundland, then by a second cable 1800 miles in length from Newfoundland to the Irish coast, and from there to London. This cable presents so great a departure from previous telephone circuits that extensive research and development are necessary to determine the most favorable methods of construction.

An additional international connection which is now being constructed is of interest, namely, a short wave radio telephone channel between New York and Buenos Aires, connecting with Montevideo.

## Planning for the Future

In one or two places in this paper mention has been made of planning for the future by the intensive study of technical problems which might, if unsolved, limit future extension of the service. The scope of this paper does not permit even an outline of the numerous research projects which it is necessary to carry forward with a view to assuring continuity of uninterrupted progress in extension and improvement of toll service. This is, however, a factor of fundamental importance both in the steps which have already been taken and those which are anticipated in future years.

From the general engineering standpoint, the plans for the continued expenditure over a period of years of large amounts for permanent extension of toll plant, call for very careful attention to the fundamental planning and layout of that plant This is particularly true in view of the large extension of toll cables and of underground toll cable conduit routes in which best engineering requires that initial construction be designed with a view to the future increase in circuit requirements for a relatively large number of years. This then is one of the important features of the engineering work of the Bell operating companies at the present time.

While fundamental plans for future development of toll plant must adequately provide for the plant extension in a given area, they must be closely coordinated with each other and with the plans for the country as a whole, particularly because of the importance of the large groups of long through toll circuits. As one element in facilitating this planning, there has recently been developed for the country a general basic routing plan designed to insure the highest practicable standards of service as to speed, accuracy, and transmission with maximum economical concentration of circuits on important routes. This plan will serve to limit the amount of switching required for handling toll calls between remote points.

## Conclusion

In the above discussion, I have endeavored primarily to give you in brief outline a general picture of the engineering aspects of the situation surrounding the recent development of the toll service side of the telephone business and to touch upon some of the technical matters which have been important factors in the progress of the toll expansion program. Detailed discussions and analyses of many of the more interesting of these problems have been presented in recent papers before this Institute, or have appeared in various of the technical publications For the convenience of those who may be interested in a more detailed consideration of these matters, a bibliography of a selected list of these papers is attached hereto.

In conclusion, I might add that those of us who are closely interested in the advancement and improvement of the toll phase of the telephone business look forward to a continued rapid development of that part of the communication art with an increasingly complex and varied engineering technique.

## Acknowledgment

The author wishes to acknowledge the assistance of many of his associates in the preparation of this paper, and in particular that of Messrs. J. B. Dunn and H. S. Osborne.

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## Discussion

**H. A. Harris:** When planning large annual additions to toll plant it is usually necessary to consider many related matters bearing on future toll service and operating methods and to know the reaction of the proposed plans upon the economical use of the balance of the plant. A plan generally known as the "Toll Fundamental Plan," considers such matters and develops all the necessary facts for use as a guide in all current toll plant construction.

A well prepared toll fundamental plan indicates, for some future period (usually some 15 or 20 years in advance), the estimated amount of toll traffic that will be interchanged and the most effective toll operating methods to be used in handling this traffic between any two points, the toll centering arrangement which will include these points and the estimated number and arrangement of circuits to be required. The plan also shows the most economical type of plant for providing the estimated toll facilities, *i. e.*, open wire, cable, or carrier system to meet service requirements in each route.

In brief, these long range plans are a safeguard against any danger of providing facilities incorrectly, either in amount or direction, and also a safeguard against the adoption or continuation of any plant arrangement or operating method which, although it may seem reasonable at the present time, might later, as the system grows, prove uneconomical.

The foundation on which all this advance planning is built is, of course, the forecast of calls per telephone or toll usage. Unlike local traffic this usage does not remain constant from time to time but varies a great deal with business activities and is sometimes subject to other influences so that in the advance planning of toll plant it is necessary to exercise sound judgment and to apply frequent reviews in forecasting the probable future trend of service demands and characteristics. Upon the results of these studies and forecasts, operating plans are adopted and construction details determined. This portion of advance planning work is therefore the key and a highly important part of toll telephone engineering.

**W. W. Walters:** Mr. Harrison, in describing the expansion of the toll plant, mentioned its changing physical character and the changing nature of the engineering problems. In this connection it may be of interest to compare some features of a specific toll cable project of 1915 with those of a paralleling project of today.

The original Great Lakes-McHenry cable extending 26 mi. across Northeastern Illinois was a pioneer achievement in the quadded toll cable field. It was installed in 1915, replacing an open wire plant suffering from the familiar sleet storm effects and was confidently expected to care for all toll growth in that region for a 20-year period. Although serving an agricultural and summer resort region wherein growth was expected to be and has been relatively slow, it was nevertheless necessary to provide some measure of relief in 1927. This was accomplished by rerouting the longer haul circuits to a relief cable installed in another location. The results proved to be temporary, however, since the rapid growth in requirements during the past three

years necessitates another relief cable on the original route by 1930.

The engineer of the relief project, although the beneficiary of 15 additional years of experience in the art of forecasting, is not so confident as his predecessors when he indicates that the Great Lakes-McHenry relief cable should care for all requirements in the path until 1940. He has learned for one thing that the projection of accumulated past performance records alone cannot possibly reflect the changing conditions of the future. His risks are smaller, however, since he is, in general, engineering for shorter periods than his predecessors did.

The original Great Lakes-McHenry cable contained 13-gage quads and 16-gage pairs with a maximum capacity of 96 circuits. Since the introduction of telephone repeaters, the same or better transmission performance can be secured economically with smaller gages, and 13-gage copper is no longer employed in toll cables. The 1930 relief cable will, therefore, be predominantly 19-gage with a capacity of 378 two-wire circuits, yet having approximately the same copper content as the original cable. In addition the new cable facilities will be segregated for four-wire operation in case circuits of this type may be required at some future date. The cable will also contain special high grade pairs suitable for the transmission of program material. The telephone circuits can furthermore be adapted to provide 200 or more superimposed telegraph channels without interference to the regular telephone service. These additional features were almost entirely absent in the original cable.

The old cable was loaded at 8700-ft. intervals and transmitted a rather narrow frequency band. The new cable will be loaded at 6000-ft. intervals and also balanced at 3000-ft. intervals to take advantage of still shorter spacings which may be introduced in the future. Rigid limits will be observed in securing a regular spacing of the loaders, an essential requirement to good repeater operation but of less importance in 1915 when repeater applications were still undergoing development trials.

When the original cable was installed the volume and quality of transmission provided was probably somewhat poorer than that given by the open wire circuits which it replaced. These impairments, however, were compensated for largely by the comparative freedom from noise and crosstalk which the cable circuits afforded so that the net result, coupled with the increased reliability of service, was probably of sufficient excellence to satisfy the standards of 1915. Transmission designs were largely directed towards providing suitable performance between terminal points connected with direct circuits, there being at the time no particular demand for long-haul, built-up connections requiring the switching of two or more circuits together in tandem. The relief cable of 1930, together with its associated facilities, will provide circuits having marked improvements in both the quality and volume of transmission and should perform satisfactorily in any type of long-distance connection which may be needed, a requirement and an accomplishment almost unforeseen in 1915.

**Burke Smith:** Mr. Harrison mentioned the transatlantic telephone circuit and referred to the increase in circuits from 1927 to the present time. I believe it was opened with one circuit and at the present time there are three, and in 1932 I think six are expected. I am just wondering what the traffic conditions are on the transatlantic circuits. I have in mind the recent stock market flurry. What were the traffic conditions during that period?

**W. H. Harrison:** When the transatlantic circuit was first opened in 1927 the average number of daily messages was about 7. In 1928 this had increased to about 30 a day and for this year the average is a little above 50.

During the stock market activity at the end of October, slightly more than 100 calls a day were handled during the last three or four days of the month. For one of these days there were close to 200 calls offered, and we were able to complete only about 140 of them. Another interesting feature of the transatlantic business is the fact that the calls offered at the two ends are nearly equal, 50 to 55 per cent being offered at this end and 45 to 50 per cent at the other end. About 55 per cent of the total calls are to or from Great Britain, about 30 per cent terminate in France, and about 8 per cent in Germany, with the remaining calls scattered among the other countries in Europe.

# The Chicago Long Distance Toll Board

BY E. O. NEUBAUER[1] and G. A. RUTGERS[1]
Associate, A. I. E. E. Non-member

*Synopsis.—The long distance telephone office serves to provide a concentration point for intercity telephone communication from a group of local exchanges and its size will depend largely upon the number of stations served by the local offices.*

*The Chicago Toll office, which serves 1,200,000 stations, has recently been largely replaced with new equipment. This equipment, together with correlated improvements in handling toll service at Chicago, is described in this paper.*

*The work of the toll operator in handling toll calls with the new equipment is compared with the former method and it is this change in operating practise which constitutes a major improvement in long distance service.*

*The paper also includes a description of the toll lines entering Chicago with their equipment arrangements including telephone repeaters and the power plants required to operate this equipment and that associated with the switchboards.*

*The addendum describes the purpose of the auxiliary and special switchboards which are required only in large installations such as Chicago.*

* * * * *

THE growth of the long distance telephone traffic along with many improvements in service have recently brought about certain significant changes in operating practise. The long distance toll user may now, in the majority of instances, remain at his instrument during the complete progress of the call. This, together with a reduction in the time interval between the placing of the call and the answer of the distant station from a former average of six to a present average of less than three minutes, brings long distance and local service very closely together, from the standpoint of simplicity and convenience to the user.

The accomplishment of this change required careful planning and supervision throughout the Bell System but did not, except in the larger cities, involve relatively large or expensive equipment rearrangements. Conditions were such at Chicago, however, that the change in practise, together with preparations in connection with the continuing toll volume increases, made it advisable to replace part and remodel the remainder of the existing toll switchboard equipment.

Such action at so large a center constituted a major problem in telephone engineering. It also included various operating and equipment features which, being of the most recent type available, make the new office one of the most completely advanced within the system. This paper describes the actions taken in the new installation and the general operating and toll circuit layout, and prefaces this description with a brief outline of the general relationship of the toll plant to that of the system as a whole.

## The General Telephone System

The telephone system is composed of local exchanges with direct completion of calls between stations within the local exchange boundaries and with switched toll line completion of calls between exchanges. It is unified as to plant standards and methods of operation, so that its whole system is as accessible to any one station as to any other, regardless of sizes of exchanges or their remoteness from each other.

At each local wire center the lines or loops from all subscribers' stations are brought to one central office switchboard for purposes of their direct interconnection. If, as in large metropolitan areas, this concentration involves too extensive a wire haul, the geographical group is split up into economic sub-areas with sub-wire centers connected together by direct local trunks.

This same general arrangement is supplied for intercity or toll connections. Adjacent and neighborhood communities are connected by direct toll lines, and more widely separated cities receive their toll service through selected toll centers or switching points strategically located throughout the system's territory.

Each toll office is a focus for all originating and terminating toll business from and to its tributary local offices, and the effect of this toll centering is to concentrate toll traffic into units large enough to permit the most economical balance between the costs of the switching operations and the costs of the toll line plant.

The Chicago toll office, at one of the great regional centers of this country, is a key switching point within the country wide network of toll lines and directly serves the 32 local wire centers with 102 central offices and the 5 suburban wire centers, which together form the Chicago Metropolitan Area. Within this area some 1,200,000 stations will have originated approximately 7,300,000 calls via this toll board during the year 1929, in addition to some 44,500,000 calls which will have been handled by the Chicago local offices themselves to nearby toll points.

## The Work of the Toll Operator

Under the toll centering arrangement the local and tributary offices are connected with their toll office by groups of recording and toll switching trunks. Prior to the change in the method of toll operation, already referred to, the recording trunks terminated on separate recording positions and a special recording operator worked only to secure the necessary details of the call from the calling subscriber. She then released the subscriber's line and passed a ticket memorandum of

1. Illinois Bell Telephone Co., Chicago, Ill.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., December 2-4, 1929.*



29-140

the call to separate completing operators at an outgoing switchboard line. These operators re-secured the subscriber over toll switching trunks, reached the distant station over the toll lines and then established the connection and timed the call.

With the change in method the recording and completing or "line" operators' functions have been combined and located entirely upon the outgoing switchboard. To indicate this method of combined line and recording work, an expression, "CLR" has been coined, telephonically, and will be used as such throughout the paper.

Since provision must be made for incoming as well as outgoing traffic and for toll center to toll center switching, we will generally find that the larger toll switchboards are divided into three groups or lines for CLR or originating business, for "inward" or terminating business, and for "through" or switched business. As in Chicago, there are also apt to be various additional special groups to meet the functional requirements of such large toll line and toll volume concentrations as are there encountered.

In handling a CLR call from a manual subscriber the CLR operator makes a permanent ticket record of the call details and then, without releasing the subscriber from the recording trunk, rings out over an idle toll line to the distant operator, using a separate pair of cords, and asks for the called station. While waiting for the called station's answer, she secures the calling subscriber's line over a toll switching trunk, using the same pair of cords used to ring out over the toll line, and releases the recording trunk. Upon receipt of an answer by the called station, she stamps the time of day in hours, minutes, and seconds with a calculagraph stamp on the ticket, and upon receipt of final disconnect signals stamps the time when conversation ended. Billing is finally made upon the basis of charges applied to the elapsed time indicated on the ticket.

One of the chief savings in time to the subscriber under this procedure, as compared to the former separate recording and completing operation, is the saving in ticket distribution time between the two sets of operators. As can also be seen, greater speed is possible when the called station number is known than when it must be looked for in a directory.

Reciprocal work must be done at the terminating end of each originating connection by an inward operator who answers the incoming toll line signal and reaches and rings the station called for by the originating toll operator. In handling switched calls, the intermediate or through operator deals only with the distant toll operators who reach each other over toll lines routed via the intermediate toll center board, these lines being connected together at the through positions by the through operator.

Toll calls are handled on the basis of connection with a particular person (a person to person call) or with someone who may answer at the called station, (a station to station call). Either class of service is available to the subscriber whether he calls by name or by number. When anyone will suffice the call is necessarily completed upon the answer of the called station and will be delayed only by a "don't answer" or "busy" condition at the called station, or by toll circuit congestion. On a particular person call, the inability to immediately reach the one person desired at the telephone specified may cause delay in addition to the above causes.

The various operations required to secure completions under conditions of postponement involve many different methods and routines which are rather technical in their applications and require additional distributions of the ticket memoranda and various specializations of work. All are designed to conserve whatever necessary time intervals are involved and to insure the definite completion of the call in the manner asked for.

## The Chicago Toll Board

An example of the specialization required is given in the following tabulation of the Chicago Toll Board positions:

| | | | |
|---|---|---|---|
| (a) CLR | 301 | (f) Directory | 44 |
| (b) Non Method | 233 | (g) Routing | 16 |
| (c) Utility | 78 | (h) Delay Quoting | 4 |
| (d) Inward | 89 | (i) Traffic Trouble | 4 |
| (e) Through | 113 | (j) Office "B" | 6 |
| Total General | 814 | Total Miscellaneous | 74 |

| | |
|---|---|
| (k) Ticket Distributing | 24 |
| (l) Ticket Filing | 24 |
| (m) Service Supervisor | 16 |
| (n) Service Observing | 20 |
| (o) Monitor Tap | 1 |
| Total Auxiliary | 85 |
| Toll Tandem | 16 |

These switchboards, which are grouped upon six floors of one building centrally located in the downtown business district of Chicago and designed for an initial service of some 32,000 toll board calls per day, are arranged to accommodate the following line and trunk equipments:

| | | |
|---|---|---|
| 1. | Toll line to all points | 2700 |
| 2. | Switching trunks to local offices | 3800 |
| 3. | Recording trunks from local offices | 850 |
| 4. | Miscellaneous interboard trunks | 1200 |
| | Total network | 8550 |

Each of the switchboard position and line group arrangements has specific functions which are somewhat abstract for the scope of this paper, and which can be only briefly summarized as in the addendum. Certain controlling factors should be pointed out here, however, as follows:

*Subgrouping and Tandem Arrangements.* The capacity of the face equipment of the CLR boards is insufficient to accommodate the whole of the recording and switching trunks on a workable basis. The CLR group has,

therefore, been subgrouped into four units, each of which serves a specific subdivision of the Chicago local exchange.

In spite of the various measures taken to reduce the space requirements for face equipment at the CLR position, it did not appear practicable to provide appearances for all of the toll lines at each CLR position. A trunking plan is therefore necessary which introduces a toll line "switching" or "tandem" board within the office itself and the CLR operators thus reach a majority of the toll lines needed by them on a trunking basis. One of the lines of CLR positions is shown in Fig. 1. This line consists of 65 positions.

*Directory and Routing Arrangements.* More than 2100 directories, covering 350 metropolitan areas and communities extending from coast to coast, are indexed and filed on a state basis at a line of directory switchboards. The CLR or other service operators communicate with the directory operators by trunks, without

Fig. 1—A Line of CLR (Combined Line and Recording) Switchboard

delay for such telephone number information as cannot be furnished by the subscriber himself. A picture of the directory positions is shown in Fig. 2.

At certain other positions, other operators specialize in quoting the routes to points not obtainable on a direct connection basis. These routings are based on frequent and thorough traffic engineering studies of the entire toll network throughout the territory involved.

*Pneumatic Tube System.* Because of the location of the various switchboards on several floors, it is necessary that means for rapidly transmitting tickets from one location to another be provided. An exhaust blower, a system of flat brass tubes and ticket distributing positions comprise a pneumatic tube system for this purpose. With one end folded to form a pocket for the tube air currents, the tickets are inserted at any position and delivered to control or distributing positions where they are checked and routed to their proper destination. Either roller or hand receiving valves permit ticket egress at the terminal points. There are two distributing desks in service and one of these is shown in Fig. 3. The wooden "trimming" panels have been removed to show the tubes.

*Engineering Problems Involved.* Consideration of the situation at the Chicago center had established the fact

Fig. 2—The Directory Positions

that the increasing toll volume growths would require equipment floor space in excess of that which could be made available without additional building operations. In 1926 it appeared that the rather appreciable equipment additions required for growth and those required to permit of change to CLR operations would tend to advance the new building work and would

Fig. 3—One of the Ticket Distributing Desks

require new switchboard line arrangements to permit this to be readily carried out.

At this same time new and improved toll switchboards of a more efficient type were being made available and it was desirable to utilize this type even though these could not be used in conjunction with the existing type boards without appreciable modifications within the

latter. These various factors after proper engineering cost study and management consideration combined to indicate that the dismantling losses upon part of the existing switchboards and the new money requirements could be justified on the basis of improved efficiencies in service and over-all economies in providing for future growth. Since a clear path for future building work could also be secured it was decided that the old switchboard was to be largely replaced.

The general building conditions were such that the new switchboards, when completed, would be to a large extent occupying the old switchboard space, and yet service must be kept upon a continuous basis upon the old boards. This was met by the invention of special "applique" circuits which were attachable to the old board circuits to make them workable with the new board circuits. By this means, old and new were placed side by side as installation work proceeded and the service was continuous and yet made ready for cut-over.

The problem in connection with the congested face equipment space of the CLR boards which, as already referred to, resulted in a toll tandem board arrangement brought into service an entirely new development designed especially for metropolitan CLR offices. This includes idle indicating lamps so arranged that only the first idle circuit to the left of the group or subgroup of toll lines is indicated, and of overflow jacks so arranged that one request for each busy toll circuit group received from the CLR operators may be held. When a circuit becomes available, the overflow jack functions to signal the operator who has requested the circuit.

It was felt also that all other equipment or operating improvements which were available should be included in this one big project. Under this head, came the terminal repeater pad arrangement to eliminate cord circuit repeaters and this was added to the already complicated plans for Chicago.

Under normal conditions, each step in the development of new equipment and operating methods is worked out in a preliminary manner and given a complete work-out on a trial basis. If satisfactory, requirements are then worked out on the basis of manufacturing production and given to the field. Field engineering considers these in connection with existing and potential conditions and includes them in cost and other studies which result in detailed specifications. The manufacturing company then carries out its detailed engineering and manufacture in accordance, ships the material and installs it.

The general plans for the Chicago project had taken nearly a year for their complete preparation and decision. It appeared that a requirement for completion by March of 1929 would be necessary. The difference in effort between the two years available for completion and the greater period normally involved in the cycle, as above referred to, needed to be carefully measured since development, engineering, manufacturing, installation, and operation, together with space rearrangements would need to be carried out almost simultaneously. This was reviewed and discussed from the system's standpoint and it was determined that with the necessary planning and coordinated effort the objective could be met. This was successfully accomplished by the date set with complete satisfaction.

The functioning of the general development and research departments and the laboratories of the Bell System, together with its ability to summon all of the necessary resources to cope successfully with abnormal requirements contributed materially toward meeting the desired objectives.

*Toll Line Equipment.* The replacing or No. 3 type of toll switchboard has its toll line signaling units included with the toll line circuit, thus omitting them from the cord circuits in the switchboard and eliminating in many cases the association of ringers with the toll line terminal equipment. This feature required the development of the "applique" devices for use in working old and new sections temporarily together, as already referred to. Fig. 4 shows the arrangement of equipment and cross-connections in a toll line and toll switching trunk.

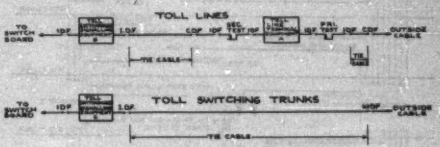


FIG. 4—DIAGRAM SHOWING ROUTING OF LINES FROM OUTSIDE CABLE TO SWITCHBOARD

*CDF* = combination distributing frame; *IDF* = intermediate distributing frame; *MDF* = main distributing frame

The toll line signaling unit receives the incoming a-c. and transmits it as d-c. to light the necessary switchboard lamps. It also, under the control of the cord circuit, transmits an a-c. signal of either 20-, 135-, or 1000-cycle frequency to the distant office, depending on the length and type of toll line.

The toll line circuit contains relays for the operation of the signaling unit, a pad control, the line signal, and transfer and multiple cut-off features.

The amount and type of toll line terminal equipment depends, for any particular line, on the type of line, the circuit layout, and whether it is also used for telegraph. All toll lines must necessarily be reduced to physical condition at this point, and many must be here equipped with repeaters of the terminal type.

In line with the switchboard replacement, all of the existing toll lines at Chicago required practically complete retermination and realinement, while on a working basis, to meet both old and new conditions. This covered some 3122 signaling units, 2450 toll line circuits

and 974 two-wire and 1210 four-wire repeaters with their associated networks and equipments. A feature of this work was the necessary coordination by many distant toll line offices and their terminal arrangements.

*Repeater Pad Control.* For many years necessary amplification of the speech currents on toll circuits switched at the toll office for the longer distances, has been provided by the use of manually operated repeaters of the cord circuit type, available for insertion in the line as required. These were completely displaced at Chicago under the conversion.

The plan carried out to displace the cord circuit repeaters and to obviate certain operating difficulties requires the operation of the toll lines at transmission equivalents low enough to permit switching without cord circuit repeaters. Since, in many toll lines, this would involve noise and cross-talk when they are used on terminal connections, the power level of such a line is reduced by the insertion of a pad when used for a

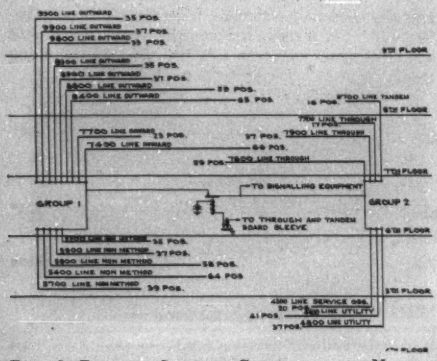


FIG. 5—DIAGRAM SHOWING CONNECTION FOR MULTIPLE CUT-OFF

terminating connection. The plan, therefore, requires circuit arrangements so that the pad will remain in the line when it is used on a terminal connection, but will be removed from the line when it is switched to another toll line on a via connection.

These pads, as has already been stated, are a part of the toll line equipment and their control is obtained by the toll line, trunk, and cord circuit equipments. The pad remains in any toll line when it is connected to an operator or to a toll switching trunk but is removed when it is connected to another toll line and the Chicago operator has cut out her set from the connection.

*Multiple Cut-off.* The amount of wiring necessary to connect lines in a large switchboard installation where the boards are located on several floors introduces transmission losses due to the bridged multiple and this is objectionable. Arrangements have, therefore, been made to cut off some of the boards for through connections. This is accomplished by so wiring the switchboards that they may be divided into two groups, (1) those at which switches to other toll lines are never made and (2) those at which switches to other toll lines are made. A relay system is then provided so that when a circuit is taken up at any position of group (2), the multiple of the positions in group (1) is cut off. This arrangement is shown diagrammatically in Fig. 5.

*Testing.* The testing and correcting of troubles on lines and equipment in so large a concentration requires appreciable specialization. A total of 46 primary and 20 secondary units of No. 5 type toll test board are provided for this purpose, with segregation between toll cable and toll open wire terminations. The primary units test against outside and the secondary units against inside office trouble.

In addition to the routine tests made at frequent intervals by the maintenance people routines have been set up for reporting the troubles of various kinds which are noted by the operators. These provide for the prompt reporting of all such troubles to the proper plant maintenance people who take immediate steps to clear up any unsatisfactory conditions.

*Power Plant.* The toll line terminal equipment requires two 24-volt batteries arranged in parallel, with a 6400-ampere hour capacity and a present peak load of 850 amperes; a 130-volt storage battery unit, with a 640-ampere hour capacity and a peak load of 75 amperes, for the plate voltage of vacuum tubes and for telegraph, and two 1000-cycle and two 135-cycle generators to supply the necessary alternating current for signaling purposes.

The toll switchboard equipment is operated by another 24-volt storage battery unit, with an existing peak load of 1350 amperes; a 28-volt battery used for busy signals, with a 1900-ampere drain in the busy hour; a 130-volt battery for vacuum tube plate current, with a 1.5-ampere drain and a 48-volt battery for special circuits, with a 5-ampere drain. All of these batteries are maintained on a continuous float basis and are provided with voltage regulators. Direct-current power supply operates the charging generators. Alternating ringer current for signaling purposes is here supplied by four 1000-cycle, two 135-cycle and two 20-cycle ringing generators.

The exhauster used for operating the pneumatic tube system is operated by an 85-hp. motor with a speed of approximately 3500 rev. per min.

*Toll Line Facilities.* The Chicago Toll Office is the center for 20 toll cables entering over six main underground routes, shown in Fig. 6, and terminating 1949 quads of facilities on the cable test boards.

There are, in addition, 152 open-wire circuits which reach the open-wire test board after their preliminary transfer at the city limits to necessary underground toll entrance cables. The routing of the open-wire lines is shown in Fig. 7.

The rapid extension of the toll cable network, by reason of the volume of toll facilities required and their better protection by cable, tends to make any growth in toll open wire seem relatively unimportant. It must be appreciated, however, that there is still an economical necessity for the continuance of an appreciable amount of this type of plant and for additions to it.

In addition to the use of toll open wire for straight circuit provision, it is highly efficient for multiple communication channel purposes. While these may be imposed to some extent on circuits in cable, it is

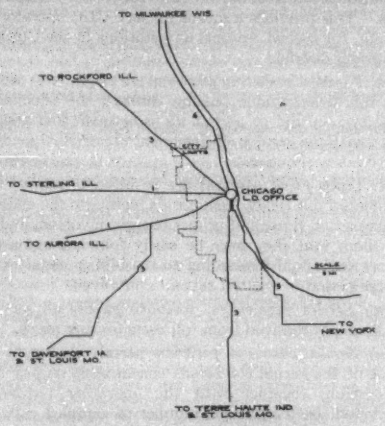


FIG. 6—ROUTE OF TOLL CABLES ENTERING CHICAGO
Figures indicate the number of cables in each route

desirable to locate carrier telephone and high frequency carrier telegraph equipment on the open-wire lines with as little cable as possible, since the cost of loading cable to transmit frequencies up to 30,000 cycles is considerable and the attenuation is large.

At the toll open-wire entrance point, there are now installed, therefore, besides the necessary open-wire terminal equipment and 132 telephone repeaters, 192 channels of carrier telegraph and 37 systems of telephone carrier.

In addition to the 1400 toll lines now in service within toll cables there are 590 telegraph channels in service in these same cables. Of these 300 are superimposed on wires used simultaneously for telephone circuits and the remaining 290 are provided upon carrier-current channels on wires which cannot simultaneously be used for talking purposes.

*Toll Traffic.* The large capital investments in the general toll plant and the expenses incident to its operation and maintenance are controlled by the volumes of toll traffic which it is anticipated will require handling by it. Since time is a factor in the engineering, manufacture, and placement of the plant, and in the employment and training of the personnel to operate it, these traffic anticipations must be upon the basis of considerable futurities, which vary from several years for switchboards to the annual seasonal peaks for toll lines and detailed monthly estimates for the operating forces.

Various statistical methods are open to use in determining what the future toll traffic will be. In general, these project past averages on future average trend lines, with past occurrences which have caused known distortions removed and proper allowances for future fluctuations included. Mathematical comparisons are checked by judgment which observes not only local but neighboring and country wide controls and potential factors, such as the general business curve.

Estimated originating call volumes must be distributed by terminating points and assembled by route paths and then combined with average conversation lengths and holding times to obtain the call-minute quantities from which toll circuit requirements are finally evolved. These same originating call volumes must be distributed by type of call and combined with operator work time allowances to obtain the traffic unit quantities from which toll switchboards position

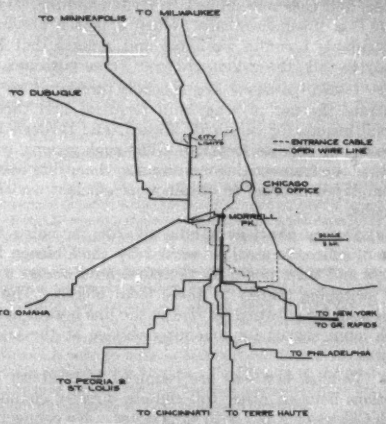


FIG. 7—ROUTE OF OPEN-WIRE LINES ENTERING CHICAGO

requirements can be set up, and the operator force requirements to operate them can be determined.

These functions of traffic toll line, traffic switchboard, and traffic force engineering are necessarily combined with general transmission, toll cable design, switchboard, terminal, and power engineering, and with traffic methods, traffic organization, and traffic operating supervising work to form a completely coordinating and efficient and economical toll system plan.

## CONCLUSION

Within this toll system plan the continual objectives are those of simplification and improvement in methods,

increase in speed and accuracy of service, more complete efficiency in the provision and use of plant, and uniformity of transmission between all points.

The marked and steady increases in toll business at Chicago and throughout the country, and the several reductions in toll rates which have been made in recent years are rather direct evidence that these technical objectives are being met to the increased comfort and satisfaction of the subscriber whose point of view is, in the last analysis, the final and ultimate control.

### Addendum

(*a*) *CLR positions*, divided into four units, each serving a selected group of Chicago local offices, record all toll calls originating within these groups and make a first attempt to complete all calls capable of an immediate start. These comprise 85 per cent of the traffic offered.

(*b*) *Non-method positions*, arranged with selected groupings of toll lines, handle those originating calls which do not result in conversation on the first attempt, such as those upon which "leave word" requests are made, and calls not subject to CLR handling, such as large lists of sequency calls. When a person previously unavailable becomes available and reports that he is ready to talk, the call starts from these positions.

(*c*) *Utility positions* are specially arranged to concentrate the use of long haul terminal and through circuit groups for outward, inward, and through business at one definite location. For such groups, which include the transcontinental circuits, the utility method is employed in order to obtain more efficient use of the circuits.

(*d*) *Inward positions* handle all calls incoming from distant offices to stations served by the Chicago local offices and these positions therefore have access to the toll switching trunks to these local offices. The toll lines used for outward service at the line boards appear with lamp signals for incoming service at the inward boards.

(*e*) *Through positions* are required to establish connections between other toll centers directly connected with Chicago but not with each other. No connections are made to Chicago stations, and the cord circuit repeaters, formerly a significant feature of this board, are now replaced with a terminal type, with automatic pad control.

(*f*) *Directory positions* are provided to secure the minimum delay in providing the distant station number in cases where the number is not known to the calling subscriber.

(*g*) *Routing positions* enable certain operators to specialize in quoting the necessary toll circuit information to CLR and "through" operators to points not reached over direct circuits. The list of actual toll centers is in itself very large and to this must be added all of the tributaries reached via these centers.

(*h*) *Delay quoting positions* are provided to inform the CLR operator of the period a call may be delayed when circuits to distant points may have been put out of service, as from storm or other trouble, or the traffic congestion is unusual.

(*i*) *Traffic trouble positions* provide a centralized bureau for the reporting of all classes of line and equipment trouble.

(*j*) *Office "B" positions* are equipped with a subgroup to toll switching trunks to local offices, together with multiple of toll terminal lines and supervisory telephone sets. This provides a means for any CLR operator to obtain, for special reasons, any stations in the Chicago centering district.

(*k*) *Ticket distributing positions* are required to center the toll ticket traffic passing through the pneumatic tube system and to permit its assortment and assignment with the greater efficiencies at the original sending and final receiving ends.

(*l*) *Ticket filing positions* are required to receive the completed toll ticket memoranda, compute the elapsed conversation time, and proper charges involved, and so file them that they may be easily found, if required, before their final forwarding to the billing department for collection of the toll revenues involved.

(*m*) *Service supervisors' positions* handle all service criticisms as received from toll users for any cause.

(*n*) *Service observing positions* permit checks to be made of the actual conditions encountered on any toll connection, together with the operating technique employed, on a sufficient number of sampled calls to enable the service as a whole to be properly gaged.

(*o*) *Monitor tap positions* enable the individual operator's work to be observed.

*Toll tandem positions*, in addition to the above, are required for Chicago office switching by reason of the lack of face equipment capacity to put all outgoing toll lines before all CLR operators.

## Discussion

**R. L. Hartman:** As Mr. Neubauer has pointed out, the engineering of toll office equipment and toll circuits is necessarily based on future requirements and any studies in this connection must definitely anticipate the toll service which the subscriber may require in the future. The present method of engineering in which the annual seasonal peak is considered in general takes care of these requirements over an extended period. Despite this generally effective engineering of toll circuits and estimation of traffic increases, there are certain periods when the amount of traffic is not in phase with the engineering and it becomes a problem to engineer the existing layout to meet more nearly the circuit requirements. Moreover, in Chicago, due to its geographical location and far spread layout, it has been found desirable to make more or less temporary changes in the existing layout to care for the sudden loads and emergency traffic peaks that result from sectional storms, earthquakes, tornadoes, and other major disasters. These large and unexpected volumes of traffic originate in areas feeding into and through Chicago and cannot be handled satisfactorily over the regular circuits. It is also often expedient to rearrange the existing layout to take care

of the normal traffic which is delayed over routes that are impaired or completely destroyed by storm breaks, line failures, etc. Further, temporary rearrangement of existing toll circuits for traffic peaks resulting from football games, automobile races, and other sporting events, as well as for localized peaks in connection with special seasons like the peach or cotton season, are desirable and efficient.

The comprehensive network of telephone circuits throughout the United States has made possible the practise of quoting alternate routes for a large part of the long-haul traffic. This regular toll circuit layout is also sufficiently flexible to permit limited additions to a number of existing groups by cutting other paralleling circuits or by building up additional facilities from circuits already in the layout. Chicago, by its geographical location, is the natural switching point for traffic originating and terminating in the Middle West, Northwest, Southwest, and the Mountain States' territories,—areas that are developing quite rapidly from a long-distance telephone standpoint. It is, of course, the logical switching center for transcontinental traffic as well. Consequently, terminating here are direct circuits from all parts of the United States. In addition, the regular circuit layout out of Chicago is such that several routes are generally possible to most of the large cities in this country and Canada. Under these conditions and with a well defined arrangement whereby the Chicago office is closely tied in with Memphis, Louisville, St. Louis, Kansas City, and Minneapolis, a large part of the work of rearranging the existing circuit layout originates here at Chicago.

The magnitude of this work can be better understood by the quotation of some figures. During recent concurrent storms in the Chicago territory and areas north and south, 120 circuits were rearranged in a 24-hr. period to take care of the normal traffic over the routes affected by the storms. An average of 20 rearrangements per day is made either to make good facilities in trouble, or to adjust for unusual traffic loads. For example, the Chicago-New York group was increased approximately 50 per cent during the recent stock market upheaval at the expense of other circuit groups but not to the detriment of the traffic over the groups used.

It will be appreciated that this "rearrangement" of existing facilities cannot be a haphazard affair but that there must be excellent and up-to-the-minute information available on the circuit groups in the Chicago board and the Western Division as a whole. In general, circuits are taken from groups over which traffic is being moved at the time without delay and it is only under the worst conditions that an attempt is made to equalize delays on various groups that can be used as interchangeable routes. Transmission is carefully considered and the additional switch often introduced by patching must not present an unjustified hazard.

Close co-operation is essential between the various departments involved in engineering a patch and arranging for it in the circuit layout. The new circuits put in the toll board must be properly marked and the operating personnel informed so that the greatest use is made of the circuits established.

Summarizing briefly, the efficient use of equipment and circuits plays quite as important a part in the general economics as proper engineering, installation, and maintenance of the facilities involved. Circuit engineering must be supplemented by a type of supervision of the current flow of traffic to the end that an overall effective use of the existing facilities will be maintained. The temporary changes in circuit layout which are originated here at Chicago are to this end, and offer effective assistance in moving congested or delayed traffic and in maintaining satisfactory relations with the users of long distance service in the Long Lines Western Division comprising approximately 75 per cent of the United States.

**W. M. Jamieson:** This paper refers to the testing required to operate and maintain the toll circuits in a satisfactory condition. The general inprovement in transmission and the increase in the speed of completing calls, such as is obtained through the use of the "CLR" method of operating, results in stricter requirements on the efficiency obtained from the toll circuits. Some time ago the volume efficiency of the circuits was stressed more than other transmission features. It was recognized that the real measure of transmission is the clearness and distinctness with which the telephone conversation was carried on, *i. e.*, upon the intelligibility of the words and the naturalness of the voice. In a broader sense, transmission depends upon many factors, including volume, distortion, noise, crosstalk, and transient currents. In the design of toll circuits, these factors must be considered in determining the type of facilities required for a certain length of circuit. The efficiency of circuits is now graded in terms of "Effective Transmission Equivalent" which includes allowances for the interfering effects mentioned above. In order to meet the transmission requirements of the various types of facilities involved, transmission tests are made before placing the circuit in service and thereafter at periodical intervals. These tests include transmission frequency runs, noise tests, quality tests, crosstalk tests, balance tests at repeater offices, line insulation and resistance unbalance tests, etc.

To take care of this feature, there are 16 transmission measuring sets installed in the Chicago Office. The tests made include between 11,000 and 12,000 single frequency measurements each month in addition to those mentioned above.

Due to the large number of switchboard and testboard positions involved in handling circuit trouble, a special setup is required to see that all trouble reports are forwarded to the proper party. On discovering a circuit in trouble, the line operator reports the trouble to the traffic trouble clerk, on a special ticket sent over a pneumatic tube. This trouble clerk arranges to make the circuit busy at the tandem board and at the same time reports the trouble to the testboard trouble clerk over a printer circuit. The Traffic Control Bureau receives the report over the same printer circuit. The testboard trouble clerk forwards the report to the proper testboard position over a pneumatic tube. After the trouble on the circuit has been cleared, the testboard man arranges directly with the tandem operator over a telephone order circuit to remove the busy signal, after which he returns the trouble ticket with a notation of the trouble found to the testboard trouble clerk. The report of the trouble being cleared is then sent to the traffic trouble clerk over the printer circuit. By utilizing telegraph printers, pneumatic tubes, and telephone trunk circuits, the circuits are placed back into service with a minimum of lost time and at the same time give an accurate record of the troubles found. In addition the Traffic Control Bureau is able to keep in constant touch with the number of circuits available for service. The feature of the testboard man arranging directly with the tandem operator to clear the busy signal saves from three to four minutes in lost time.

Mention is made of the large concentration of toll telephone and telegraph facilities in toll cables. The protection of this cable plant is a matter of great concern, since the loss of one or more cables would result in a very serious service impairment. Insulation tests on spare pairs in these cables are, in general, made hourly and more frequently in adverse weather. In addition, a portion of the working pairs is successively tested each night so that all conductors in each cable are tested at least monthly. Upon the first sign of a threatened failure, splicing and construction crews and sections of emergency cables are dispatched to the measured location of the trouble. Inspection of the cable in the suspected location is made and if no evidence of a sheath break is found through which moisture could penetrate, a test opening is required. When the sheath break is found, the cable can often be boiled dry with hot paraffin. Sometimes the moisture can be eliminated or reduced sufficiently to permit service by applying oil pumped nitrogen gas to the cable at the manholes adjacent to the sheath break. If the cable is thoroughly satu-

rated, the above methods are usually not successful and an emergency section of cable must be pulled in place and spliced to replace the faulty section. Emergency supplies of gas and cable are stored at strategic locations in both the metropolitan and suburban areas. Cable crews engaged in repair or construction work are required to call a central point periodically so the nearest crew can be utilized in an emergency and the cable restored in the shortest possible time.

Many cables are placed under permanent pressure using nitrogen gas with an alarm system so as to increase the speed of clearing sheath breaks. Experience so far indicates that only ⅛ as many service interruptions occur on aerial cable under pressure, and 1/75 on underground cables as compared to those not under pressure. At present there are six toll cables out of Chicago under gas pressure and plans have been made to place the toll cables under pressure by the end of 1929.

**H. S. Osborne:** The very great development of toll business has greatly increased the importance of improving the means for interconnecting the small toll centers of the country for taking care of the extremely large number of relatively small items of traffic between widely distant points.

There are about 2700 toll centers in the United States through which this traffic is handled, and the problem is to provide a routing so that any one of those 2700 toll centers can be connected to any other one rapidly, with a minimum number of switches and with adequate clearness of transmission.

Fortunately, the development of the business and of the changes in practise has helped in bringing about improvements in this general problem of switching.

There has been a very marked tendency toward an increase in the concentration of toll circuits along a given route. With the old practise, where we were relying on open wire lines, a toll line carrying 40 wires and 30 circuits constituted a heavy route. Now a single aerial cable toll line carrying two cables will have as many as 600 circuits. On the most important routes of the country are being developed underground cable routes which will ultimately carry many thousand toll circuits. This tendency for concentration on toll routes has its parallel in the practicability of setting up simplified and improved toll switching systems.

There have been selected out of the 2700 toll centers in the country 150 important switching centers which are designated as primary outlets, and, as indicated by that name, those points are the points through which the switched business of the toll centers is primarily handled, although not exclusively, because alternate routes are provided where they are economically warranted.

These primary outlets are interconnected by direct circuits within as large areas as practicable, generally within a State, which means that within such an area any two toll centers can be connected together with a maximum of two intermediate switching points. That constitutes a material improvement in the handling of these items of switched business over the arrangements which were practicable before. It reduces not only the number of switches but helps greatly in making it possible to provide adequate transmission.

To handle the countrywide business, there have been selected, as was shown in the chart in Mr. Neubauer's paper, eight regional centers, and each primary outlet is connected to at least one of these regional centers. Chicago is probably the most important of those regional centers, there being already direct circuits to Chicago from 75 out of the 150 primary outlets of the country, so we might say, roughly, that half the telephones of the country can talk to Chicago without more than one intermediate switch. If they do not want to talk to Chicago, they still find Chicago a very important point in the process of getting through connections to other distant parts of the country.

**J. A. Caparo:** What relation exists between the different signaling frequencies and the efficiency of transmission?

**E. O. Neubauer:** On telephone lines the frequency of 1000 cycles is the most efficient of the three. The frequency bands of the telephone lines are such that the lower frequencies are transmitted with rather low efficiency, as I said before in connection with the 20-cycle system. For that very reason 20 cycles is suitable only for short circuits and those not equipped with telegraph apparatus. The 135-cycle systems are used more extensively but on account of the low efficiency of telephone lines at that frequency, frequent repeaters of that 135-cycle current are necessary. But the 1000-cycle system being a very important frequency in the voice range, is transmitted with considerable ease over the telephone line. In other words, the transmission frequency characteristics of the toll line are rather poor at frequencies as low as 20 cycles, and they become comparatively very efficient at frequencies over 200 up to about 3000 cycles.

# Air Transport Communication

BY R. L. JONES[1] and F. M. RYAN[1]

Member, A. I. E. E. Member, A. I. E. E.

*Synopsis.—The successful operation of an air transportation system depends in no small degree on the communication facilities at its command. Rapid and dependable communication between transport planes in flight and the ground is essential. Two-way radio telephony provides this necessary plane-to-ground contact.*

*The design of a radio telephone system for this service requires quantitative knowledge of the transmission conditions encountered in plane-to-ground communication. An experimental investigation of these conditions over the available frequency range has been carried out and the results are described.*

*A complete aircraft radio telephone system designed for the use of air transport lines and an airplane radio receiver designed for reception of government radio aids to air navigation are also described.*

## Introduction

PROBABLY nothing has contributed more to the safety and reliability of present long distance transportation systems than the associated communication and signaling facilities. With ocean-going steamships constant communication is maintained through the medium of the radio telegraph, providing not only the communication necessary in times of emergency or peril, but also routine daily weather information and such instructions as are necessary to insure the safe and efficient handling of ships at sea and in port. Similarly, on our principal railroads, the fastest trains are dispatched by wire telephony and further protected by electrically operated block signal systems.

For airplanes the very great speed and the greater dependence on weather conditions make it necessary to provide more frequent and more complete communication contacts than are required in the case of either ocean or rail transportation. The highest degree of reliability and safety can only be achieved with this mode of transportation when instantaneous communication with ground is available to the pilot throughout his flight. This can only be provided through the medium of radio and preferably by the use of radio telephony, since telephony has an advantage over telegraphy in requiring no skilled operator as well as insuring much more rapid communication. It also has the advantage of making possible direct communication between the pilot and the air transport dispatcher located on the ground, thereby avoiding delay and the possibility of misunderstandings that might grow out of the necessity of transmitting information through a third and perhaps fourth party.

On air lines equipped with radio the dispatcher on the ground provides the pilot in flight with frequent weather reports, information relative to landing conditions, the positions of other planes flying along the same section of airway, and other data which may be useful in safely maintaining a regular schedule. The pilot, in return, keeps the dispatcher informed as to his progress along the airway and the weather conditions encountered. This frequent routine personal contact between pilot and dispatcher insures satisfactory communication in time of emergency. In case of a forced landing the ground organization is advised of the position of the plane and adequate arrangements can be made for the prompt care of passengers, mail, or express.

It is, however, in the avoidance of accident that the radio is vitally necessary. For example, many of our Western airports are reached only by crossing one or more mountain ranges. Frequently upon crossing the mountains a pilot is confronted with a blanket of clouds which must be pierced to reach port. With accurate radio information as to the "ceiling" or height of the underside of the cloud bank from ground, a descent can be made with confidence and safety or, in case of inadequate ceiling, the plane may be diverted to another port.

The problem of designing a radio telephone system to provide service of this character is discussed in this paper which also describes the equipment that has been developed.

## Transmission Tests

An essential preliminary to the actual design of such a radio telephone system is a decision as to what frequency range the apparatus should be designed to cover. The carrier frequency for any radio service is determined to a considerable degree by the distance over which it is necessary to communicate. As the principal airports along the airways of the United States are, in general, spaced about 200 miles (see Fig. 1), a range of reliable transmission of about 100 miles will insure constant contact between planes in flight and radio ground stations installed at these ports. Experience has shown that the frequency band now employed for broadcast service, that is, 550 to 1500 kilocycles, is well suited for transmission at this distance. However, these frequencies are not available for aircraft communication and consideration was therefore given to bands both above and below this range.

The International Radio Telegraph Convention of 1927 allocated a frequency band of from 315 to 350 kilocycles exclusively to air mobile service. This

1. Bell Telephone Laboratories, New York, N. Y.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.*



29-151

convention also allocated a number of other bands in the range 350 to 550 kilocycles to general mobile service. These bands have admirable transmission characteristics. However, they provide for but a small number of telephone channels and have the further disadvantage of requiring a very large transmitting antenna which is of course a severe handicap in the case of an airplane

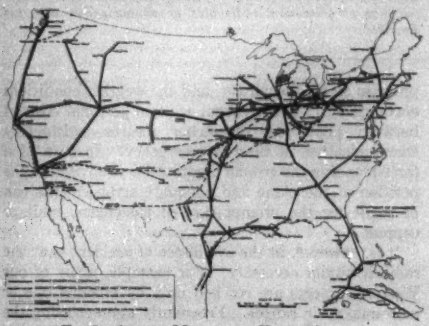

Fig. 1—Airway Map of the United States

installation. A number of bands in the frequency range of 1500 to 6000 kilocycles was also allocated to mobile services by the convention of 1927. Attention was turned to this frequency range and experimental

Fig. 2—Cabin Monoplane Employed in the Development of Radio Systems for Airplanes

tests undertaken to determine its suitability for this class of service.

For the conduct of these tests a five-place cabin monoplane has been operated from Hadley Airport, New Jersey, as a base. Measurements of strength of received signals have been made both transmitting from plane to ground and from ground to plane. In the latter case a radio field strength measuring set was installed in the airplane. These transmission tests have been supplemented by similar tests made in California employing a biplane mail ship.

One of the striking results of this investigation has been the disclosure of the manner in which signals of these frequencies vary in strength with the plane's altitude. Fig. 4 is a record of the strength of signals

Fig. 3—Radio Field Strength Measuring Set in Use in Airplane

received from a 500-watt transmitter located at Whippany, New Jersey, and operating at a frequency of 1510 kilocycles during daytime flights from Whippany in

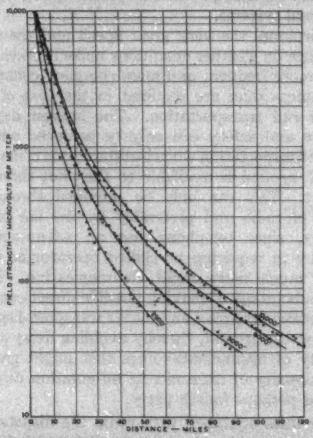


Fig. 4—Strength of Daytime Signals Received in Airplane from 500-Watt Ground Station Operating at 1510 Kilocycles

the general direction of Philadelphia. A comparison of the field strength as given graphically by the curves shows the influence of altitude of flight on the strength of signals. Figs. 5, 6, 7, and 8 show transmission from plane to ground to have similar characteristics. These curves are the result of plane-to-ground daytime transmission tests made in California. The curve for each

altitude is the result of averaging the data obtained in flights in three directions from Oakland Airport.

For all of the tests in both California and New Jersey the airplane was equipped with a radio telephone transmitter having a carrier power of 50 watts and a quarter

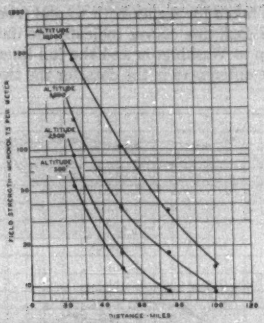


FIG. 5—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 1625 KILOCYCLES

wave trailing wire antenna. During many of these tests the field strength measurements were supplemented by telephone intelligibility tests. These were made by reading lists of 25 disconnected words and endeavoring to record them at the receiving end of the

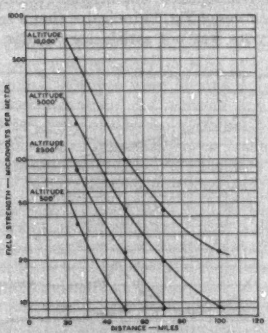


FIG. 6—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 2525 KILOCYCLES

circuit. Fig. 9 shows the results of such tests which were made at the same time that the transmission data shown in Figs. 5, 6, 7, and 8 were taken. An idea of the satisfactoriness of the telephone circuit provided with varying distance and with different carrier frequencies may be had from the curves of Fig. 9. In interpreting these curves, it is to be noted that for the circumstances of these tests a result of 50 per cent or

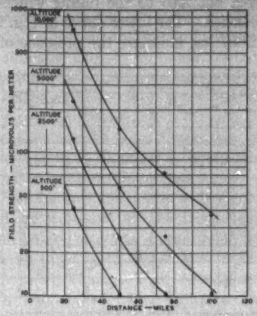


FIG. 7—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 3450 KILOCYCLES

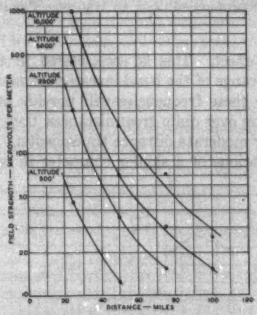


FIG. 8—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 5630 KILOCYCLES

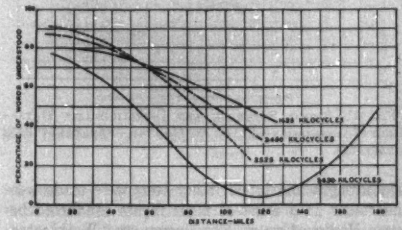


FIG. 9—AVERAGE INTELLIGIBILITY DATA FOR DAYLIGHT FLIGHTS—TRANSMISSION PLANE TO GROUND

better corresponds to a satisfactory condition for conversation.

It will be noted that, in general, greater field strengths

were obtained from the lower frequencies and a higher degree of intelligibility provided. The lower intelligibility at the high frequencies is not alone due to low field strength but also to the fading which occurs at these frequencies. The lower curve of Fig. 9, which is for 5630 kilocycles, indicates the presence of the "skip

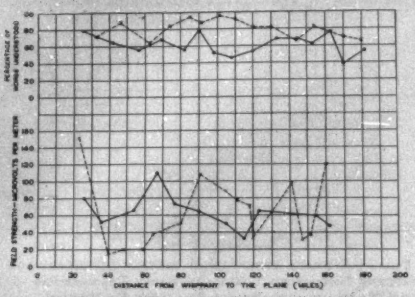


FIG. 10—SIGNAL STRENGTH AND INTELLIGIBILITY DATA—NIGHT TRANSMISSION—PLANE TO GROUND—FREQUENCY 1608 KILOCYCLES

distance" effect. This is encountered in the higher frequency range of the band investigated and indicates that while these frequencies will provide satisfactory transmission over quite great distances, they are not so reliable for moderate distance transmission.

Investigations of a similar character in which both

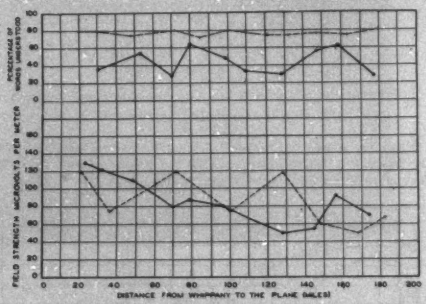


FIG. 11—SIGNAL STRENGTH AND INTELLIGIBILITY DATA—NIGHT TRANSMISSION—PLANE TO GROUND—FREQUENCY 3452 KILOCYCLES

field strength and intelligibility tests were made were undertaken in a series of night flights conducted between Hadley Airport, New Jersey, and Washington, D. C., during the month of May, 1929. In this case the transmission was also from plane to ground, field strength measurements being made at Whippany, New Jersey. Figs. 10, 11, 12, and 13 record the results of these tests. Although a great deal more fading was encountered during these tests than during similar ones made in the daytime, as indicated by the percentage of words understood correctly, it was found possible with the three lower frequencies used, 1608, 3452, and 4108 kilocycles, to maintain practically continuous communication with the plane in flight. At each frequency, data were taken for flights both to and from Washington. The dash line curves indicate the data obtained on the trip to Washington and the full lines the return trip. The differences in the data for the two directions

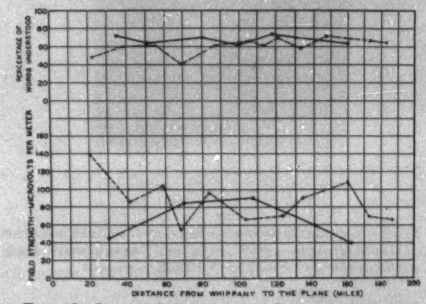


FIG. 12—SIGNAL STRENGTH AND INTELLIGIBILITY DATA—NIGHT TRANSMISSION—PLANE TO GROUND—FREQUENCY 4108 KILOCYCLES

are believed to have been due more to variations in the interference present from other stations than to any change in transmission conditions. Examination of the upper curves of Fig. 13 indicates that a frequency of 5690 kilocycles was not satisfactory under these con-

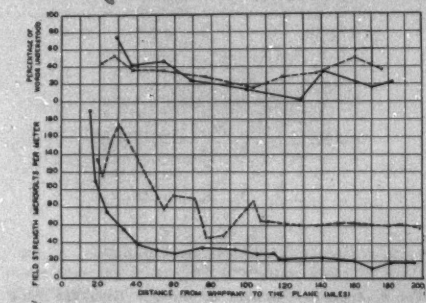


FIG. 13—SIGNAL STRENGTH AND INTELLIGIBILITY DATA—NIGHT TRANSMISSION—PLANE TO GROUND—FREQUENCY 5690 KILOCYCLES

ditions. This was mainly due to excessive fading and accompanying distortion effects.

A study of the transmission data presented here and similar data from other tests has led to the conclusion

that in the frequency band 1500 to 6000 kilocycles, satisfactory channels can be found to meet the requirements of domestic air transport operation. In general, the lower frequencies of this band appear to provide the most satisfactory transmission. However, the use of these frequencies is only practical when trailing wire antennas are employed. It may, therefore, be desirable in some cases to use the higher frequencies of

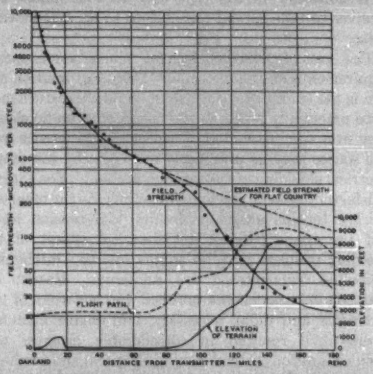


Fig. 14—Signal Strength in Airplane—Receiving from 500-Watt 325-Kilocycle Ground Transmitter

the band with fixed antennas of relatively small dimensions in order to avoid the use of the trailing wire which, while being satisfactory from an electrical point of view, offers some mechanical disadvantages. This would somewhat restrict the range of communication but would offer a satisfactory solution of the problem provided ground stations were located at sufficiently frequent intervals along the airways and adequate communication provided between stations.

With an increase of the density of air traffic along the principal airways it is expected that wire telephone facilities will be provided for inter-field communication and for extending the plane-to-ground telephone circuit to distant points on the airway. There is a number of engineering problems involved in the connection of radio and wire facilities so as to provide a comprehensive telephone dispatch system but there appear to be no insurmountable difficulties and such an arrangement has been set up experimentally on frequent occasions at Whippany, New Jersey, where the experimental ground station is located. But traffic on most airways has not yet grown to the point where such a wire telephone network can be justified. A very useful auxiliary service which is also believed to have a permanent place is the telephone typewriter or printing telegraph system which is being used for the interchange of weather information between fields on many of the principal airways.

The band of frequencies of 1500 to 6000 kilocycles is not suited to direction-finding purposes over any great distance. In general, it is necessary to use moderately low frequencies for this purpose and the Department of Commerce, with this in mind, adopted for airway radio beacons the band of frequencies internationally allocated exclusively to radio beacon service (285 to 315 kilocycles). Weather information is usually broadcast in the adjacent exclusive aircraft band, 315 to 350 kilocycles, although at some airports the weather and beacon signals have been alternately transmitted on the same frequency in order to avoid the necessity of the pilot retuning his radio receiver.

To provide information as to the signal strength that would be available at the frequencies of such weather and beacon stations, a number of transmission tests has been made with frequencies in these bands. In this frequency range, little variation in signal strength is encountered with changes in altitude. Fig. 14 shows the results of such measurements made on a flight from Oakland, California, to Reno, Nevada. The signals were provided by a 500-watt radio transmitter installed at Oakland Airport. This curve is especially interesting as it shows the greater attenuation introduced by the presence of a mountain range. The dash curve in this figure indicates the transmission conditions found over flat country.

## Antennas

Although the use of trailing wire antennas for aircraft radio purposes has been quite general in military practise for some time, no accurate data have been available as to their resistance characteristics over the frequency range, 1500 to 6000 kilocycles. As this information is necessary in order to properly design

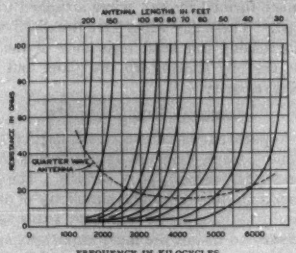


Fig. 15—Resistance Characteristics of Trailing Wire Antennas

transmitting equipment for use with such antennas, measurements have been made employing a substitution method. The results of these measurements are shown in Fig. 15. It will be noted that for quarter wave antennas the resistance varies between 15 and 42 ohms.

As to receiving antennas, Fig. 16 is illustrative of a general type of self-supporting, stream-lined mast

antennas which are being widely used with airplane radio receivers for the reception of weather and beacon signals. The mast shown is of hollow wood construction with an internal conductor and extends approximately seven feet above the fuselage of the plane. Similar masts of metal construction may also be sucessfully used.

For transmission they are not generally suitable

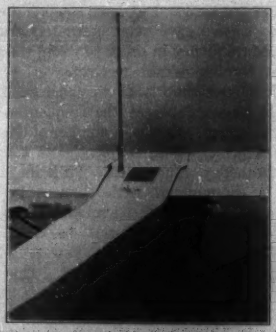

Fig. 16—Typical Installation of Self-Supporting Stream-Lined Vertical Antenna for Reception Purposes

owing to the relatively small effective height of such antenna structures. However, they may be employed at frequencies above 3000 kilocycles but with considerable sacrifice in efficiency compared with that to be had with the trailing wire. In some cases, the efficiency has been increased by the use of an umbrella arrangement formed by guy wires attached to the top of the mast. These guy wires have the disadvantage of greatly increasing the head resistance of the antenna structure, thereby slowing up the plane and reducing its carrying capacity.

## General Requirements

Radio apparatus for aircraft installations is called upon to meet more stringent requirements than such apparatus for any other type of service. The principal requirements are reliability and simplicity of operation. In practically all mail planes and many transport planes it is necessary to install the most important apparatus elements in locations totally inaccessible in flight. The equipment is usually operated by one not especially skilled in the manipulation of radio apparatus. In mail planes it must be completely controlled by the pilot. The apparatus must be sturdy and capable of withstanding continual vibration, yet it must be compact and light in weight.

It must meet unusual electrical requirements. For example, with the small receiving antenna usually provided the radio receiving equipment must be unusually sensitive in order to receive satisfactorily the comparatively low field strengths available. It must be capable of delivering a very high output level in order to make the signals audible over the noise of engine, propeller, and wind which is experienced in most present-day planes.

This high acoustic noise level is also an important factor in determining the design of microphones and telephone receivers for use in aircraft installations; and it is necessary in the case of both microphone and receiver to take special precautions to exclude external noise.

The use of radio equipment places some special requirements on the airplane. The usual ignition system is the source of such violent electrical disturbances as to practically preclude the reception of radio signals even over very moderate distances. Interference from this source may be practically overcome by the proper electrical shielding of the ignition system. For entirely satisfactory results, shielding must include the magneto, the low tension magneto circuits, high-tension leads, and the spark plugs. The electrical aspect of the shielding problem is quite simple but the mechanical difficulties encountered are numerous. Recent co-operative attacks on the problem by government departments and radio, accessory, and engine manufacturers have resulted in considerable progress and shielded ignition systems having electrical and mechanical characteristics, equal if not superior to the unshielded systems, are being made commercially available. Should engines of the Diesel type come into general use, the shielding of ignition systems will cease to be an important problem.

In addition to shielding, it is desirable to bond all metal parts of the plane in order to avoid noises in the

Fig. 17—Aircraft Radio Receiver for Weather and Beacon Reception

receiving equipment from intermittent contacts between various metal parts of the plane. In case transmitting equipment is installed, such bonding is essential protection against the possibility of high voltages developing between such parts and resultant sparks or arcs. In planes of all-metal construction the provision of such bonding is a comparatively simple matter.

## Airplane Radio Receivers

Fig. 17 shows a radio receiver designed for reception

of the government weather and beacon signals over the frequency range 285 to 350 kilocycles. The design of this equipment was given precedence in our program over the design of a complete two-way radio telephone system in order to make the government radio aids to air navigation available as soon as possible. This equipment, however, constitutes a desirable supplement to the two-way system. This 8-A receiver is of high sensitivity, an antenna input of 10 microvolts

Fig. 18—Wind-Driven Generator for Supplying Filament and Plate Power for Aircraft Radio Receivers

being sufficient to enable it to deliver an audio frequency output of 6 milliwatts. It can be expected to give consistent reception for government weather reports from the 2-kw. ground stations at a distance of 125 miles; and it has been successfully used at a distance of 200 miles.

Equipotential cathode vacuum tubes are employed throughout the receiver. The cathode of each tube is heated indirectly from an auxiliary filament. This arrangement eliminates the possibility of the introduction of noise from the filament supply source. Four tubes are used in the receiver. Three are of the shield grid type, two being employed as radio frequency amplifiers and the third as a detector. The fourth does

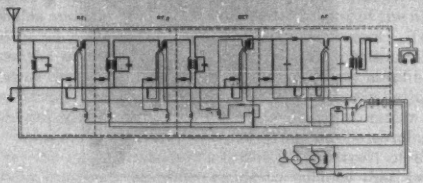

Fig. 19—Schematic Circuit of Low-Frequency Aircraft Radio Receiver for Weather and Beacon Reception

not contain a shield grid and is employed as an audio frequency amplifier.

The circuit arrangements are shown in Fig. 19. There are three tuned circuits, one for the antenna and one for the output circuit of each of the stages of radio frequency amplification. A special gang condenser is employed for simultaneously tuning these three circuits. The amplification of the receiver is controlled by a potentiometer which varies the shield potential of the two radio frequency amplifier tubes.

The receiver is mounted in a metal box about 12 in. long by 8 in. high and a little over 4 in. deep. Complete with vacuum tubes, it weighs about 13 lb. Both filament and plate supplies may be obtained from a small wind-driven generator having a diameter of only

Fig. 20—High-Frequency Remote Controlled Aircraft Radio Receiver for Two-Way Communication

Fig. 21—High-Frequency Remote Controlled Aircraft Radio Receiver for Two-Way Communication—Cover Removed

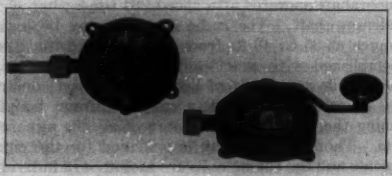

Fig. 22—Remote Tuning Control for Aircraft Radio Receivers

a little over 3 in. Complete with propeller, it weighs only about 7 lb. This generator is driven at 6500 rev. per min. by a constant speed propeller. A dynamotor has also been successfully used for furnishing the plate supply for this receiver from a 12-volt battery in ships so equipped. The battery is then used directly for the excitation of the filament circuit.

Figs. 20, 21, and 22 show a design of aircraft radio

receiver designed for remote control. Two receivers of this general design have been developed, one with a frequency range of 250 to 500 kilocycles for beacon and weather broadcast reception and one with a range of 1500 to 6000 kilocycles for two-way communication.

The circuit arrangement in each of these receivers is similar to that of the 8-A already described for weather reports and broadcast as will be seen by a comparison of Figs. 23 and 19. An additional radio frequency input stage has, however, been provided. This input stage, while not tuned to the carrier frequency to be received, is provided with a special input filter, to avoid interference from unwanted stations which sometimes results from detection or modulation in such untuned amplifiers. Arrangement is also provided for adapting the receiver to antennas of various dimensions.

Remote volume control is accomplished by mounting the potentiometer which controls the shield grid potential of the radio frequency amplifiers in a small unit which is located within reach of the pilot. The

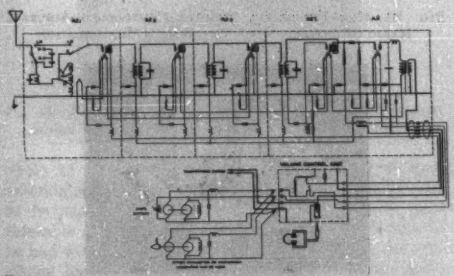

Fig. 23—Schematic Circuit of High-Frequency Aircraft Radio Receiver

remote tuning is accomplished by the use of a flexible shaft operated at a speed 264 times that of the condenser shaft. The radio receiver may be located as much as 35 to 40 ft. from the pilot and the tuning accomplished with practically no backlash. The receiver, while necessarily of light and compact construction, is extremely rugged, a cast aluminum bedplate forming the base for the support of all the apparatus units. Thorough shielding is provided for the circuit elements and the tuning coils are mounted in individual copper shielded containers. These coil assemblies plug into sockets similar to those provided for the vacuum tubes. Three sets of coils are employed to cover the frequency range of 1500 to 6000 kilocycles. A welded sheet aluminum top cover protects the apparatus from dirt and moisture.

A cushioned mounting base is provided for these receivers. This base is permanently installed in the airplane and the receiver may be readily removed therefrom. A single plug connector provides for all power supply and output leads from the radio receiver. This is quickly detachable from the receiver as is also the flexible cable which attaches to the condenser driving head. The receivers are about 6 in. by 10 in. by 12 in. and weigh about 16½ lb. complete with tubes.

## Airplane Radio Transmitter

Figs. 24 and 25 show the radio transmitter which

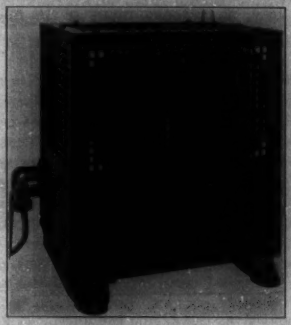

Fig. 24—High-Frequency Aircraft Radio Transmitter for Two-Way Communication

has been designed for airplane installations. This transmitter has a carrier output power of 50 watts and is capable of complete modulation. A transmitter of this power was designed as the transmission tests

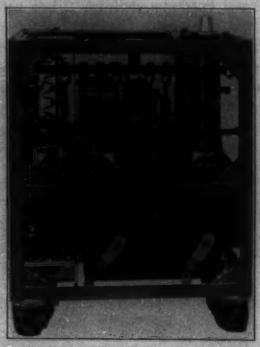

Fig. 25—High-Frequency Aircraft Radio Transmitter for Two-Way Communication—Front Panel Removed

described had shown it to provide a satisfactory range and it could be built of reasonable size and weight. Moreover, its power supply requirements are moderate and can be met satisfactorily in the present size planes.

The transmitter may be adjusted to any frequency in the range of from 1500 to 6000 kilocycles. The

effective use of the frequency range available for aircraft two-way communication requires that the stations be maintained closely upon their assigned frequency. This has been accomplished in the design of this aircraft radio transmitter by the employment of a quartz crystal controlled oscillator. The quartz crystal is clamped firmly between two metal electrodes, the lower one of which is held at a temperature of 55 deg. cent. by an imbedded electrical heater controlled by a thermostat of the mercury-column, contact making type. The entire unit is enclosed in an isolantite housing and arranged to plug into a socket similar to those employed for the vacuum tubes.

The crystal controls the frequency of the oscillations generated by a 5-watt vacuum tube. It is so ground that these oscillations have a frequency of one-half that which it is desired to radiate. A second 5-watt vacuum tube is employed as a frequency doubler. The output of this doubler tube excites the grid circuit of a final radio frequency amplifier which delivers a carrier power of 50 watts to the antenna circuit. This final stage of amplification is neutralized. The plate supply to this

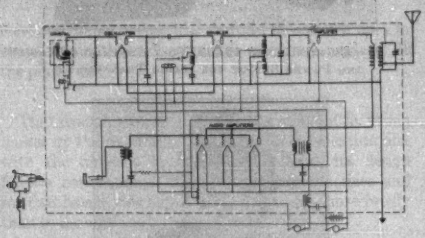

Fig. 26—Schematic Circuit of High-Frequency Aircraft Radio Transmitter

final amplifier is modulated by the introduction into its plate circuit of the speech frequency output of three 50-watt tubes connected in parallel. The grid circuit of this audio amplifier is fed from the output of the airplane microphone through an input transformer. The transfer of the audio frequency power from this amplifier to the plate circuit of the radio frequency amplifier is through a transformer designed to properly adjust the impedance of the load circuit. D-c. saturation is avoided in this transformer by so arranging the windings that the magnetization due to the plate current of the radio frequency amplifier tends to balance that produced by the plate current of the audio amplifier.

The transmitter, like the receivers, is arranged so that it may be quickly removed from an airplane. All power supply to the transmitter is fed through a readily removable plug provided with a locking ring. The speech input and the control circuits for starting and stopping the oscillator are connected to the transmitter through a three-conductor telephone plug. The transmitter measures about 9 in. by 12 in. by 15 in. and weighs, complete with crystal holder and vacuum tubes, 32 lb.

### Two-Way System

The plane terminal of the two-way telephone link is comprised principally of the radio receivers and transmitter described. It is to be noted that "push-button" operation is used. This appears to be desirable on account of the close juxtaposition of the apparatus on the plane and for conservation of frequencies. The short-wave system is so designed that the same carrier frequency may be used both for plane-to-ground and for ground-to-plane transmission. In addition to the things which have been described there is a number of important accessories which are of interest in understanding the operation of the system.

The radio transmitter requires for its operation a d-c. plate supply of 400 milliamperes at 1050 volts and a filament supply of about 15 amperes at 10 to 12 volts. A typical power supply system consists of a 12-15-volt, 50-ampere automatically regulated generator gear connected to the airplane engine, across which is connected a 6-cell, non-spillable lead storage battery of 65 ampere-hours capacity. The filaments of the transmitter are fed directly from this generator-battery combination and the plate supply obtained from a dynamotor operating from this same supply. A smaller dynamotor supplies the 215-volt plate supply necessary for the receiver plate circuits. Double voltage engine-driven and wind-driven generators furnishing 12-15 volts for battery charging and 1050 volts directly for the transmitter plate circuits have also been used successfully.

Fig. 27 shows a schematic diagram of both airplane and ground stations, including many of the switching features. A master control switch having three points serves to control the power supply for the radio receivers and transmitter. In the first position, everything is "off," in the second position, the filaments of the radio receivers and the dynamotor furnishing plate supply to the receivers are energized. In this position, which is normal while in flight, the heater circuit of the quartz crystal chamber of the radio transmitter is also energized. The third position of this switch serves to energize the filaments of the radio transmitter and to start the dynamotor furnishing plate supply to the transmitter. In this position, everything is in readiness for transmission. However, no oscillations occur in the transmitter and reception is possible. In order to transmit, it is then only necessary to press a push button which starts the oscillations in the radio transmitter. In some installations this push button is located on the hand microphone. In others it is located on the "stick" so that the pilot may operate it without moving his hand. During a conversation, this button is pressed while talking and released while listening. Relays perform all of the necessary switching functions.

Owing to the very high acoustic noise level in many airplanes, it is necessary to employ a telephone trans-

mitter of a special type. Fig. 30 shows a hand type microphone which has been developed for this use. In speaking, the rubber mouthpiece is held tightly to the lips and practically all noise is excluded from the transmitter. The closed cavity into which the speaker talks is so shaped as to avoid serious distortion of the speech.

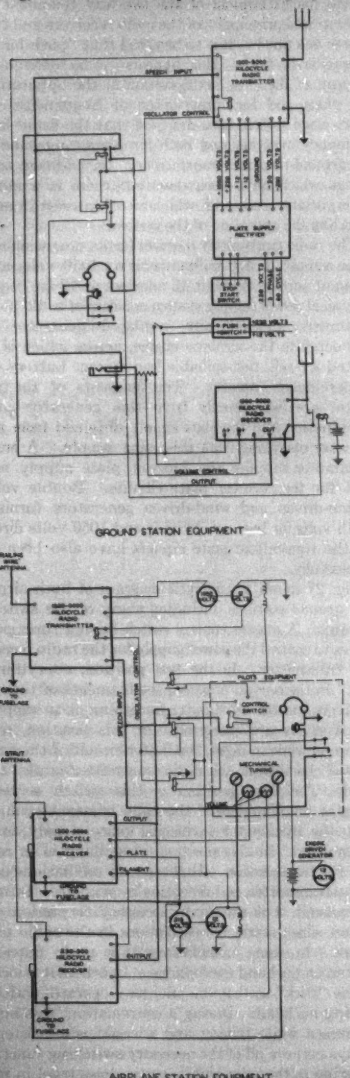


Fig. 27—Diagram Showing Equipment of Airplane and Ground Stations for Two-Way Communication

Fig. 28—Dynamotor Furnishing 1050 Volts Supply to the Airplane Radio Transmitter

Fig. 29—Engine-Driven 14-1050-Volt Generator Furnishing Power Supply for Radio Transmitter

Fig. 30—"Silencer" Type Telephone Transmitter for Airplane Use

Fig. 31—Special Pilot's Telephone Set for Use in Mail Planes

In some airplanes the noise level is not so severe and it is possible to employ transmitters with very much less shielding. Fig. 31 shows a telephone set for the use

of mail plane pilots which employs such a transmitter. The transmitter mounting is so arranged that the instrument may be dropped below the pilot's chin or turned up over his head when not in use.

Head telephone receivers similar to those employed by telephone and radio operators may be satisfactorily used in airplane work. A headset employing a small phonette type of radio receiver originally designed for the hard of hearing has been developed, however. These

Fig. 32—New Transport Plane Laboratory

receivers, which weigh less than an ounce, are used in connection with small ear molds which are made to fit the pilot's ear.

### Ground Station

The ground station contains the apparatus which makes up the fixed terminal of the communication link with the airplane in flight. In general, its design follows conventional radio engineering practises and for that reason this paper refers to it much more briefly than to the airplane terminal.

Fig. 33—Interior of New Transport Plane

The radio receiver is practically identical in fundamental design with the high-frequency receiver for airplane use, which has already been described. A special radio telephone transmitter has been developed for ground stations. This transmitter has a carrier power output of 400 watts and is capable of complete modulation. A single radiation-cooled vacuum tube is employed in its output stage. It may be adjusted to any frequency from 1500 to 6000 kilocycles and is provided with crystal frequency control similar to that employed in the airplane radio transmitter. The power supply for the plate circuit of this transmitter is ordinarily obtained from a three-phase rectifier employing tubes of the hot-cathode, mercury-vapor type.

### Conclusion

This paper has outlined experimental results fundamental to airplane communication and described the system of apparatus resulting from the associated development work. This apparatus is just becoming available and regular transport planes of several lines will shortly be equipped with it. The Bell Telephone Laboratories has recently added to its smaller ship, a large transport plane (Figs. 32 and 33), fitted as an air laboratory, in order that its future studies may proceed with enlarged scope. This is an all-metal, tri-motored ship. The future holds many interesting problems in the study of communication as an aid to travel and commerce by air. The work described here is a beginning to which future engineering will add many interesting records.

## Discussion

**S. M. Hamill:** I should like to ask what form of voltage control is used on the generators to counteract the varying speed of the drive.

**S. C. Hooper:** (communicated after adjournment) The problem of air transport communication should include provision that the weather and beacon services are so uniform that any plane equipped with radio will find the system similar in any section of the country, and the listening frequencies of ground stations always the same, so that any plane, whether it be transport, private, or government, would at all times be able to avail itself of weather data, bearings, beacon services, and terminal communications without the necessity of consulting documents and data.

Also, it should be borne in mind that direction findings for numerous airports not on the transport routes is going to be an important matter for individual planes desiring to make port in thick weather. Experience in the Navy indicates that every plane must carry a "homing device," *i. e.*, a radio compass, for this purpose. The carrier waves of broadcasting stations, scattered as they are throughout the country, offer a fine opportunity of taking bearings from a plane, provided the plane is equipped with a "homing device." It must also be borne in mind, in this connection, that satisfactory radio bearings cannot be obtained at frequencies much higher than 1000 kilocycles.

**F. M. Ryan:** The generators are directly geared to the airplane engine and are, of course, subject to wide variation in speed. In commercial transport work that speed is not as wide as in military work, but it may be as large as two to one in some cases. Such regulation as Mr. Hamill mentioned is very important. It is usually accomplished with a regulator not unlike the Tyrrill regulators used in power practise. That is a relay which intermittently opens and closes part of the field current. Ordinarily the voltage may be held within a few per cent.

Another type of power supply for the transmitter as well as the receiver is, of course, the wind-driven generator. In that case the fan is arranged with a blade the pitch of which tends to change with the speed and thereby is made self-regulating. These hold within about 2 per cent in speed. If the machine is suitably compounded, the voltage will be satisfactory under varying load conditions.

# The Future of Higher Steam Pressures
## in Steam Electric Generating Stations

BY IRVING E. MOULTROP[1]
Fellow, A. I. E. E.

***Synopsis.***—*Construction and operating experience has shown that a large part of the theoretically possible gains in efficiency due to higher steam pressures has been obtained in practise.*

*What are the future possibilities of higher pressures?*

*The biggest problem before station designers today is to reduce the cost of construction per unit of capacity. Some engineers have suggested that we should build cheaper and less economical stations. This is an unsatisfactory answer to the problem. The proper answer is to maintain the high standards of efficiency that have been established and reduce the cost of construction by intensive study and better design. Better engineering in the future is the answer to the problem.*

*By the use of large turbine generator units and large steam generating units, the unit cost of construction can be reduced materially. The present practise of installing several boilers to serve one turbine generator increases the cost of construction. The use of large steam generating and turbine generator units will reduce the unit cost of high-pressure stations more than it will reduce the unit cost of normal pressure stations.*

*If the steam generating units match the turbine generator units in capacity, we can design for unit construction. This unit construction will not only reduce the cost of construction but will also simplify operation.*

* * * * *

MUCH has been written about the present state of development in the use of higher steam pressures in steam electric generating stations. The plants in service and under construction have been discussed at length in the technical press, and it would be useless to endeavor to present to you a detailed picture of what has been accomplished. It is sufficient to say that a large part of the theoretically possible gain in efficiency has been obtained in practise, and there is every reason to believe that we will, in the near future, obtain as near the theoretical efficiencies possible as we have in stations designed for more moderate operating pressures.

It would appear to be of more use to attempt to take stock and discuss the future possibilities of higher pressures.

In meeting our every-day problems, we are prone to see only the immediate job before us and to lose sight of the broad economic problem with which we are dealing. It is becoming more and more necessary to keep the broad problem before us continually and to so conduct our every-day work that it will fit into the larger picture to the best advantage.

A résumé of the accomplishments of the past is helpful only in focusing our attention on the possibilities of the future. The work done so far in raising the operating steam pressure has produced results that are very satisfactory. They are satisfying principally, however, because they indicate that we have made progress and lead us to believe that we will continue to do so in the future.

Looking back at the development of the steam electric generating station since Mr. Edison started the Pearl Street Station in New York City, what can we learn of particular moment to guide us in the design of new stations?

Many things have been accomplished and the best of these should be incorporated in the new installations that we are about to make.

Many costly mistakes have been made and these should not be repeated, for while it is excusable to err, to repeat an engineering error is an economic waste.

Let us select for discussion a few salient points of a general nature, and let us confine ourselves to those points that need to be kept constantly before us in our new designs.

First and foremost, we find that in the past we have so designed our stations that the fixed charges on the cost of construction are several times the combined cost of fuel, maintenance, and operating labor. It is therefore apparent that by attention to this fact we can make the largest saving in the cost of generating electrical energy. This problem undoubtedly takes precedence over all others before the industry today. What is the answer?

Some engineers have gone so far as to recommend that we forget our efforts for higher thermal efficiencies and build cheaper and less economical generating stations. That is not a satisfactory answer. It is not right that we should cast aside the accomplishments of the past, for the facts of the case prove that those accomplishments have resulted in reducing the cost of supplying electric service.

What we should do is to maintain the higher efficiencies that have been obtained and at the same time reduce the cost of construction by more intensive study and better design.

Better engineering in the future is the answer to our problem.

We are doing better engineering today than in the past because of the accumulated engineering data available and because of the extensive research work of the past few years. Better engineering will result in more economical designs, more economical use of the materials of construction, more economical production,

1. Chief Engineer, The Edison Electric Illuminating Company of Boston, Boston, Mass.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.*



29-145

greater simplicity and ease of operation, and probably higher thermal efficiencies.

As a matter of fact, we are fortunately trapped by circumstances for our own good. We cannot afford to build stations today of the same design as those built a few years ago. A careful study will show that if our fuel cost us nothing we could not afford to build stations with as low thermal efficiencies as were built ten or fifteen years ago. No! The answer to the problem is not to take a backward step but to go forward. By better design we can maintain the high standards of efficiency and at the same time reduce the cost of construction and the fixed charge item in the cost of supplying electric service to our customers.

As electrical systems have grown in size, the capacity of the prime movers and generators has grown likewise. The use of larger turbine generator units, when intelligently used, has reduced the unit cost of generating stations irrespective of the operating pressure. However, it appears from the facts available at this time that the use of large turbine generator units favors the higher pressure stations more than it does those designed for more moderate pressures. Today a 50,000-kw. unit for 1200-lb. pressure costs somewhat more than one designed for 350-lb. pressure, but a 125,000-kw. unit costs about the same whether designed for 1200- or 350-lb. pressure.

It would therefore appear advisable in high pressure stations to install as large-sized turbine generator units as practical from the operating standpoint. The recent designs of turbines that give practically the same economy over wide ranges of load have made it advisable today to use larger units than would have been advisable a few years ago for the same system load conditions.

Interconnections of electric systems also permit the installation of larger turbine generator units than would be advisable without interconnections. This factor should not be lost sight of if the fullest advantages are to be obtained by interconnections.

In the past, the size of our steam generating units in our stations has always lagged behind the size of our turbine generator units. From three to five boilers are often installed to serve one turbine generator with a resultant large increase in the unit cost of our boiler plants when compared with a design in which the steam generating unit matches the size of the turbine generator unit.

There seems to be no basic reason why the steam generating units should not match the turbine generator units in reliability. Already steam generating units have been operated with availability factors in excess of 90 per cent. If this performance can be matched consistently, there seems to be no reason why one steam generating unit should not supply all of the steam for operating one turbine generator unit. We can then have unit construction, one boiler feed pump, one boiler, one turbine, one condenser, one circulating water pump, and one auxiliary power supply. A reasonable number of cross-connections will insure continuity of service and will reduce the unit cost of spare equipment.

It is also true that this better balance between the size of steam generating units and turbine generator units is desirable irrespective of the operating pressure employed, but the accomplishment of the proper balance will make a greater reduction in the unit cost of the high pressure stations because of the higher unit cost of high pressure boiler plant equipment.

The argument of "the larger the unit, the lower the unit cost" carries throughout the station, for it applies to station structures, piping, and auxiliaries. It likewise applies to transmission lines, substations, and distribution systems right up to the customer's meters. The basic reason for this is the fact that the larger units permit the most economical use of the materials of construction, labor, and supervision.

Construction experience has very definitely shown that the size of the unit has a great deal to do with the comparative cost between high-pressure and moderate pressure installations. Undoubtedly a 5000- kw. 1200-lb. installation would cost more per kilowatt than one for 350 lb., while for much larger units there appears to be little if any difference in unit cost. This is undoubtedly the reason why comparative studies for small plants for industrials usually show that the normal pressure installation is the cheaper, all factors considered.

The recent A. S. M. E. Steam Table Research Committee's publication of the Total Heat Entropy Diagram extended to 3500 lb. per sq. in. and 1000 deg. fahr. total steam temperature has very clearly pointed out that for every steam temperature there is a theoretically economical pressure. The higher the temperature, the higher the economical pressure. For a temperature of 750 deg. fahr. and the regenerative reheat cycle, the economical pressure is in the neighborhood of 1400 lb. per sq. in. In other words, the steam temperature is in reality the governing factor.

Already the Detroit Edison Company has decided to lead the way in an attempt to raise the operating steam temperature to 1000 deg. fahr. They have purchased a turbine generator to operate with steam at moderate pressure at this temperature for their new Delray Station.

As the difficulties with the higher temperatures are worked out, the higher temperatures will be combined with higher pressures and there is a possibility that we will be faced with the necessity of raising operating pressures even higher than 1400 lb.

The development of equipment suitable for utilizing steam at 1000 deg. fahr. will result in justifying the use of higher pressures without reheat, and who can say that with reheat 3200 lb. per sq. in. will not be justified?

If the time comes when pressures considerably in excess of 1400 lb. are justified, we must depart radically from our present designs of boilers. We must abandon

thermal circulation in boilers and water-cooled furnace walls and adopt forced circulation. Just because we cannot at once reconcile our minds to such a radical departure in design is no reason for our feeling that there is nothing in the idea before it has been given a thorough trial. Some European engineers believe that forced circulation is advisable for pressures as low as 1500 lb.

The European trend is distinctly toward higher steam temperatures at moderate pressures because the engineers over there believe that the unit cost of high pressure equipment is too great to be justified by the fuel savings to be obtained by its use. On the other hand, in America the trend is just the other way; *i. e.*, higher pressures at moderate temperatures. It is the opinion of American engineers that higher temperatures call for the use of alloy steels and the proper alloys are not available today at prices that make their use profitable.

There is no doubt that many engineers on both sides of the Atlantic Ocean are fully alive to the proper relation between pressures and temperatures, and you can find many instances where certain companies are going far ahead of the general trend. Two noteworthy examples of this are the Detroit Edison Company's purchase of 1000 deg. fahr. equipment, and the recent purchase of a 300,000 lb. per hr., 3200 lb. per sq. in. Benson boiler for the Langerbrugge Station in Belgium.

We have been told on many occasions that the laws of diminishing returns will preclude going much higher in pressures or temperatures, and yet both in America and Europe engineers are going ahead and accomplishing results with higher pressures and temperatures that may force a revision or a reinterpretation of that law of diminishing returns. It is indeed very dangerous to draw definite conclusions from trends; it is wiser to watch the accomplishments of the pioneers.

The experience thus far gained in the construction and operation of high pressure and high temperature stations has very clearly shown that the design and operation calls for engineering talent of the highest type. Designs and construction details must be worked out with the greatest care or otherwise the cost of construction will increase to a point where the fixed charges will offset the savings in fuel. On the other hand, if the proper skill is exercised there does not appear to be any additional capital burden and the greater economy pays a handsome dividend on the effort expended. The argument that greater skill is required is no valid reason for refraining from using the most economical equipment any more than a merchant should refuse to enlarge his business for fear that the larger and more profitable business will require more careful planning and attention.

Construction experience has shown also that high-pressure stations need not be confined to base load operation. Since they can be built for practically the same unit cost as low-pressure stations, they impose no additional capital burden and can be justified for supplying the normal load of the system. This fact will undoubtedly greatly increase the use of higher pressures in the future because it is seldom practical to operate a generating station as a base load station for a long period of years.

Just as the hand-fired grate for large boilers has passed into the discard with the development of efficient automatic fuel burning equipment, so have "rule of thumb" design, construction, and operating practises passed on. Brains instead of brawn rule today.

# The Fault Ground Bus

## Its Use and Design in Brunot Island Switch House of Duquesne Light Company

BY R. M. STANLEY[1] and F. C. HORNIBROOK[2]

Fellow, A. I. E. E. Non-Member

*Synopsis.—This paper describes the ground protection in the Brunot Island switch house of the Duquesne Light Company at Pittsburgh, Pa. This switch house constructed on the vertical isolated-phase plan, is divided structurally into several completely insulated sections.*

*The well known fault ground bus system of protection is applied and made effective by the special features of construction not heretofore used.*

*Details of building construction and of fault ground bus application are given.*

*Arrangements for heating, ventilating, and lighting the buildings are such as not to interfere with phase isolation and insulation.*

*Oil circuit breaker mechanisms are insulated where necessary to maintain the building subdivision into insulated sections.*

*The fault ground bus location, connections, and special details of construction are outlined. Preliminary tests, relay settings, and operating results are given.*

* * * * *

### Introduction

THE Brunot Island switch house constitutes the largest 12-kv. switching center on the Duquesne Light Company's System in Pittsburgh.

Greater Pittsburgh and vicinity are supplied with electric energy from two principal generating stations, Colfax and Brunot Island.

Colfax station of 280,000-kw. capacity is located on the Allegheny River about 14 miles from the down town district.

Brunot Island station, located on an island in the Ohio River about four miles from the down town district, has a total capacity of 110,000 kw. Adjacent to this station there is now under construction a new generating station known as the James H. Reed station to contain initially one 60,000-kw., 75,000-kv-a. steam turbo generator with space for a second similar unit in present building. Ultimate extension is possible for several more units. A large part of the district supplied by the Duquesne Light Company system is enclosed by a 66-kv. transmission loop, the north branch extending from Colfax Station around the north and west sides of the city and the south branch from Colfax station around the east and south sides of the city, merging at Brunot Island switch house. Power is supplied, at present, from this switching center mainly by means of 12-kv. underground cables carried from the island across two channels of the Ohio River to various step-down switching centers supplying industrial customers' substations, distribution substations, and low-voltage networks. Approximately half of the total system load is found within a radius of about four miles from Brunot Island.

The Brunot Island switch house, completed and put in operation in 1928, replaced a switch house which was outgrown as regards capacity and adequacy of switchgear.

In the new 12-kv. switch house the connections include a main bus, a transfer bus, and a synchronizing bus. The main and transfer buses are sectionalized and the grouping of generators, feeders, and transmission line circuits is such that a bus section can be retired without impairment of service or overload of connections. The main connections are shown in Fig.

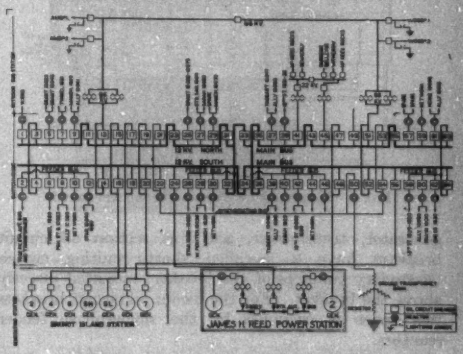


Fig. 1—One-Line Diagram of Main Connections

1, One-Line Diagram. With this provision for the retirement of portions of the equipment by the flexibility of the switching scheme, ordinary operating conditions are met. But abnormal operation due to the eventual breakdown of insulation at some point is also considered in the switch house design. To that end the isolation and insulation of phases is maintained in an unusual degree. This condition is made effective by the introduction of certain features not hitherto used in the design of the structures, and arrangement of equipment.

1. Byllesby Engineering & Management Corp., Chicago, Ill.
2. Byllesby Engineering & Management Corp., Pittsburgh, Pa.

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29-159

### Switch House Arrangement

The switch house is a five-floor structure 225 ft. long by 90 ft. high by 40 ft. wide with vertical isolated-phase arrangement, each of the three upper floors containing one of the phases of the switchgear bus structure. (See Figs. 1, 2, and 3.) There are 64 oil circuit breakers, mounted on the phase floors, along with the disconnecting switches. Each oil circuit breaker is made up of three single pole elements, mounted vertically in line, one element on each phase floor. The

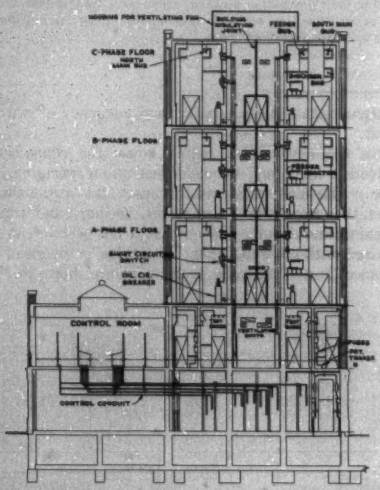


Fig. 2—Side View of Switch House Apparatus

generator, transformer, and bus section oil circuit breakers have a so-called short-circuiting switch (secondary contacts of the breaker) mounted directly above the breaker. For the feeder oil circuit breakers this space is occupied by the single-phase feeder reactors.

Each oil circuit breaker with its disconnecting switches is operated as a unit from a motor-operated mechanism located on the floor below the lowest phase floor. On the same floor with the oil circuit breaker operating mechanism are concrete cell structures housing instrument transformers, line disconnect switches, and disconnect switches for transferring 12-kv. feeder cables to a 30-kv., 25-cycle test bus and special disconnecting switches for testing 12-kv. feeder cables are also located on this floor. The ground floor is used for conduit for control wiring between the switch house and the power station.

The switch house has a two-floor annex, with the control room on the second floor and the 12-kv. feeder testing equipment, 250-volt control batteries, and battery charging sets on the first floor.

The testing equipment includes a motor-generator set with a testing transformer giving a 25-cycle test voltage up to 30,000 volts.

Below the phase floors the circuit arrangement is the usual three-phase grouping with barriers separating the phases. Single-phase leads coming from each of the three-phase floors are brought together on the second floor of the switch house.

Below the ground floor there is a cable vault under the entire building, which provides the desired flexibility, for routing the outgoing and incoming cables.

### Electrical Connections

There are three main buses in the switch house, one running the full length of the building on the north side and divided into six sections designated the North bus; one running the full length of the building on the south side and divided into two sections designated the South, or Transfer bus; and a synchronizing bus which

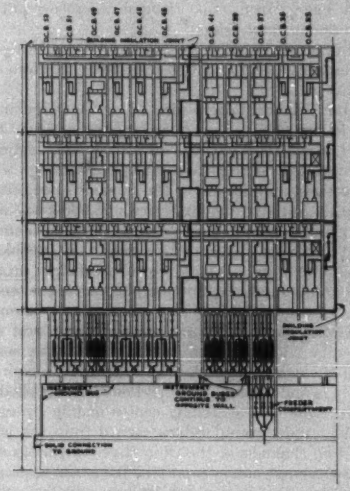


Fig. 3—Switchgear Bus Structure

parallels the transfer bus on the south side of the building. (Fig. 1.) Three sections of the North bus and one section of the Transfer bus, directly opposite, comprise one of two switching units.

A switching unit consists of a number of breakers connected to a generator bus which is the center unit of the North bus just described. On each end of this generator bus is a feeder bus to which are connected three or more feeder breakers. Opposite these feeder sections on the south side of the building are short

sections of the feeder bus connected to the feeder sections mentioned above and also connected to the Transfer bus. The Transfer bus is also connected in

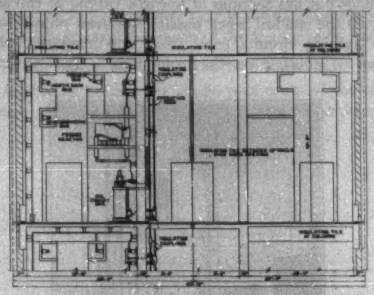

FIG. 4—SHOWING INSULATION OF SECTIONS OF BUILDING

general to the same circuits to which the generator buses are connected. Typically, each generator section contains switching for one or more generators

FIG. 5—BUILDING SPLITS

Center or mechanism aisle on "A" phase floor showing longitudinal and cross-wise building splits. These splits are located at the black lines shown over the doors. Ventilating ducts are shown above with ebony asbestos insulating splits to maintain isolation between phase sections. The mycalex insulating couplings in the oil circuit breaker mechanism rods can be seen on the bell cranks at floor level. For each set of three rods, the rod on the right operates the breaker and short-circuiting switch while the two rods on the left operate the disconnect switches.

Rods operate bell crank mechanisms enclosed in vapor-proof cast iron covers. Above these may also be seen gas vents from oil circuit breakers and part of mechanism which mechanically interlocks protective doors of oil circuit breaker cells.

Note that no conduit crosses a building split.

which are also connected to the transfer bus opposite. This generating bus also contains typically one or more transformer circuits and a synchronizing circuit and these circuits are also connected to the transfer bus by circuit breakers.

### INSULATION OF SECTIONS OF THE BUILDING

In order to maintain phase insulation, the three upper floors, each containing one phase of the bus structure, are insulated from each other and from ground. This is accomplished by placing on each floor a layer of standard hard-burned floor tile of high electrical and compressive strength, using insulating compound instead of mortar in the joints. (Fig. 4.) The steel reinforcing in the concrete structure is not continuous, but tile underlies all reinforced concrete walls, columns, and barriers. Besides this horizontal insulation of the phase floors, the building is further subdivided as follows:

With the purpose of using the fault ground bus sys-

FIG. 6—BUILDING SPLIT AND RISERS ON "A" PHASE FLOORS

Passage way between phase sections on "A" phase floor showing insulating building split on back wall. This also shows the risers to the phase floors of one fault ground circuit with "A" phase connection dropping off and being carried on bar copper.

tem of protection the building is split vertically with insulating joints to correspond with the sectionalizing of the main bus. One vertical split follows the longitudinal axis of the building as indicated in Figs. 2, 5, and 6. Crosswise vertical splits divide the building into six sections lengthwise, corresponding to the six sections of the North bus, as shown typically in Fig. 4. The building is thus divided on each phase floor into twelve insulated sections.

The building construction, therefore, is of reinforced concrete consisting of phase rooms built as though complete boxes were set one upon another, each comprising sides, top, and bottom, so that a breakdown of electrical apparatus or connections must be confined to the inside of this box or room.

### Heating and Ventilating in Relation to Phase Isolation

The entire building is heated and ventilated by the indirect method. Steam is piped from the adjacent steam station to the basement of the building. Runs of piping to the roof in the stairwells at the front of the building are insulated from the phase rooms by inserting insulating couplings in both the main header and in the condensate return lines. In addition the pipes are supported by insulated brackets.

Two 13,000 cu. ft. per minute fans driven by 7.5-hp. motors are located under housings on the roof, one at each end of the building. Steam is supplied to heating coils and air is forced past these coils down through sheet metal ducts to the phase rooms. Paralleling these ducts are exhaust ducts which take the air from the room again, this being exhausted by other fans located on the roof. Dampers are provided to regulate the flow of air and to balance the system. Where ducts pass from one phase room to another on the same floor or to another floor, the metal duct is not continuous but has insulating joints of ebony asbestos so that the phase isolation is preserved.

### Lighting in Relation to Phase Isolation

Lighting of phase rooms is accomplished in the following manner:

At the end of each phase room are recesses in the concrete wall at a suitable height from the floor containing two 100-watt lamps. (Fig. 7.) In front of these lamps is a heavy sheet of glass which diffuses the light and illuminates the phase rooms very efficiently. The supply circuits to these lamps as well as to other lights in the center aisles, etc., are brought from one to one ratio insulating transformers of which there is one for each of the 36 insulated phase rooms. (Fig. 8.) Conduit carrying feed to the insulating transformers from lighting cabinets on *A* phase floor is not continuous but has sections of micarta tubing of the same size as the conduit when passing between phase floors. No lighting circuits cross from one insulated phase room to another on the same floor. The insulation interposed on wires and on transformer is sufficient to prevent the flow of fault ground current to ground through the lighting system and the liability of damage to station lighting circuits is eliminated.

Fig. 7—Phase Section Showing Lights

Phase section showing lighting fixture at end of room and opening to exhaust ventilating duct directly above. Oil circuit breakers are in the compartments to the left and bus runs in the flues on the right

Fig. 8—Insulating Light Transformer

Center or mechanism aisle showing lighting cabinet on "A" phase floor and insulating lighting transformer, of which there is one for each of the 36 insulated building sections. Note that conduit to the lighting cabinets from the floor below has sections of micarta tubing through the floor to prevent grounding of the phase section. The mycalex insulating couplings in the oil circuit breaker operating rods can also be seen

### Switchboard Control and Instrument Circuits in Relation to Phase Isolation

Oil circuit breaker control wiring is brought to the motor mechanism located on the floor below the lowest phase floor so that interference with oil circuit breaker operation cannot result from failure on the phase floors.

Secondary circuits of current transformers in the buses between sections on *A* phase floor are insulated before reaching the switchboard instruments by means of a 5-ampere, 15,000-volt current transformer of one to one ratio located just below the phase floor. (Fig. 9.) The frame and secondary winding of the bus tie current transformer are connected to the fault ground bus (Fig. 10), while the frame and secondary winding of the isolating current transformer are connected to the instrument ground bus. By use of this isolating current transformer, fault ground current resulting from breakdown of apparatus or failure of insulation on the lowest phase floor cannot reach the control board.

The same protective scheme is used in connection with current transformers in the synchronizing reactor circuits and can be applied to other circuits should it later prove desirable. However, current transformer failures have been so rare that it seems unnecessary to make this general extension of the fault ground system.

### Switchgear in Relation to Phase Isolation

As stated before, the single pole units of the three-phase breaker equipments are mounted vertically in

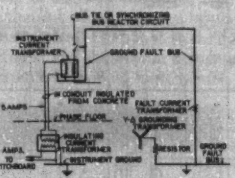


Fig. 9—Insulation of Circuits by Use of One-to-one Ratio Transformers

line on the three-phase floors and are operated from a motor-mechanism located below the lowest phase floor.

The rods which operate the breakers, disconnect switches, and short circuiting switches have insulating micalex couplings for maintaining phase isolation. The distance between mechanisms, rods, walls, etc., and the insulating couplings is such that an operator is not liable to touch any part of equipment belonging to one phase room while standing on the floor belonging to another phase room.

### Switchgear Interlocks and Operation

Mechanical interlocking of oil circuit breakers, disconnecting switches, test switches, and doors in front of compartments was adopted in preference to any other form of interlocking. Line disconnecting switches or test switches cannot be operated until the oil circuit breaker is open. Doors in front of oil circuit breaker cells cannot be opened, if the oil circuit breaker or disconnecting switches are closed.

Certain interlocks are inherent in the main control of the switchgear. In the closing operation a charging control switch causes a motor in the operating mechanism to compress a pair of springs and at the same time the disconnecting switches are closed. The main control switch is then operated, a spring is released, and the oil circuit breaker is closed. The opening operation, using only the main control switch, releases the other spring previously compressed, opens the circuit breaker and after that the disconnecting switches.

When an oil circuit breaker is tripped out by relays during a system disturbance, the oil circuit breaker only is opened and the disconnecting switches remain closed until the control switch is turned to the opening position. This feature avoids the possibility of rupturing a heavy current on the contacts of the disconnecting switches.

### Ground Protection

Ground faults in generators and their auxiliary transformers operate through differential relays to isolate the equipment affected. Power transformer banks including high-tension buses are also protected by differential relays. Feeder grounds are taken care of by the usual ground relays.

A grounding transformer bank of 10,000-kv-a. capacity is connected, in star, to the 12-kv. bus and is provided with a grounding resistor of 15 ohms. The secondaries of this bank are in closed delta. Current transformers in the ground connection of this bank operate high-speed recording instruments and give an alarm in the event of an appreciable flow of ground current.

### Fault Ground Bus System

For the protection against insulator breakdown in the 12-kv. bus and its connections, two general

Fig. 10—5000-Ampere Disconnecting Switch Compartment

5000-ampere disconnecting switch in compartment to the right of the oil circuit breaker compartment, so located as to prevent copper or other vapor from communicating to next main or fault bus section on the right from sections on left; (part of isolation scheme). The insulated fault ground circuit is shown passing through the left-hand wall into the oil circuit breaker compartment and to the right into an adjacent bus section. One tap fastens to the disconnecting switch base which is insulated from the building by means of a sheet of micarta and by the use of micarta bushings where the mounting bolts pass through the base. Another tap is connected to the frame and secondary winding of the bus section current transformer. This transformer is supported by the bus and is not fastened to the concrete. Bus section current transformers are located in "A" phase only.

Note sheet of ebony asbestos at right to prevent flashover to concrete

schemes may be applied. The application of bus differential protection as used in certain of the Duquesne Light Company substations would have involved the use of a large number of additional current transformers, introducing difficulties in the matter of space requirements. Further, phase isolation as previously described would have become more difficult with the introduction

of additional conduit runs. Therefore, the fault ground bus system of protection was chosen.

Switch house faults may include failure of switchgear during normal or abnormal operation, failure of connected equipment such as reactors, and the breakdown of insulators supporting buses or connected circuits. The effect of the failures enumerated is lessened by the isolation of phases and due to the insulation between phases and sections. These breakdowns will cause phase to ground faults limited to a single-phase floor and a single room.

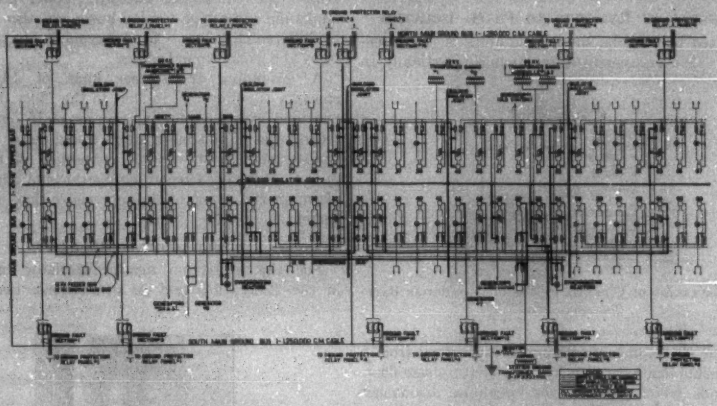

Fig. 11—Diagram of Fault Circuits

## Description of Fault Ground Bus

For each of the twelve insulated building sections, there is one uninsulated fault ground circuit. The fault ground bus consists partly of 2-inch by ¼-inch copper bar closely paralleling the main connections and connected to certain non-current carrying parts of switchgear, and partly of insulated 1,250,000 cir. mils copper cable. Considering one switching unit alone there is one fault circuit for the main or generator bus on the north side of the building, one for each of the two feeder sections on the north side of the building, one for the transfer bus on the south side of the building and one for each of the two feeder sections on the south side of the building. (Figs. 11 and 12.) Each phase of a particular fault circuit is insulated beyond the point where connection is made to the equipment and the three phases are brought to a common connection below the lowest phase floor after passing through current transformers. A fourth current transformer of the same ratio as those in the separate phases is connected in the common lead to ground. (Fig. 13.)

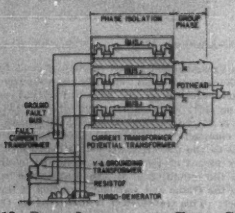


Fig. 12—Phase Insulation of Fault Circuit

Fig. 13—Fault Panel and Current Transformers

Insulated copper cable risers to the three-fault ground buses in the three isolated phase rooms.

Risers and common connection to transformer ground each provided with current transformers

Relay panel with equipment for three separate fault ground bus sections

All the metallic parts in the switchgear, in the bus supports, reactor supports, etc., which are separated from bus potential by insulators are connected to the fault ground bus by a bar of ¼ inch by two inch copper. (Figs. 14, 15, and 16.) Where a fault circuit is continued into an adjacent insulated section of the building, it passes through an insulating bushing and is mounted on insulators after crossing the insulating building split.

Two additional fault ground bus circuits which protect the synchronizing reactor circuits are mounted on insulator supports throughout and make solid connections only to equipment which has been insulated from the building construction.

All 14 fault ground bus circuits are brought together after passing through individual fault ground bus current transformers to a common fault ground bus of 1,250,000 cir. mils cable which is solidly grounded at the same point with the Star Delta 10,000-kv-a. grounding transformer bank described under Ground Protection.

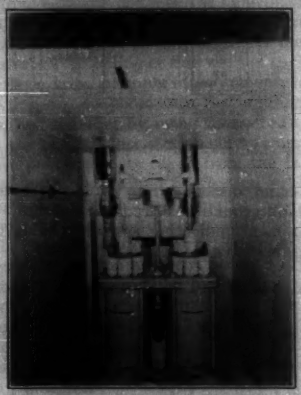

Fig. 14—600-Ampere Compartment

600-ampere oil circuit breaker compartment with reactor on shelf above. Uninsulated fault circuit is on the left making connection to the breaker, back wall contacts, and bus support insulators. Cell door interlock is shown on the left wall. It passes through the back of the compartment and attaches to pipe operating mechanism in the center aisle. Fault circuit passes up through the reactor and disconnect switch compartments and thence to bus flue

In general the fault ground bus circuits parallel the sections of the main bus and the various branch circuits from each bus section, present branch connections of each fault bus circuit being limited to regions considered as of greatest hazard. Certain bus runs where insulators are not subject to stress due to mechanical shock of adjacent operating equipment are, for the present, not provided with fault ground bus protection. Provision has been made for future extension of the fault ground bus wherever it shall prove desirable.

## Fault Ground Bus Operation

In the case of a single failure from phase to ground, current will flow through the phase transformer and also through the transformer in the common connection, which, through the action of the associated overload and auxiliary multi-contact relays, will trip the breakers in the fault section. For complete protection in this class of failure there would be required only one current transformer in the common ground connection.

Fig. 15—2000-Ampere Compartment

2000-ampere oil circuit breaker compartment showing uninsulated fault ground circuit on the right, and cell door interlock rod on left

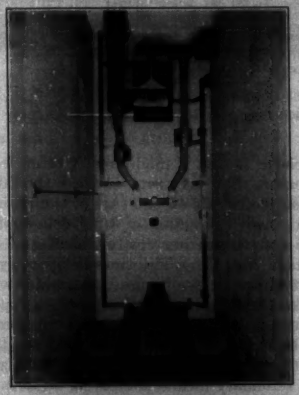

Fig. 16—Unfinished Compartment

Bus tie breaker compartment No. 55-5000 ampere. Breaker unit removed to show fault ground bus connections to breaker supports

Fault circuit to the left is uninsulated while one on right is insulated since it crosses an insulated building split to the phase section on the right. Connections of the insulated fault circuit are made to the breaker equipment through gaps which are shown supported by micarta brackets

However, in the case of two simultaneous line-to-ground failures, one of which may have resulted from the other, very little current might flow through the common ground connection and the action might have to result largely from current in the individual phases of the fault ground circuit.

### Fault Ground Bus Overlapping Protection

In the case of tie breakers between two sections of a bus, provision has been made for clearing the fault from either side of the tie breaker since the fault may occur from either section to the tank of this breaker. It is apparent that the tank of the tie breaker should be connected to both fault circuits but to do so would destroy the selectivity. Another possible solution would be to create a third fault circuit to include the tie breaker alone, which would trip the circuits on both sides of the tie breaker. The disadvantage of

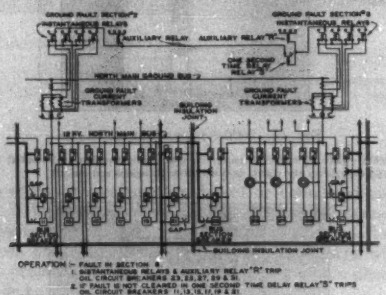


Fig. 17—Connection of Relays and Circuit Breakers

such a scheme is that it might result often in tripping more breakers than necessary to clear the fault. For this reason the circuit on one side of the tie breaker is tripped through the action of time delay relays only after the first circuit has cleared itself and the fault still exists. (Fig. 17.) The time delay relays are set to operate after a delay of one second, which would give the breakers involved on instantaneous tripping sufficient time to clear. When two fault circuits are brought to a tie breaker, one only is connected solidly to the breaker, the other being connected through a gap which acts as a secondary means of clearing adjacent circuits in case of continued arcing on a tie breaker after the breaker has opened.

Certain disconnecting switches at the bus sections are mounted in separate cells and are protected by two fault ground systems. For instance, in the case of oil circuit breaker No. 43, the left-hand disconnecting switch is above the oil circuit breaker while the right-hand disconnecting switch is located in a compartment just outside the barrier wall at the end of the phase room. (Fig. 18.) This right-hand disconnecting switch is thus located so as to prevent a short circuit from spreading into another phase room. If the right-hand disconnecting switch should break down or become involved in trouble inside the phase room, the next adjoining bus section must be cleared. For this reason

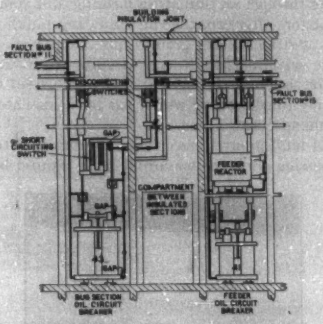


Fig. 18—Location of Disconnecting Switches

the right-hand disconnecting switch base is tied in with the fault ground bus circuit to the right. A typical arrangement indicating special gaps in the fault ground bus is shown in Fig. 19.

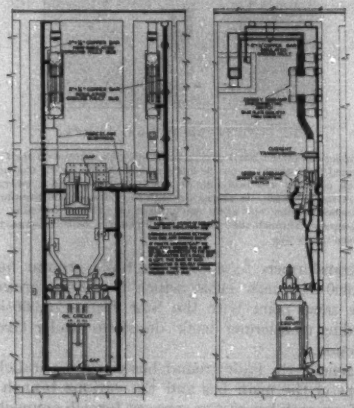

Fig. 19—Showing Special Gaps in Fault Ground Bus

The following preliminary tests were made before cutting the fault ground bus in service.

### Insulation Resistance

A large portion of the fault ground system was installed after the 12-kv. circuits had been placed in service. Immediately on grounding the various fault

circuits and before making any resistance tests between phase floors or between adjacent building sections, an unexpected amount of current was found to flow in the fault circuits under normal operating conditions in the station. In the case of station or system disturbances where short circuit current flowed through sections of the station buses, currents in the fault circuits reached values sufficient to operate certain fault ground relays. It was, therefore, apparent that the protection scheme could not be used until the cause for this stray current had been determined and eliminated.

The first step was to measure insulation resistance between phase floors and between adjacent insulated building sections on the same floor. The building was considered as consisting of 36 boxes (12 per floor) insulated from adjacent boxes on the same phase floor and from adjacent phase floors. Resistance measurements could have been taken directly from the mats of reinforcing steel in the ceiling or side walls of each insulated room. Since large amounts of equipment, however, in each section are anchored into the building construction and tied together by being connected to the fault ground bus of the same section, it was assumed that resistance measurements taken from the fault ground bus itself with the ground connection broken should give more accurate results.

There is one insulated fault ground circuit for each of the 12 building sections. Portions of these circuits which cross over into adjacent sections are insulated when they cross an insulated building split, and make connections only with equipment which has been insulated from the building construction. The resistance to ground of the insulated portions of the circuit is so high as compared with that of the uninsulated portion that these connections do not appreciably affect the total resistance.

Resistance measurements were made with a direct reading "Megger" ground resistance tester having ranges of 0-3, 0-30, and 0-300 megohms. The common connection to the fault circuit under test was opened at the current transformers below the bottom or *A* phase floor and resistance measurements were taken from each phase to ground and between phases. These measurements were taken with the fault circuits in adjacent sections grounded. It was, of course, necessary to obtain an outage on all equipment connected to the circuit under test as a safety precaution and it would, therefore, have required a large portion of the station equipment out of service, if fault circuits in each adjacent building section were to be opened at the same time. By leaving the fault circuits in adjacent sections grounded, any low resistance ties between building sections, and consequently between fault circuits, would be indicated by low readings on the circuit under test. However, where it was possible to clear fault circuits in adjacent sections, this was done and resistance measurements were taken between similar phases on these adjacent circuits.

The minimum resistance of phases to ground on any uninsulated fault circuit when placed in service was 6 ohms and the maximum 25 ohms. On any one fault circuit the resistance to ground generally increased from one phase to the one above although this was not always the case, due probably to lower resistance ties to ventilating ducts, conduit, steam pipes, etc. The average resistance to ground on the top phases was higher although the maximum and minimum values varied but slightly. The resistance between adjacent phases of any one fault circuit varied from 9.5 ohms to a maximum of 30.5 ohms. The resistance of any phase to the same phase in an adjacent fault circuit varied from 11 to 41 ohms and was generally found to be higher on the top phases for any two adjacent fault circuits.

In several cases the resistance of phase to ground was zero and where such conditions were discovered it was found that circulating current existed in the fault circuit. Some of the causes for these conditions found and corrected were as follows:

1. Low-resistance ties across insulated building splits due to tie wires which were used to hold the insulating tile in place in the forms while concrete was being poured and which had not been cut when the forms were removed. These often tied the reinforcing steel mats in adjacent sections together.
2. Guy wires for construction equipment such as brick scaffolds and material elevators which were anchored through the walls or roof and consequently grounded the reinforcing steel in the particular section.
3. Conduit for ventilating motors crossing the roof split above the top or *C* phase.
4. Steam pipes passing from the heating system on the roof above the top of *C* phase down to the basement and thence to ground.
5. Defective insulation to ground of equipment connected to insulated fault circuits.
6. Foreign conducting material in the gaps on tie breakers fault ground bus connections.

When these causes for low resistance had been found and corrected, it was discovered that the circulating current in the various circuits had disappeared entirely under normal and short circuit conditions on the station and system. Tests of circuits under actual ground conditions inside the station were next made as follows:

## The First Series of Tests

In this series of tests the ground current was limited to approximately 400 amperes by the 16-ohm resistor in the neutral of the station grounding transformer bank. The instantaneous relays were set for 2.5 amperes to operate on a ground current of 100 amperes. All equipment associated with the fault circuit under test on instantaneous tripping was cleared from the rest of the station and system. Ground was applied by means of a cable connected to the line side of one of the breakers involved, and to the fault ground bus

in the breaker compartment. All breakers were closed except the one selected to energize the fault which generally was not the same as that to which the ground was attached, thus providing for double protection in case of faulty operation. The fault was then energized from the 12-kv. bus by closing the breaker and all breakers involved in instantaneous tripping were tripped by action of the fault ground relays. The back-up protection of tie breakers through action of the timing relays was not tested simultaneously with the instantaneous tripping, since large additional amounts of equipment would have been required in the outages. Timing relays were tested separately without actually tripping the breakers involved with one second setting. This was found to give the breakers on instantaneous tripping sufficient time to clear as the maximum time required for the largest breakers to clear the arcing contacts was found on previous tests to be 21 cycles.

Grounds were applied as above described on each phase of each of the 12 fault circuits. For each test readings of current were taken in each phase of the circuit under test, in the neutral of each of the other fault circuits, and the ground current in the station grounding transformer bank. In the majority of the fault circuits there was no indication of current flow. This series of tests would indicate that no trouble will be expected from incorrect relay operation for grounds inside the station.

### Second Series of Tests

It was uncertain, however, whether the current in other fault circuits was due to actual leakage between insulated building sections or due to induction between sections of the fault bus and the 12-kv. buses. If the latter proved to be the case, there was a possibility of incorrect relay operation under short circuit conditions outside the station where the current through certain sections of the 12-kv. buses might exceed by many times the station ground current as limited by the station ground resistor. For this reason a series of tests was run on certain of the fault circuits with grounds applied on 12-kv. circuits at substations remote from the switch house and with the station ground resistor reduced to one-fourth its normal resistance, thus allowing ground currents of approximately 1400 amperes to flow. The circuits selected to apply the grounds were such as to give the longest possible paths for induction between the fault bus and the 12-kv. buses. In this test as in the previous tests, meters were inserted in all fault circuits including the one under test. In no instance was there faulty relay action or indication of stray currents due to this disturbance to the switch house.

### Relay Settings

(a) Instantaneous overload relays operated from the 200/5-ampere fault ground bus current transformers are set for 2½ amperes to operate on a fault current of 100 amperes. This setting was determined from the amount of stray current that was found to flow during ground tests in circuits other than the one under test and gives a factor of safety against incorrect relay operation. It was thought desirable to operate on the lowest possible value of fault current that would insure correct operation.

(b) Time delay relays were set for one second for back-up protection on bus tie oil circuit breakers. Previous tests had shown that the large bus tie breakers required 21 cycles to clear the arcing contacts so that the complete opening operation would be completed in 4/10 second and with the time delay relays set for one second, there is ample time for a fault to clear before the operation of the back-up breakers.

### The Fault Ground Bus in Service

Between the time of the last series of tests and the time that the fault ground protection system was put into service, observations were made daily of any operation of fault ground relays on system or station disturbances. Before locating the causes for the circulating current which existed in several of the fault circuits prior to the tests, there had been operations of the fault ground relays due to system disturbances which would have virtually isolated the station had the breakers controlled by these fault ground relays been tripped. No indication of such conditions existed during this period of observation which extended for several weeks and so the system was put into operation on May 3, 1929. These same observations are being continued and certain recent severe system disturbances prove that no incorrect operation need be anticipated from this cause. It is proposed to make periodic tests on certain of the fault circuits similar to those described and also to make further resistance measurements between fault circuits to see if the aging of the building will increase this resistance and make correct operation even more certain. A few resistance measurements taken three months after the initial check showed the resistance to ground on one fault circuit to have increased 30 per cent.

During routine station and system operation one operation of the fault ground system has occurred and this was due to accidental contact with a 12-kv. circuit rather than a breakdown of equipment. A workman cleaning insulators on dead equipment came in contact with an energized contact of a disconnect switch causing an arc which carried to the fault ground bus circuit in the compartment. The 12-kv. section was isolated immediately through action of the fault ground relays. An idea of the speed in which the entire operation took place can be gained from the fact that the man escaped with comparatively minor burns.

### Conclusions

It is expected that the foregoing application of the fault ground bus system of protection to an isolated-phase switch house will give service of an unusual degree of reliability.

For any possible failures of switchgear, feeder reactors, or bus reactors, the disturbance in the switch

house itself should be limited to a relatively small amount of apparatus.

For each protected section a low resistance path of high current capacity is provided and single-phase or other fault currents are definitely directed so as to immediately clear the switch house of the cause.

The insulation and isolation of the separate building compartments renders more effective the protection by the fault ground bus.

Back-up circuit breaker protection actuated by relays with a small time delay serves to prevent the spread of the disturbance outside of the phase room in which it originates in the event of a continued arc.

While it is not claimed that the fault ground bus is anticipatory in its functions, it is expected that failure of the insulation of a bus section or flashover of switchgear will cause that section to be cleared promptly, so that the loss of synchronous apparatus on the system will be avoided.

With the concentration of generating capacity in such switching centers as that of Brunot Island, where short circuits of unusual magnitude are to be considered, the fault ground bus system offers a protective scheme which acts to relieve in a measure the duty of oil circuit breakers, to safeguard service, and reduce life hazards.

With reference to costs, it may be stated that the isolated-phase vertical arrangement described, resulted in a cost of switch house, switchgear, and accessories, including oil circuit breaker and instrument control, fault ground bus, heating, ventilating, lighting, etc., considerably lower than corresponding designs of grouped phase arrangement on which studies and estimates were made.

The type of building construction adopted resulted in a cost slightly in excess of a design estimated on, which was based on ordinary standards for building construction omitting insulating joints and segregation of phase rooms.

The fault ground bus and the associated details of electrical and mechanical construction involved in the isolation and segregation of phase rooms and groups of switchgear, buses, etc., amounted to a relatively small percentage of the total cost. Apparently phase isolation of this type compared with grouped phase design is, inherently, less expensive, and it is believed that there is afforded by this design a superiority of operation, greater safety, and the minimizing of faults in an indoor switching station.

## Appendix

A list of the main equipment controlled from the switch house follows:

*Generators*

5 generators, each 14,400 kw.
1 generator, 35,000 kw.
1 generator, 60,000 kw., on order, 1930 installation.
1 station auxiliary generator, 2300-volt, 3000-kw.

*Transformers*

2 40,000 kv-a. banks 11/66 kv.
2 15,000 kv-a. banks 11/22 kv.
1 10,000 kv-a., star delta grounding bank with a 15-ohm grounding resistor for the 11-kv. system.
Station auxiliary banks, 2300- and 440-volt.

*Feeders* (11 kv.)

27 feeder positions, 17 of these positions being bifurcated, making a total of 44 feeders.

*Reactors*

*Synchronizing Reactors with Resistors*

2 sets of three single-phase units, each of 4/10 ohm resistance and of 2000-ampere capacity.

*Feeder Reactors*

For each feeder position a set of three single-phase units, each of ½-ohm resistance and of 600 amperes capacity.

One set of these is used in the supply to the 11-kv. grounding bank.

## Discussion

**A. W. Rauth:** It is readily seen that the purpose of this construction is not to eliminate faults but to isolate the fault in the shortest possible time after it occurs. The more common station design is such that the relays on the station feeder breakers must be given a time setting so as to make them selective with substation breaker relays. The station relay time setting often becomes rather long and if any bus-protection scheme other than differential protection is used the bus protection relays must be given a still longer time setting so as to be selective with the station feeder breakers. The insulated fault ground bus provides an excellent means of using sensitive, instantaneous relays that operate only in case of station faults. If a fault occurs outside the station the fault current path is not through the station protective relays since the entire building is insulated from ground except for the fault ground bus. This is a much better method for bus protection than the differential method. The differential method in addition to requiring a large number of current transformers, has the disadvantage that it is difficult to balance satisfactorily a large number of current transformers (on account of their dissimilar characteristics) so that sensitive relays can be used that will not operate on through faults.

The use of the fault ground bus reduces the required interrupting capacity of breakers only if it is assumed two line-to-line or three-phase faults will not occur. This is a reasonable assumption because a line-to-ground fault should occur before any other fault occurs in this type of installation. Provision is made, however, for two simultaneous ground faults and therefore the breakers cannot be as small as one might conclude by considering only the maximum ground current.

Reference to the causes of low resistance and zero resistance between phase and ground indicates that there are possibilities of the various insulated building sections becoming electrically connected. Such connections could readily cause faulty relay operations, also considerable care must be taken when changes or additions are made so that the various insulated sections do not become electrically connected. The current transformer leads are insulated from the switchboard by one-to-one insulating transformers which may cause inaccurate metering.

Since the amount of fault ground current is limited by the connected synchronous capacity, the reactance of the various circuits, the reactance of the grounding transformer and the neutral resistor, why was it considered necessary to use a neutral resistor instead of providing a smaller grounding transformer which would accomplish the same purpose?

**S. M. Hamill:** The same difficulties, which Messrs. Stanley and Hornibrook mentioned in their paper, of freeing the fault bus from foreign grounds were experienced at the Columbia Station of the Columbia Power Company. After the foreign grounds were removed, a permanent test set was installed for the purpose of measuring the resistance of the fault bus to ground, so that any foreign grounds occurring in the future could be detected and removed before they might cause incorrect relay operations.

A disconnecting switch was installed in the fault bus just ahead of the connection with the station grounding system. This switch was paralleled with a safety gap having a breakdown voltage of 250 volts, so that should a flashover occur when a measurement was being taken no injury to the operator would result. The resistance measurement is made with 120 volts d-c. supplied through a voltmeter from the small motor-generator set. A toggle switch is arranged on the switchboard so that either section of the fault bus may be measured. These measurements are made three times a day.

With this apparatus it is not necessary to obtain a main bus outage to determine that the fault bus is in satisfactory operating condition.

I should appreciate it very much if Messrs. Stanley and Hornibrook would clear up a point in their paper which I have missed. It seems to me that, since pains were taken to insulate the apparatus connected to the fault bus from ground, very little additional benefit to fault bus operation could be derived from insulating the building sections. Also, it seems that this would not materially decrease the possibility of a phase-to-phase short circuit, since a simultaneous flashover of two different phases would have to go to the fault bus which is a solid metallic circuit for all phases.

**H. R. Summerhayes:** This matter of protection against trouble on buses has been studied by some of the best brains in the electrical industry for the last twenty or thirty years. Only two well established systems of bus protection have resulted. One is this fault ground bus, and the other is the differential protection.

The differential protection, on account of the number of current transformers and the difficulty of balancing them, is well adapted only to stations in which a small number of large circuits go from each bus section, like a station in which you step up to a high voltage, that is, one having a few large transformers and one or two generators connected to each bus section. In such a case the differential protection is relatively simple and is effective.

In a station like Brunot Island, where you have a large number of feeder circuits connected to each bus section, the differential protection is not only expensive but complicated, and, on account of the great amount of equipment involved, may not be so reliable. The ground fault bus seems to be the best scheme. In using the ground fault bus, however, very close attention must be paid to detail, as was done by the designers of this station. Every part of the building must be insulated from the other parts.

There are other ways to accomplish the same thing. For instance, in each room, each bus section could consist of a number of steel cells, or the switches could be mounted on steel framework, and all of that steel framework supported on porcelain insulators and grounded only through a fault bus. That could be done inside of the building, or, as has been done in the State Line Generating Station, such a steel equipment could be erected outside of the buildings, and the posts supporting each bus section insulated from the ground and connected to the ground only through current transformers. The State Line equipment offers an ideally easy way to arrange a fault bus.

In arranging a fault bus and going through the difficulties of insulating the building and all the close attention to detail, some expense is involved. In this case, apparently, this expense was justified, since it seems that one life has been saved by the quickness of the equipment in snuffing out the fault. A considerable amount of expense is justified, aside from any question of safety to employees, by the fact that a bus trouble may be very serious, involving the shutting down of the whole station if the buses are not sectionalized.

**G. B. Dodds:** From an operating standpoint I should like to say that from the tests made on this installation, we are thoroughly satisfied that this protection will function satisfactorily for faults inside of the station and that it will not operate for faults outside of the station.

There are several reasons why we feel it is preferable to the standard differential protection, among which are the increased sensitivity for small fault currents without increasing the danger of operating on outside faults; and the decreased probability of defective wiring causing false operation for through faults. We had an example of this latter trouble when during a line fault we dropped one complete bus section at one of our large stations due to a ground on a current transformer lead. We also believe that fault ground bus protection will be maintained more easily than standard differential protection, and we feel that the insulation between different sections will improve rather than deteriorate as time goes on and the concrete dies out.

In regard to the question asked concerning the reason for using resistance in the neutral of our grounding bank rather than getting the necessary impedance by increasing the impedance of the grounding bank itself: one factor was the effect of the phase angle of the fault current on the direction ground relays which we had installed on our system. These relays obtain potential from inside the delta of a set of star-delta-connected auxiliary potential transformers, and have the greatest closing torque when the current in the current coil of the relay and the potential on the potential coil of the relay are in phase.

We have found from tests that with reactance only in the neutral, relays of this type would reverse their polarity under some conditions of fault, and also in case their polarity did not reverse, a very small amount of closing torque would be obtained due to the phase angle between the current and potential.

As we did not wish to discard all of the ground relays on our system, we retained the resistor in the neutral of the grounding bank. However, there is now available a means of changing our relays over so that they will work properly on a system grounded through a reactor, and we are considering the use of a reactor in the neutral of a new grounding bank which is to be installed.

**D. D. Higgins:** In the Chicago stations with the fault ground bus over the last two years we have had something like six or seven faults, and all of them have been cleared very promptly, and a minimum of damage has occurred. In one or two cases it was rather difficult to find where the fault had developed. We consider that the fault ground bus is one of the outstanding advancements in switch-house design. But I do want to point out that as long as we are grounding buses for the protection of workmen, we are not entirely free from the hazards of three-phase bus short circuits which are beyond the scope of fault bus protection. That is one thing that the designers must keep in mind.

**F. C. Hornibrook:** Mr. Hamill asked a question concerning the need for insulating the various sections of the building one from the other, since pains had been taken to insulate the equipment to which the fault ground bus was attached.

This question is misleading and shows that we have not made entirely clear just what equipment is insulated from the building construction. On the twelve uninsulated fault ground circuits connection is made to equipment which is anchored solidly into the building construction so that the reinforcing steel in the walls and ceilings as well as the bases of the equipment are maintained at ground potential. The only case in which equipment is insulated from the building construction is when such equipment is connected to a fault circuit that has crossed an insulated building split which is the case with bus tie oil circuit breakers and certain disconnect switches. Equipment associated with the synchronizing bus tie circuits is also insulated from the building construction since the fault ground bus protection of these circuits overlaps that of the main bus protection and must be kept separate and selective.

# Increased Voltages for Synchronous Machines

BY C. M. LAFFOON[1]

Associate, A. I. E. E.

***Synopsis.***—*The appreciable increase in the rating of generators, generating stations, and interconnected systems has resulted in large currents to be handled by generators, circuit breakers, reactors, cables, and station bus structures. This paper covers a discussion of the limitations on large generators and generating equipment by the present standard voltages of generation, the necessity for increasing the values of generated voltage, and the design, manufacturing, and operating problems involved in building high-voltage turbine generators.*

* * * * *

At the present time serious consideration is being given to increasing materially the generated voltages of steam-turbine generators. Generators of higher output are being required to meet the needs of growing loads. The increased currents which must be handled have imposed heavy duties on equipment such as circuit breakers, switches, cables, reactors, and other auxiliary apparatus. On account of the limitations of such equipment and the growing cost and complication of handling heavy currents, it is thought desirable to increase the generator voltage which will allow a corresponding decrease in current.

Approximately 90 per cent of the power companies in this country generate at either 13,200 or 13,800 volts and most of the remainder at 11,000, 12,000, and 12,800 volts. During the last three years several large generators have been built with 22,000-volt windings and even higher voltages are being considered.

It is the purpose of this paper to discuss the effect of increased generated voltage on the manufacture, cost, performance, dimensions, and reliability of large turbo generators. The paper is not intended to cover other phases of the matter such as reduced central station cost or decreased losses. These things must be determined for each particular station or power system on the basis of cost, performance, reliability, and life of the combined generating and distributing equipment.

It should be pointed out that in the majority of cases in this country higher voltages are not needed for the sake of facilitating the transmission and distribution of electrical energy. In most cases it would still be necessary to use step-up transformers. Most of the generating stations are located considerable distances away from the distribution centers and consequently rather high transmission voltages are required which would necessitate using step-up transformers even though the generated voltages were doubled.

Two other points should be mentioned. The first is that from the standpoint of the generator alone it is possible to build very large machines at the present voltages. It is feasible to build 4-pole, 60-cycle, 1800 rev. per min., single-unit generators with present standard 11,000 to 13,800 voltage windings for ratings up to 125,000 kv-a. at 80 per cent power factor. The data in Table I are arranged to show the currents, number of conductors, number of slots, number of parallel circuits, and the winding arrangement for turbine generators of representative ratings from 62,500 kv-a. to 187,500 kv-a. for various voltages.

TABLE I

STATOR CURRENT, CONDUCTOR, AND SLOT REQUIREMENTS FOR 4-POLE, 1800-REV. PER MIN. TURBINE GENERATORS AT DIFFERENT VOLTAGES

| Kv-a. | Volts 11,000 | Volts 12,000 | Volts 13,800 | Volts 16,500 | Volts 22,000 | Volts 33,000 |
|---|---|---|---|---|---|---|
| 62,500 Kv-a. | | | | | | |
| Amperes | 3280 | 3000 | 2610 | 2185 | 1640 | 1092 |
| Conductors | 80.75 | 88.4 | 101.4 | 121. | 161.5 | 242. |
| Slots | 84.0 | 60 | 72 | 60 | 72 | 60 |
| Connection | YY | YYYY | YYYY | Y | Y | Y |
| Conductors per slot | 2 | 6 | 6 | 2 | 2 | 4 |
| Amperes per slot | 3280 | 4500 | 3920 | 4370 | 3280 | 4368 |
| 75,000 Kv-a. | | | | | | |
| Amperes | 3935 | 3605 | 3140 | 2625 | 1970 | 1312 |
| Conductors | 67.4 | 73.5 | 84.4 | 101 | 134.5 | 202 |
| Slots | 72.0 | 72.0 | 84.0 | 54.0 | 66.0 | 54.0 |
| Connection | YY | YY | YY | Y | Y | Y |
| Conductors per slot | 2 | 2 | 2 | 2 | 2 | 4 |
| Amperes per slot | 3935 | 3605 | 3140 | 5250 | 3940 | 5248 |
| 93,750 Kv-a. | | | | | | |
| Amperes | 4915 | 4500 | 3920 | 3280 | 2460 | 1640 |
| Conductors | 54 | 58 | 67.7 | 80.75 | 107.8 | 161.5 |
| Slots | 54 | 60 | 72 | 84 | 54 | 54 |
| Connection | YY | YY | YY | YY | Y | YY |
| Conductors per slot | 2 | 2 | 2 | 2 | 2 | 6 |
| Amperes per slot | 4915 | 4500 | 3920 | 3280 | 4920 | 4920 |
| 125,000 Kv-a. | | | | | | |
| Amperes | 6560 | 6010 | 5230 | 4375 | 3280 | 2190 |
| Conductors | 40.3 | 44 | 50.7 | 60.5 | 80.75 | 121 |
| Slots | 72 | 84 | 54 | 60 | 78 | 60 |
| Connection | ΔΔ | ΔΔ | YY | YY | YY | Y |
| Conductors per slot | 2 | 2 | 2 | 2 | 2 | 2 |
| Amperes per slot | 3800 | 3470 | 5230 | 4375 | 3280 | 4380 |
| 187,500 Kv-a. | | | | | | |
| Amperes | 9835 | 9020 | 7835 | 6555 | 4920 | 3280 |
| Conductors | 27 | 29.4 | 33.8 | 40.5 | 53.8 | 80.8 |
| Slots | .... | .... | .... | .... | 54. | 60. |
| Connection | .... | .... | .... | .... | YY | YYYY |
| Conductors per slot | .... | .... | .... | .... | 2 | 6 |
| Amperes per slot | .... | .... | .... | .... | 4920 | 4920 |

These data are based on machines designed for 80 per cent power factor conditions and operate at approximately unity short circuit ratio. It is apparent from the data in this table that from the standpoint of required number of conductors and stator slots, the most satisfactory voltage range for large turbine generators is from 13,800 to 22,000 volts.

The other point is that the limit in circuit-breaker

1. Power Engineering Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

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29-156

duty can also be met by providing the generator with two or more independent windings and by separating the generating station and system into units which are tied together only at points on either a high-tension or a low-tension network.

These alternatives should of course be considered though they cannot be fully discussed here.

## Problems Involved in the Manufacture of High-Voltage Generator Windings

*Type of Insulation.* The most important problem involved in the design and construction of high-voltage rotating machines is the insulation of the stator windings. A satisfactory insulation material for use on the strands, conductors, and coils of high-voltage windings should conform to the following specification requirements:

1. High breakdown strength when subjected to voltage.
2. Low dielectric losses at normal operating voltages and at test voltages.
3. High resistance to corona and static discharges.
4. Non-hygroscopic.
5. Relatively high thermal conductivity so that the stator copper losses can be dissipated with a minimum temperature drop through the insulation.
6. Sufficient mechanical strength and flexibility for applying it to the strands, conductors, and coils in a satisfactory manner.
7. Resistance to vibration and movement.

Mica is the only material available at the present time which approaches all of these desired characteristics. Its most serious limitation is that it is available only in small sheets or flakes, and does not have high mechanical strength. In order to put mica in such shape that it can be applied to conductors as insulation, it is necessary to apply it to a paper or cloth base to give sufficient mechanical strength. The desired degree of flexibility is obtained by using relatively thin flakes and building up layers of overlapping flakes, together with a satisfactory bonding material. The characteristics of the bonding material should correspond to the desirable characteristics of the insulating material. It is especially essential that the amount of bond and its vapor pressure be low, so that gases will not be liberated when subjected to heat and cause looseness in the insulation layers, and swelling or bulging of the insulation at the unsupported sections. The built-up insulation can be made in the form of tape or wide sheets, and applied to the coils in these forms.

Treated cloth is also a satisfactory insulating material. It is stronger mechanically and more flexible than mica tape, and when properly impregnated has a higher voltage breakdown strength. Its most serious limitation is that it is susceptible to injury from corona, static discharges, and high temperatures. Its application is confined to parts of the coils, connectors, and leads which are of unfavorable shape, and difficult to insulate with mica tape, and which operate at relatively low temperatures and are free from corona and static discharges.

After doing a large amount of development work and making tests on insulated coils, it is felt that the insulation materials which are used on present lower voltage windings, are satisfactory for higher voltage windings. It is necessary to give more care and supervision to the manufacturing operations in building the insulation, applying it to the coils, handling the coils through the respective manufacturing processes, assembling the coils in the machine, making insulation tests, and conditioning the machine prior to going into service.

*Application of Insulation to High-Voltage Stator Coils.* In building coils for high-voltage generator windings, the individual strands and conductors of multiple turn coils are insulated throughout the entire length with mica tape. The company with which the writer is affiliated uses micarta folium wrappers for the straight part of the coil sides. The end turns, connectors, and leads are insulated with mica tape, treated cloth tape, or a combination of both kinds of tape. The micarta folium insulation used on the straight portion of the coil has been improved during the past few years by the introduction of a bonding material which has a lower dielectric loss, higher breakdown strength, and greater flexibility than the older type bond. The increased flexibility of the wrapper makes it feasible to use a greater percentage of mica in the micarta folium. The micarta folium wrapper is in one piece with respect to the length of the coil side, and is wrapped on and baked simultaneously by means of an electrically heated automatic wrapping machine. All coils are "steam" pressed on the straight parts after insulating in order to remove the volatile matter and obtain a more compact insulation free from air spaces. The treated tape on the end turns, connectors, etc., is applied by hand. Special attention is given to the design and actual manufacturing operations in making the joint between the two kinds of insulation, so that it will satisfactorily withstand the voltage stresses which exist under actual operating conditions.

*Tests on Insulation for High-Voltage Windings.* The use of treated cloth tape on the end turns for the coil insulation is desirable on account of the fact that with its greater mechanical strength than mica tape, it can be applied more tightly, and a more compact insulation obtained. Numerous tests have been conducted to determine whether the end insulation and the joint between the mica folium and the end insulation were satisfactory for high-voltage windings. Coils were insulated on the ends with treated cloth tape and with several grades of mica tape. The mica tape was vacuum treated before being applied to the coils. All tests were made at usual room temperatures. The average value of breakdown voltage for the coils insulated with mica tape for 13,200-volt normal operation was approximately 75 kv. and for the coils with an equal thickness of treated cloth insulation, the breakdown voltage was

100 kv. Mica tape for 22,000-volt operation failed at an average value of approximately 100 kv., whereas coils insulated with an equal thickness of treated cloth withstood approximately 140 kv. The voltage was applied momentarily in all cases. All of the test results indicated that treated cloth tape is more satisfactory for insulating the end windings than mica tape and that 25 to 50 per cent greater test voltage can be withstood. The test results indicate that mica tape is also a satisfactory insulation for the end turns and other related parts.

A test bar approximately 8 ft. long was made to represent a section of a stator coil for a large capacity 22,000-volt turbine generator. The bar was insulated with micarta folium suitable for 22,000-volt service, and the ends were covered with micarta tubes in order to obtain sufficient creepage for testing at high voltages. The joints between the micarta folium insulation on the bar and the micarta tubes were sealed with treated cloth tape. The bar was tested at 65 kv. for one minute and did not fail. The test voltage was then raised to 100 kv. and held for 30 seconds and no failure occurred. In making the test, the tin-foil grounding sheath was extended out over the joint, whereas in an actual generator, a long creepage distance is provided from the joint to ground. Built-up sections with 22,000-volt micarta folium insulation have been tested at 175 to 200 kv. momentarily without failure.

Steps have been taken to eliminate corona and static discharge around the end windings during testing and under normal operating conditions. In the slot portion, the coil is covered with asbestos tape, and a relatively high resistance conducting material is applied to this portion of the coil. No slot cell is used and the entire embedded surface of the coil is at ground potential; consequently, no static discharge can take place from the coil surface ground. The ends of the coils are covered with a layer of asbestos tape which acts as a high-resistance conductor and decreases the amount of discharge at the end of the slot and around the end windings.

With higher voltage windings, it is felt necessary to keep metallic structural parts remote from the end windings in order to decrease corona and reduce the voltage stress on the end portions of the winding. The coil ends are roped down to micarta coil supports which are distributed around the end winding periphery at frequent intervals. Fig. 1 shows the coil ends and method of bracing, which is to be used on large 22,000-volt, 1800-rev. per min. turbine generators. In the case of higher voltage stator windings, the mechanical stresses on the end turns are reduced due to the fact that the currents are smaller. Hence, the coil end bracing is a less difficult mechanical problem than for the case of lower voltage machines of the same rating.

*Insulation Tests.* It is necessary, in the construction of higher voltage generators, to increase the magnitude of the voltage for the insulation tests at the different stages of the manufacturing operations, and the difficulties involved in making the insulation tests increase very rapidly as the test voltages are increased. In view of the fact that the dielectric losses increase very fast for high voltages, it is felt advisable to consider the necessity for maintaining the test voltages for appreciable lengths of time. With the prolonged high-voltage test, the insulation heating due to dielectric losses and surface creepage may become so great that injury to the insulation will result, and the test actually produce more harm than good. It is believed that the present standardized final test voltages of twice normal plus 1000 for one minute can be satisfactorily met for 22,000-volt machines. However, for final test voltages in excess of 50 kv., the length of test should be materially reduced. A shorter time of voltage application

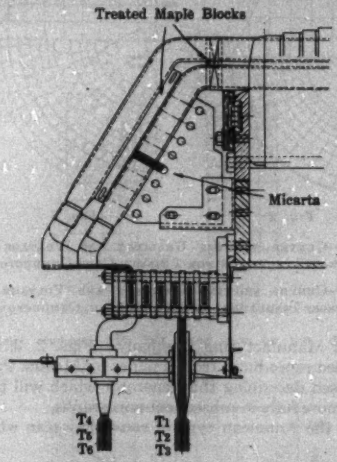


Fig. 1—Showing Method of Bracing Coil Ends on 22,000-Volt Generator

should be satisfactory to locate any defects in the insulation, and would be considerably less liable to injure the insulation by excessive heating. If desired, two or more tests of shorter duration could be made with sufficient time interval between tests to permit the insulation to cool.

*Shape of Conductors and Voltage Gradient.* In designing the conductors of high-voltage windings, special consideration must be given to the shape of the conductors in order to limit the potential stresses at different sections of the insulation. It is not only necessary that the average voltage per unit thickness of insulating material be kept within the safe working range, but stress concentration due to sharp corners and edges must be avoided. The circular conductor is the ideal shape from the standpoint of minimum stress concentration. Fig. 2 shows the electrostatic field for a

circular conductor with insulation thickness required for a 22,000-volt winding. For a given total voltage to ground, the series concentric cylindrical conductor arrangement is the ideal arrangement from the standpoint of minimum potential gradients, as shown by Figs. 3 and 4. This type of conductor was used in the construction of a 33,000-volt turbine generator by the

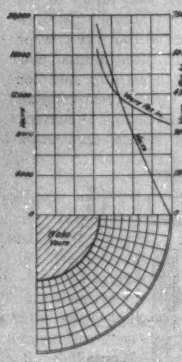

Fig. 2

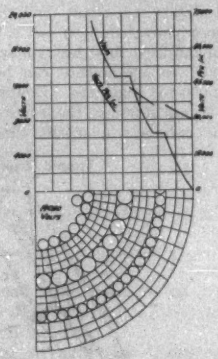

Fig. 3

Fig. 2—Curves showing Gradient and Voltage Drop Across Insulation for a Single-Core Conductor

Fig. 3—Curves showing Gradient and Voltage Drop Across Insulation with Concentric Conductors

Parsons Manufacturing Company. Figs. 2, 3, and 4 have been reproduced from a paper by Messrs. Parsons and Rosen describing this generator which will be discussed more fully in subsequent paragraphs.

With the American type of construction in which it

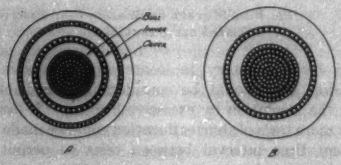

Fig. 4—Sections through Conductor Bars

is considered necessary and essential that the coils be placed in open slots, it naturally follows that the conductors are rectangular in shape. If standard rectangular copper sections were used for the strands, the built-up conductor and coil would have relatively sharp corners, and there would be stress concentration at these points. The electric field for a conductor with square corners is shown in Fig. 5. In this particular case, the field would be as shown in Fig. 6, if the corners of the coils were provided with a radius equal to one-quarter of the copper width. Since the present practise is to transpose strands of the conductor in the buried part of the coil, it becomes a difficult and expensive proposition to put the necessary radii on the respective strands by hand. In this connection, it is felt that a half-round strip or strip with well-rounded corners, should be placed at the top and bottom edges of the top and bottom coils respectively. This strip would be insulated from all of the strands except possibly one and provided with the usual amount of strand insulation. This strand would assume the potential of the

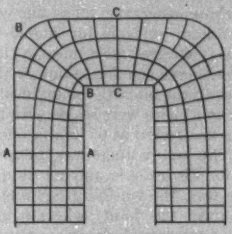


Fig. 5a—Electrostatic Field

Rectangular conductor with square corners. (33,000-volt insulation)

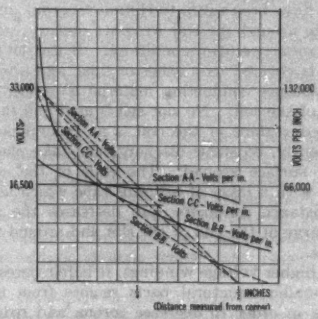


Fig. 5b—Volts and Volts per Inch

Rectangular conductor with square corners. (33,000-volt insulation)

conductor to which it is applied, and would aid materially in reducing the stress concentration at the corners as shown in Fig. 7. In all of these cases, the outside surface of the coil is provided with an asbestos tape covering which is filled with a high-resistance grounding compound. The electrostatic fields are based on the outside surface of the coil being at ground potential. As a further means of reducing the concentration of stress on different parts of the insulation, it is proposed that equipotential surfaces be provided at different intervals in the insulation. The wrappers can be applied in approximately three parts, and conducting

films can be located at the corners of the coil over restricted sections, and thus establishes definite potential surfaces. The type of conducting material and its arrangement can be controlled so that no resistance losses of appreciable magnitude are introduced due to circulating currents. The magnitude and distribution of the electrostatic field are shown in Fig. 8.

*Temperature Gradient through Insulation.* It is

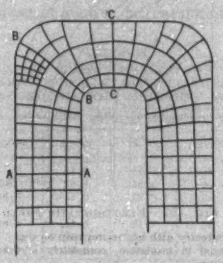


FIG. 6A—ELECTROSTATIC FIELD

Rectangular conductor with round corners. (33,000-volt insulation)

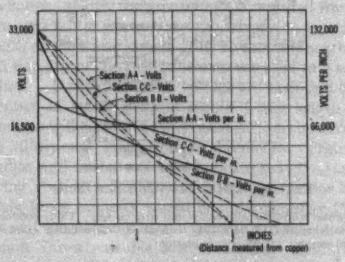


FIG. 6B—VOLTS AND VOLTS PER INCH

Rectangular conductors with round corners. (33,000-volt insulation)

necessary in the construction of higher voltage windings to use an increased thickness of insulation on the stator coils. There will be a corresponding increase in the temperature drop through the insulation in dissipating the stator copper loss. After the unit is placed in operation, the insulation is subjected to difficult service conditions on account of the relative movement between the insulation and the copper due to appreciable temperature differences. Whether this increased duty on the insulation will appreciably reduce the life of the winding below that now obtained on lower voltage machines can only be determined after several years of operation.

## EFFECT OF INCREASED VOLTAGES ON GENERATOR COST, WEIGHT, AND PERFORMANCE

In extending the design of any apparatus into unknown regions, there is a forced necessity for basing engineering judgment and conclusions on past experiences, and present available information. There are insufficient data available at the present time to determine the best thickness of the insulation for the higher voltage generator windings. With a given type of insulation, the optimum thickness of insulation must be based on a compromise between the average volts per inch of insulation and the total thermal drop through the insulation due to the stator winding copper loss. Based on experience with micarta folium insulation on

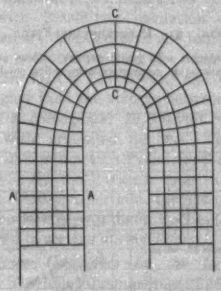


FIG. 7A—ELECTROSTATIC FIELD

Rectangular conductor with half round strip on top. (33,000-volt insulation)

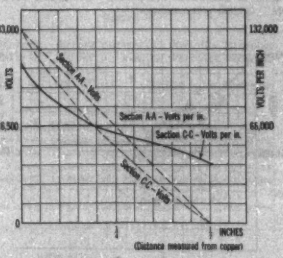


FIG. 7B—VOLTS AND VOLTS PER INCH

Rectangular conductor with half-round strip on top. (33,000-volt insulation)

13,200-volt machines, it is believed that the insulation thickness should be increased approximately 45 and 110 per cent respectively for 22,000- and 33,000-volt windings. The data in Table II have been arranged to show the total space required for micarta folium

insulation for different voltages and slot combinations on 4-pole, 1800-rev. per min., 60-cycle turbine generators.

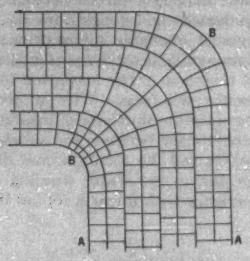


FIG. 8A—ELECTROSTATIC FIELD

Rectangular conductor with round corners. Three conducting films equally spaced in insulation, completely surrounding conductor. (33,000-volt insulation)

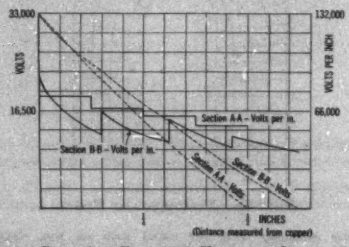


FIG. 8B—VOLTS AND VOLTS PER INCH

Rectangular conductor with round corners. Three conducting films equally spaced in insulation, completely surrounding conductor, all of equal length. (33,000-volt insulation)

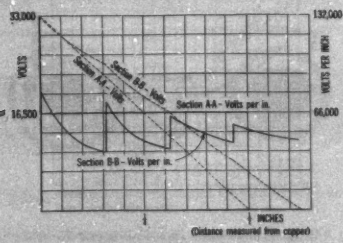


FIG. 8C—VOLTS AND VOLTS PER INCH

Rectangular conductor with round corners. Three conducting films equally spaced in insulation, completely surrounding conductor; length adjusted to give equal areas under films. (33,000-volt insulation)

On the basis of the data in this table, 40 per cent greater total insulation space is required for a stator with 84 slots than for 60 slots for any given voltage, and for any given slot combination, 110 per cent more insulation space is required for the 33,000-volt winding than for the 13,200-volt winding. If the 33,000-volt winding necessitated the use of 84 slots, an increase in the total insulation space of approximately 200 per

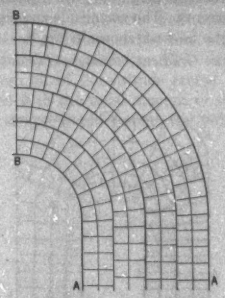


FIG. 9A—ELECTROSTATIC FIELD

Rectangular conductor with half round strip on top. Three conducting films equally spaced in insulation, completely surrounding conductor. (33,000-volt insulation)

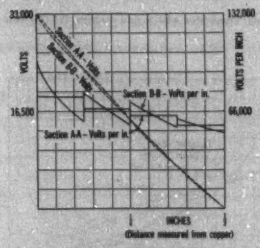


FIG. 9B—VOLTS AND VOLTS PER INCH

Rectangular conductor with half-round strip on top. Three conducting films equally spaced in insulation, completely surrounding conductor, all of equal length. (33,000-volt insulation)

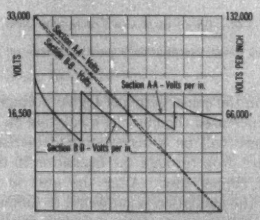


FIG. 9C—VOLTS AND VOLTS PER INCH

Rectangular conductor with half-round strip on top. Three conducting films equally spaced in insulation, completely surrounding conductor; length adjusted to give equal areas under films. (33,000-volt insulation)

cent would be required over that for a 13,800-volt winding with a 60-slot stator core. In the case of the lower voltage windings, the handicap of increased

insulation space for the larger number of slots and consequent reduction in available space for the copper is more than offset by the increase in the external surface of the copper for dissipating the copper losses. However, in the case of higher voltage machines, the total insulation space required is so great that no space is available for the copper with the larger number of slots, and it is necessary to use a relatively small number of slots.

With the increased thickness of insulation on the coils for high-voltage windings, it is necessary to work the stator copper at a lower current density on account of the higher thermal drop through the insulation. This means that a greater percentage of the stator periphery is required for the stator copper than for lower voltage machines. With the greater space required for insulation and stator copper, it is necessary to increase the length of the stator core in order to keep the magnetizing flux density in the teeth within a range of safe working values. If the rating and voltage are such that a larger number of stator slots is required, the length of the machine will have to be increased further, on account of the additional insulation requirements. Preliminary studies and estimated costs indicate that the manufacturing cost of a 22,000-volt turbine generator of relatively large capacity would be approximately 20 to 25 per cent more than that of a generator of the same rating wound for a suitable lower voltage. Similarly, the increase in cost for a 33,000-volt generator would be on the order of 40 to 50 per cent. There would be a corresponding increase in the weight and dimensions of generators when built for high-voltage service.

TABLE II
INSULATION SPACE REQUIRED FOR 4-POLE, 1800-REV. PER MIN., 60-CYCLE TURBINE GENERATORS WOUND FOR DIFFERENT VOLTAGES

| No. of slots | Per cent of stator periphery required for different voltages | | | | |
|---|---|---|---|---|---|
| | 11,000 | 13,200 | 16,500 | 22,000 | 33,000 |
| 54 | 12.0 | 13.9 | 16.3 | 20.2 | 30.2 |
| 60 | 13.2 | 15.4 | 18.1 | 22.4 | 33.6 |
| 66 | 14.6 | 17.0 | 19.9 | 24.7 | 37.0 |
| 72 | 16.0 | 18.5 | 21.7 | 26.9 | 40.3 |
| 78 | 17.3 | 20.1 | 23.5 | 29.1 | 43.7 |
| 84 | 18.7 | 21.6 | 25.3 | 31.4 | 47.0 |

The efficiency of such units would be reduced due to the greater bearing and windage friction losses on account of the increased rotor weight and dimensions and increased load and excitation losses. With the relatively small number of wide slots which are required the ratio of slot opening to air gap will be materially increased, and this will result in an increase in the rotor pole face losses. It is expected that the efficiency of the high-voltage machines will be from 0.25 to 0.5 per cent less than for a suitable lower-voltage machine. Whether such units can be justified from the cost and performance standpoints depends on the savings that can be made in the cost and performance of circuit breakers, cables, and other related auxiliary equipment.

## History of High-Voltage Synchronous Machines In the United States

The earliest high-voltage synchronous machine built by the Westinghouse Company was a 6000-kw., 16,500-volt, 50-cycle, 750-rev. per min. turbine generator for the Edison Electric Company of Los Angeles in 1906. A 15,000-kv-a., 18,000-volt, 50-60-cycle frequency changer set was built for the Southern California Edison Company in 1919. Synchronous condensers of 5000-, 10,000-, and 15,000-kv-a. rating at 18,000 volts were built for the same company in 1921 and 1923. These machines have experienced no cases of stator winding trouble since installation.

The 11,000-volt, single-phase turbine generators for the Norfolk and Western, New York, New Haven, and Hartford, and Virginian Railways Companies are provided with 19,000-volt insulation on the stator windings and are operated with one terminal grounded. The electric potential between the main insulated lead and grounded lead is 11,000 volts and is therefore 40 per cent higher than the voltage between terminal and neutral of a three-phase 13,800-volt machine when operating with grounded neutral. These machines have been in continuous service since 1915 and 1924 respectively. At the present time, a 70,600-kv-a., 22,000-volt, 1800-rev. per min. turbine generator is on order for the Northern Indiana Public Service Co. and will be placed in service during 1930.

*High-Voltage Generators by the General Electric Company.* The following machines of 16,500 volts and above have been built by the General Electric Company.

SYNCHRONOUS CONDENSERS (SALIENT POLE)

| No. of each rating | Rating | Date of Installation |
|---|---|---|
| 2 | 12,500-kv-a., 500 rev. per min., 22,000 volts, 50 cycles | 1919 |
| 1 | 15,000 kv-a., 900 rev. per min., 24,000 volts, 60 cycles | Under construction |
| 2 | 12,500 500 " " " 22,000 volts, 50 cycles | 1928 |
| | Turbine Generators | |
| 1 | 100,000-kv-a., 1500 rev. per min., 16,500 volts, 50 cycles | 1928 |
| 2 | 61,765-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles | 1928-1929 |
| 2 | 72,941-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles | 1929 |
| 1 | 89,411-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles | 1929 |
| 1 | 100,000-kv-a., 1500 rev. per min., 16,500 volts, 50 cycles | Under construction |
| 2 | 116,667-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles | Under construction |

*High-Voltage Generators by the Allis-Chalmers Company.* An 1800-rev. per min., 115,000-kw., 95 per cent-power factor, 18,000-volt generator is being built by the Allis-Chalmers Company for the Public Service Company of Northern Illinois. This unit is expected to be placed in service during the early part of 1931.

*High-Voltage Generator by the Parsons Company.* During the past year, a 25,000-kw., 33,000-volt, 3000-rev. per min., 50-cycle turbine generator was built by the Parsons Mfg. Company for the North Metropolitan

Electric Power Supply Company of England. A complete description of this machine was given by Messrs. Parsons and Rosen in the *Proceedings* of the Institution of Electrical Engineers in the early part of 1929. Since this is the first large capacity 33,000-volt generator to be placed in service, it seems advisable to call attention to some of the outstanding design features and compare them in a general way with the type of design of American-made machines.

This machine is interesting from design and construction standpoints, in that cylindrically-shaped concentric conductors, Fig. 4, are used in the stator winding, and partially closed circular-shaped stator slots are provided in the stator core. With this construction, the insulated conductor must be inserted in the circular tunnel-shaped slots at the ends of the machine and pushed through the entire core length. This requirement practically precludes the possibility of obtaining a snug fit between the conductor insulation and the perimeter of the circular slots. The inevitable looseness of the coil sides in the slots permits air spaces to exist and gives a poor heat transfer constant from the insulation to the stator iron which results in higher stator winding temperatures. It also leaves the coil free to vibrate, which may result in damage to the insulation. A further disadvantage of the bar and end connection type of winding used on this machine is the difficulty of making the electrical and insulation joints between the bar and end connectors at the ends of the stator core on account of the restricted space for working. These conditions do not exist to any appreciable extent in the case of machines of American design in which the conventional type of open rectangular-shaped slots is used. In assembling the coils in open rectangular-shaped slots, it is only necessary to push the coil radially through the depth of the slot and side packing can be readily applied, hence a snug fit can be obtained at all points.

The cylindrically-shaped coil sides of the 33,000-volt machine consist of the concentric conductors, and each conductor is provided with insulation equivalent to approximately one-third of the total insulation thickness necessary for full voltage from line to neutral. The conductors of each phase are arranged in three groups, and the three groups connected in series. The group nearest the neutral point of the winding consists of all of the outer conductors and the group nearest the lead terminals consists of the central conductors. With this winding connection system, the total insulation limits the breakdown to ground and the voltage gradient on the insulation is reduced due to the fact that definite series voltages are applied at definite points in the insulation. The cylindrically-shaped conductor lends itself readily to the application of the insulation and is free of corners which introduce high electrostatic stress concentrations. The disadvantage of this type of conductor is that for a given copper section the surface available for dissipating the copper loss is a minimum. The watts loss due to the central conductor must flow across the total or three insulation thicknesses, whereas the losses of the other two conductors flow across one and two thicknesses of insulation respectively. With rectangular-shaped conductors, the heat dissipating surface is appreciably larger per conductor, and the loss of each conductor is dissipated through the total thickness of insulation adjacent to the conductor. When comparing the relative conductor and insulation dimensions given in the paper by Messrs. Parsons and Rosen, with a three-conductor rectangular-shaped coil side on the basis of the same copper sections and same total thickness of insulation, the thermal drop in the insulation would be from 25 to 75 per cent greater for the cylindrical-shaped conductor. The actual increase in thermal drop through the insulation depends on the ratio of surface area of the rectangular and circular-shaped conductors. With the total thickness of insulation required on a 33,000-volt machine, the increase in the stator copper temperatures would therefore be approximately 7.0 to 21 deg. higher for this cylindrical concentric conductor type of coil side.

The coils farthest remote from the neutral or ground potential have only two conductors, and additional insulation is provided to give greater protection against voltage stresses due to potential surges. This feature can be handled in a similar and equally effective manner with the American type of rectangular shaped coils. At the present time, experimental investigations are under way to determine the voltage distribution between turns when the stator winding of a synchronous machine is subjected to voltage surges of different shaped wave fronts. It is hoped that this investigation will determine whether there is a need for providing additional insulation on the end turns.

The data covering the electrical characteristics of the generator show that the short-circuit ratio is only 0.6, whereas a short-circuit ratio of approximately unity is required by an increasing number of American central station companies. The efficiency of the generator, which is given as 96.5 per cent at 25,000 kw., 80 per cent power factor, is approximately 0.5 to 0.75 per cent lower than the corresponding efficiency of a 60-cycle, 1800 rev. per min. American generator of the same rating, except wound for one of the present standard voltages.

## Summary and Conclusions

At the present time, there is a definite need for materially increasing the generated voltage of large steam-turbine generators due primarily to the limitations in the current-carrying capacity of the oil-filled type of circuit breakers and to the increased cost of switches, reactors, and cables for the relatively high current values at present standard voltages. Based on the results of tests and research development, and on the operating experience with several 18,000-volt synchronous condensers and 11,000-volt single-phase

turbine generators which are provided with 19,000-volt insulation and operate with one terminal grounded, it is felt that turbine generators wound for voltages between 16,500 and 25,000 volts should give satisfactory operation, provided adequate judgment and precautions are followed in their operation. It would not be recommended that a high-voltage generator be connected directly to a transmission line or distribution system unless the existing conditions were such that the windings would not be subjected to potential surges of dangerous magnitude. The cost of a 22,000-volt turbine generator will be 20 to 25 per cent more than for a similarly rated machine of suitable lower voltage. In the case of large capacity units, the increase in cost and reduction in efficiency of performance will probably be more than offset by the reduction in cost of step-up transformers, cables, and bus bars.

In the case of 33,000-volt machines, there is no operating experience available for such voltages; consequently, it will be necessary to complete a comprehensive program of research development and obtain reliable operating data on 22,000-volt generators before concluding that it is feasible to build satisfactory 33,000-volt generators. As the situation now stands, the building of a 33,000-volt machine of relatively large capacity and great importance should be undertaken jointly by the manufacturer and purchaser, as a development proposition.

ACKNOWLEDGMENTS

The writer is indebted to Mr. J. F. Calvert of the Power Engineering Department and Mr. M. G. Leonard, Summer Student, for preparing the electrostatic fields and voltage gradient curves for the insulation on the rectangular-shaped conductors.

## Discussion

**R. W. Wieseman:** Mr. Laffoon has given us a very interesting paper on armature insulation of synchronous machinery. This paper shows very clearly that present day voltages offer no limitations to the size of synchronous machines.

In the paper, it is stated that treated cloth tape is mechanically stronger than mica tape. This is quite true when the tapes alone and the application of the tapes are considered. We are not, however, so much interested in the tape as we are in the finished insulation on the coil or bar. When mica tape or mica sheet insulation is securely cemented to a coil, it has a mechanical advantage over treated cloth insulation for large coils because mica will stand more compression and more handling than cloth insulation.

Treated cloth tape can no doubt be applied to the end portions of the coil more tightly than mica tape. On the other hand, if the mica is applied to the coil with a reasonable degree of tightness, thoroughly filled by a vacuum process, and then cushion-pressed and cemented at high temperature to the copper, a superior insulation will result.

We are in full agreement with the statement that low-voltage insulations are satisfactory for higher voltages, provided they can be thoroughly filled and protected from corona and high temperatures. This is somewhat difficult to do in air-cooled machines and so on large important machines all mica coils are recommended.

I should like to ask Mr. Laffoon why the mica tape was vacuum-treated before it was applied to the coil. This treatment may make the tape dry and stiff and it may be difficult to apply it to the coil tightly. Mica tape must be quite flexible so that it can be applied readily and it should be dried or cured after it has been applied to the coil.

The paper states that test results at room temperature indicated that cloth tape is more satisfactory for insulating the end windings than mica tape because the cloth tape stands 25 to 50 per cent more test voltage. These tests do not give a fair comparison between cloth and mica. Cloth will always stand a higher short-time voltage than mica at room temperature. Under actual operating conditions of higher temperatures and continuously applied voltage, the mica will usually stand a higher voltage and last longer than any kind of varnished fabric insulation.

Perhaps another reason why the mica did not compare so favorably with cloth is because the mica was not completely filled. To obtain the best results with mica tape insulation, all voids must be eliminated by thoroughly filling the mica with an insulating compound and the mica must be cushion pressed into a solid mass and securely cemented to the copper.

Asbestos tape is a very effective slot armor and grounding sheath for the slot portion of the coil. This tape should not be carried too far around the end portion of the coil because the surface leakage currents may overheat the end winding.

The rounding of sharp corners on high-voltage armature conductors is a step in the right direction not only because high-voltage stresses are reduced but also because the insulation itself will not be damaged so readily as when it is bent around sharp corners. Below 25,000 volts it is perhaps not so economical to employ specially shaped conductors with round corners, but in the region of 33,000 volts, conductors which give more uniform voltage stresses in the insulation can certainly be used to advantage.

In conclusion, our experience with high-voltage all-mica insulation has shown that the mica must be securely cemented to the copper and completely filled by a vacuum pressure process. It must be a homogeneous insulation (without joints) throughout the entire periphery of the coil, and it must be protected from corona and high-voltage gradients by suitable grounding sheaths.

**P. L. Alger:** I agree with the author in his broad conclusions, that standard insulating materials and methods can be successfully applied in machines up to 33,000 volts, and that a voltage of about 22,000 is economically desirable on the largest turbine generators.

I am not in full accord with Mr. Laffoon, however, in regard to tests on such high-voltage insulation. I consider that insulation should be designed primarily for long endurance under service conditions, and that the best measure of such endurance is the length of life of a coil under about four times normal voltage stress at a temperature of about 100 deg. cent. Many life tests of this kind have shown that coils with high momentary voltage strengths at low temperatures are often inferior to coils made of more enduring materials with lower momentary voltage strengths. For these reasons I believe any shortening of the time of high-potential tests to be unwise, and that a more reasonable procedure, if high-voltage machines are to be given special consideration, would be to reduce the voltage slightly and extend the time of test to five minutes.

The reason for requiring high momentary voltage tests has been to insure strength to resist the voltage surges which occur in practise. I consider, however, that the time is approaching when more rational means of protecting against surges than arbitrary insistence on high momentary voltage tests will be adopted. The real economic gain from high-voltage machines cannot be secured until they can be directly connected to transmission lines, and this cannot be done until surges are adequately protected against. It is well known that voltage oscillations

occur in machine windings under impressed surges, to an even greater degree than they occur in transformers. The accompanying cathode ray oscillogram (Fig. 1) taken on a 24,000-volt synchronous condenser illustrates this phenomenon. Curve *b* shows the form of a voltage wave of about three microseconds front impressed on the three lines simultaneously, and curve *a* shows the resulting voltage at the ungrounded *Y* point. The internal voltage oscillates at about 10,000 cycles frequency, and rises to about twice the impressed value. As the voltages in other parts of the winding are also high, and as the turn-to-turn voltage is high at several points in the winding, it is very desirable to use external means to prevent the application of such surges to the terminals if possible. When the *Y* point is grounded, the voltage oscillations are less severe, but in this case, triple harmonic currents flow to the lines, which may give rise to telephone interference, especially with salient-pole machines.

I believe, therefore, that we cannot yet reap the full advantage of high-voltage machines, but that we are rapidly progressing in our understanding of the difficulties in the way and that ultimately we will have means for protecting against surges, while we will tend toward the use of longer times and lower voltages in high-potential tests.

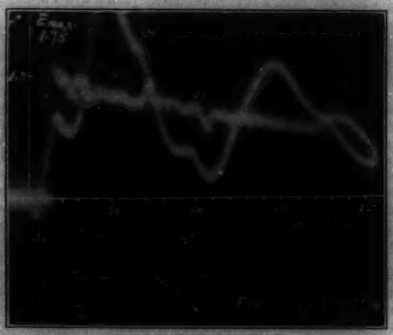

Fig. 1

There are several details in Mr. Laffoon's paper to which I wish to refer briefly. He remarks that the mechanical stresses on the end windings are lower in high-voltage machines, because of the lower currents. Since the current in each coil side of a machine of a given size and kv-a. rating is the same whatever the voltage, I do not see why the end stresses are any different either.

In the table on the seventh page the second two 12,500-kv-a., 22,000-volt condensers were built by the British Thomson Houston Company. These machines, and the very notable Parsons generator referred to by Mr. Laffoon, show that England is doing very constructive work along these lines. In Mr. Laffoon's discussion of the temperature rise of the Parsons generator, he seemed to overlook the fact that the graded insulation used results in only two-thirds the temperature rise of a normal machine of the same conductor surface area. This effect offsets the lessened area of the cylindrical conductors used and I believe the net result should be about a normal temperature rise instead of an excess of 7 to 21 deg. as Mr. Laffoon suggests.

**Theodore Schou:** It is very interesting to listen to the various points on insulation. Naturally, the points referred to apply to very large machines. But I do take a little exception against mica as compared with built-up insulation. My personal experience during the last twenty years has been that mica has to be treated very carefully and selected very carefully and inspected very carefully, if it is to be any good. For moderate capacity machines, I believe the so-called built-up insulation with a series of dips and tapings is the best protection. Naturally, it takes more time, but it does not necessarily take more labor to produce a good high-voltage coil with a series of dips. I do believe that such an insulation is very good for a moderate size machine, both synchronous motors and generators.

I should like to hear Mr. Laffoon's comments on the built-up insulation as to mica.

**S. L. Henderson:** When the subject of increased voltages for synchronous machines is considered, the question naturally arises as to the feasibility of connecting such machines directly to the line without intervening transformers. This question will arise in those sections where there is a local low-voltage distribution which is now fed by transformers connected to 13,800-volt generators. Instances can be found of distribution direct from 13,800-volt generators and there would seem to be sufficient precedent for direct distribution at these higher generated voltages. However, the conditions are not exactly parallel.

Studies made in connection with transformers have shown that the voltage surges coming from lightning discharges are of greater importance than those arising from switching. Tests with a half microsecond wave-front impressed on a generator, show that 80 per cent of the initial voltage at the terminals of the machine is impressed on the first coil and if a two-microsecond wave is impressed, 60 per cent of the voltage is impressed on the first coil. This means that several times the phase voltage may be impressed across the first coil at the time of a lightning stroke, and consequently there will be very high voltages between turns of this first coil. Subsequent to the initial surge, high voltages may occur in coils removed from the terminal, due to an internal oscillation in the machine.

The amount of lightning voltage which can reach the machine is dependent on the setting of the lightning arrester, and, therefore, the first few turns are subjected to a higher voltage surge.

The voltage generated by revolution per turn for a given size machine is essentially the same, irrespective of the terminal voltage, so that no more turn insulation is required on the high-voltage machine than on the low. However, if we also consider the lightning voltage, the turn insulation must be increased as the terminal voltage is increased.

The higher voltage machine, if it is to be connected directly to the line, not only must have increased insulation to ground but also increased insulation between turns. Further, present tests would indicate that this increased turn insulation would need to be placed on other coils besides the terminal ones. This will lead to increased size of machines and may lead to mechanically weak coils because of the small percentage of copper in the coils.

It may be possible to decrease the voltage gradient by the use of condensers or lightning arresters tapped into the winding at various points, and while such devices are theoretically correct there is some question whether these may not lead to more trouble than the lightning. Means can also be taken to retard the front of the incoming wave and so reduce the percentage voltage on individual coils.

However, until considerably more research work can be accomplished on the effects of lightning and on means for combatting, we are not safe in assuming that it is possible to transmit at these increased voltages. Even after we have completed our work we may find that the increased cost of making the generator safe and the hazard of the auxiliaries will still make it desirable to transmit through transformers.

**J. F. H. Douglas:** I should like to compare Fig. 9a with Fig. 7a. I wish to point out the superiority of the flux distribution

in Fig. 9A. I should like Mr. Laffoon to comment on whether this theoretically superior construction in Fig. 9A results in such increased costs that it is impracticable from that point of view.

**J. F. Calvert:** To arrive at the electrostatic flux fields shown in Figs. 5A, 6A, 7A, 8A, and 9A, certain physical properties and boundary conditions had to be established. The following assumptions were made.

1. The insulating materials have a uniform specific inductive capacity in all directions.

2. There is not sufficient current flow (under 60-cycle conditions) to have any appreciable effect upon the potential field.

3. In Figs. 8A and 9A the conducting sheaths terminate at practically the same cross sections through the conductors.

4. The conductors are quite long so that the end effects do not have an appreciable effect on the flux and potential distribution within the central portion of the machine, so far as the conditions between any two adjacent pairs of conducting surfaces are concerned.

5. In determining the data given in Fig. 9A, there are equal capacities between each adjacent pair of conducting surfaces. This means that the inner conducting sheaths project further on the ends than the outer ones.

From assumptions 1 and 2, it may be written that,

$$V = \frac{e}{c}$$

or

$$\Delta V = \frac{\Delta e}{K} \frac{\Delta l}{\Delta a}$$

for a small volume

where

$V$ = potential difference between two equi-potential surfaces

$e$ = charge at end of electrostatic tube of flux

$c$ = capacity

$l$ = length along a flux tube

$a$ = cross section of tube

$K$ = specific inductive capacity.

From assumptions 3 and 4, it appears that the field between any adjacent pair of conducting surfaces need only be considered for unit distance in the axial direction of the machine. This reduces the problem to two dimensions and permits an easy graphical solution, and

$$\Delta V = \frac{\Delta e}{K} \frac{\Delta l}{\Delta w}$$

where $w$ = width of the flux tube in the planes of the figures (5A to 9A). Then when $\frac{\Delta l}{\Delta w} = 1$, the field between two conducting sheaths may be drawn in curvilinear squares, as shown in the drawings. Along any flux tube, there will be equal potential differences between the surfaces which cut off curvilinear squares from this tube. Between two potential surfaces, there will be equal flux tubes represented by the space between the flux lines which cut out curvilinear squares.

This is the entire problem in Figs. 5A, 6A, and 7A, because the conducting surfaces occur only on the inside and outside, of the insulation. The potentials and gradients can be determined with reasonable accuracy from the drawings made on this basis.

In Figs. 8A and 9A it is found convenient to divide the space between adjacent conducting surfaces as described above for the entire insulation. Then the capacity for each space is

$$K \times \frac{\text{number of unit flux tubes}}{\text{number of unit potential differences}}$$

Where $K$ = the specific inductive capacity, a unit flux tube is any size, and the unit potential difference is that which cuts a curvilinear square from the unit flux tube.

Since the total electrostatic flux from the inner conductor must reach the outside surface, the potential of each conducting surface may be computed and the potentials and gradients between these surfaces found as for Figs. 5A, 6A, and 7A.

The unit tubes between one pair of adjacent conducting surfaces may or may not be chosen the same as that between the next pair. It is more convenient to choose them so that there will be an even number of equal potential differences or squares between adjacent surfaces. However, if the flux tubes are chosen to be of the same magnitude throughout, there will be the same number of tubes crossing every potential line, yet there may be sharp changes in the boundaries of these tubes at the intermediate conducting surfaces. This is illustrated in the sketch accompanying this discussion, Fig. 2.

**C. J. Fechheimer:** It is well to consider what difficulties are associated with winding machines for voltages of the order of 33,000. The thought that comes to one's mind is that the wall thickness of the insulation becomes so great that there is but little space left for the copper. Thus, if the practise that has been followed in the past were to be continued in the future, a single wall thickness would be of the order of 0.5 in. If the copper width were equal to this, the slot width would then be 1.5 in. Although this is greater slot width than is usually employed, the copper would occupy only one-third, which would mean that the slots would have to be very deep or the machine considerably larger than at present. As the heat generated in the copper must be conducted through the insulating walls, with so great wall thickness it is necessary to operate at materially reduced watts per sq. in., which in turn implies larger section of copper, thereby again increasing the size of the machine. These factors then

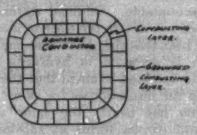


Fig. 2

lead to the questions: is it economically worth while to go to high voltages; if so, how can it be done practically? It is not my purpose to answer the first question as that has been discussed by Mr. Laffoon and others. I shall attempt, however, to consider the second and discuss some of the possibilities.

Coils which have been insulated for operating voltages of 13,200 have stood up to 140,000 volts before failure, indicating that if the insulation were not impaired after placing the coils in the machine they could withstand approximately 18 times normal voltage to ground if the neutral point is grounded. This would at first seem as an unnecessarily high factor of safety. During the process of placing the coils the insulation is frequently injured, and due to various uncertainties arising during manufacture, some coils fail at considerably lower voltages. Consequently the practise is to put on greater wall thicknesses than may seem necessary. Therefore, one important thing is to improve our processes of manufacture, so that greater uniformity will be obtained and the insulation less damaged when the coils are placed in the slots.

Another reason why our present wall thickness cannot with safety be much decreased, is that entrapped between layers of insulation are impurities, such as air, moisture, or other extraneous material. A tiny air pocket having a specific inductive capacity of unity in series with insulation having a specific inductive capacity of about 4 or 5 will be overly stressed with attendant internal corona. Such corona is productive of internal loss which heats the insulation and in all probability is the source of high-frequency oscillations at or near the peak of the voltage wave. These would not only tend to reduce the strength

of the insulation as a whole but if of long duration might cause failure. This then leads to the important conclusion that the insulation can be materially improved provided these voids be filled with some insulating material, preferably of values of specific inductive capacity corresponding to those of the main insulation and of approximately similar dielectric strength.

For many years engineers have struggled with these problems. Various impregnating compounds have been used, some with more success than others; while the voids have been reduced, but they have not been eliminated. The great successes achieved by the cable manufacturers in the use of oil-filled cables for operating voltages up to 132,000, indicates the possibility of this as one road for improvement; either employ insulation which is well treated with oil before the coils are put into the slots and possibly supplement by subsequent oil treatments, or run the entire stator in oil. The latter suggestion has been offered a number of times, particularly by A. B. Field. In the event that oil is used, it does not seem likely that the distance from the copper to the iron can be reduced. However, it seems that the net thermal drop from the copper to the slot sides for a given value of watts per sq. in. can be materially lowered, owing to the high thermal conductivity of the oil compared with that of occluded air, and of the possibility of some small internal convection currents within the oil. A stator which is operated with oil as the cooling medium would have the means of transferring the heat from the solid surfaces to the oil, far more readily than with air. The flow of the oil could be maintained readily by means of an external pump, and the heat abstracted by water in a suitable external heat exchanger. At present it does not appear that the mechanical difficulties of keeping the oil from leaking are unsurmountable. Oil-filled stators have been used in Europe on phase converters for electric locomotives and the reports so far have been that they have been eminently successful.

A stator which is operated in hydrogen has considerable advantage over one operated in air in that the corona discharge is not damaging to the insulation as far as we know at present. However, hydrogen has nearly the same specific inductive capacity as air and corona forms at substantially the same voltage gradient as in air. There is then still the possibility of internal losses and the likelihood of high-frequency oscillations being produced. With compact insulation it is doubtful whether all of the air trapped between layers is supplanted by hydrogen, and if it is supplanted a considerable period of time will be required. Nevertheless, a machine operated in hydrogen should be considerably safer at the high voltages than one operated in air because of the freedom of damage from external corona and because the fire risk is reduced owing to the absence of a supporter of combustion.

It is well to consider the high-voltage generator from the construction standpoint. The use of round slots has been proposed frequently, but they are objectionable because they are uneconomical in magnetic material, as the teeth become very narrow and are worked at high magnetic densities, and because a shoved-through coil construction is necessary. The idea of rounding the corners and preferably of making the ends of the copper semicircular as shown in Fig. 7 in Mr. Laffoon's paper, is excellent for two reasons: The voltage gradient is much more uniform, and the mechanical weakening of the insulation, which practically always accompanies the use of sharp corners, is materially reduced. The additional gains to be obtained by the use of conducting material at intervals as indicated in Fig. 8 is well worthy of consideration, although it is believed that the complication is hardly justified. It should be possible to embody the feature of rounding the coil ends, thereby reducing the wall thickness, and obtain more economical proportions. At the present time it is believed that grading of insulation, that is, the employment of materials of different specific inductive capacities, is not warranted, at least for voltages of the order of 33,000.

The scheme proposed by Messrs. Parsons and Rosen shown in Fig. 4 is not desirable for a number of reasons: there is necessarily a high thermal drop from the bull conductor to the outside; it is uneconomical from the standpoint of magnetic material; as it requires a shoved-through construction, the joints at the ends would be liable to be weak dielectrically; and the end windings are too complicated. The American practise of using rectangular open slots is the one to which we should by all means adhere.

Perhaps twenty years ago it was the practise in this country to use concentric windings as is still the practise in Europe. The concentric winding for high voltages has the advantage that only half as many coils are used and that the space occupied by the insulation between the two coils in the slot is eliminated. For high-voltage machines this space is appreciable. Nevertheless, the one coil per slot winding is undesirable for a number of reasons, for instance, that usually the wave form produced contains more ripples and the load losses are generally greater. With two coils per slot suitably chorded, the wave form is so close to a sine that the troubles, such as telephone interference, arising from higher harmonics, are practically eliminated.

**P. Sporn:** Mr. Laffoon's paper deals primarily with synchronous alternators and most of the principles laid down apply to synchronous alternators only and do not apply to synchronous condensers. I am referring, of course, to high-voltage synchronous condensers.

The problem that the synchronous condenser at high voltages presents to the designer is that of building a machine that will not only stand the normal and abnormal power-frequency stresses but also be able to stand impulses and surges, if it is to operate on a high-voltage bus from which overhead transmission lines are fed out.

The increased use of power makes 24,000, 33,000, 44,000, and 66,000 volts no uncommon voltages for what might be very accurately called distribution purposes. Many substations exist today where the lowest voltage existing in the station is a voltage of that order. To regulate these voltages properly the synchronous condenser is the logical tool to use, but the limitation of voltage that has been existing makes it a very expensive tool. In many cases, of course, a low voltage can be economically obtained by the use of a three-winding transformer but the three-winding transformer has the objection that it places definite limitations on the impedance arrangement possible between the three voltages, and makes it necessary very often to compromise on impedance arrangements to the great detriment of system stability. The use of a high-voltage condenser operating at the same voltage as the distribution bus, whatever it happens to be, automatically eliminates this difficulty. To make this feasible, however, it will be necessary to carry on more development work than has been carried on to date in the direction of obtaining either better impulse strength with materials that have been used heretofore in synchronous machines (although this is obviously difficult), or to go to entirely new materials. The development of oil-impregnated cable definitely points the way in one possible direction but very little has apparently been done in following up the lead. This seems regrettable.

It was thought for a while that the use of hydrogen-filled machines would solve this difficulty and we have a 15,000-kv-a. 24,000-volt synchronous condenser under construction on our system at the present time. However, while this makes possible the use of materials that would normally be difficult, if not impossible, to use and thus permits the obtaining of greater impulse strength than is possible with mica for example, it nevertheless falls short of meeting the necessary requirements as to strength. It would appear to be time to try new insulating materials operating in media other than gases.

**R. B. Williamson:** (communicated after adjournment) It should be noted that the 33,000-volt machine referred to in the paper has a graded insulation, *i. e.*, all parts of the winding are not provided with 33,000-volt insulation to ground. In the

machine described by Parsons and Rosen, one-third of the concentric conductors have 33,000-volt insulation to ground; one-third, 22,000; and the outer third, at the neutral, 11,000. On the other hand, the 22,000-volt machines so far built in this country, have all conductors insulated for 22,000 volts to ground. With the graded insulation it is possible to build 33,000-volt machines without making the slot space requirements for insulation too great. On the other hand, if all the conductors were insulated for 33,000 volts the space taken up by insulation would be so large that such a machine would be of abnormal design and excessively high cost. If, therefore, all conductors have to be insulated for the full voltage, the 33,000-volt machine is at a considerable disadvantage. Whether or not a generator voltage of 33,000 will be used in future in America, will depend very largely on the attitude of operating engineers as regards the use of graded insulation in large turbo generators. At present, many of these engineers feel that, with resistance or reactance in the neutral ground, conditions might arise where the 11,000-volt insulation on the ground end of the winding would not be sufficient to withstand the transient voltages met with under service conditions.

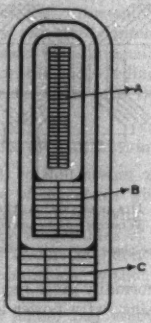


Fig. 3

The construction of the machine described by Parsons and Rosen is objected to in the paper on account of its not being well suited to the open-slot construction generally used in America and because of the arrangement of conductors not being as good from the heat-transfer standpoint as that of rectangular conductors. It may be pointed out that Messrs. Parsons and Rosen have proposed another arrangement, as shown in the accompanying Fig. 3. This would be well suited to open slot construction with diamond shaped end connections as used in this country. The high-voltage conductor *A* presents the largest area for transmitting heat through the insulation, and conductors *B* and *C* present areas of less amount, approximately proportional to the thickness of insulating wall. Thus where the insulation is thickest the watts per square inch transmitted through the insulation are least and it is possible to design a coil of this kind so that the temperature drop through the insulation will be approximately the same for all three sections. At the same time the current density may be as high in the high-voltage conductor as in either of the others. Metal sheaths can easily be inserted as shown by the heavy lines in order to insure equal voltage stress in the three sections of the insulation. This type of coil would suit open-slot design as well as coils of the usual type. The coil ends could be of diamond shape and the only additional complication would be in the coil connections required to carry out the grouping of the three voltage sections. So far as the graded insulation feature is concerned, it is equivalent to the concentric arrangement.

**C. M. Laffoon:** There is no disagreement with Mr. Wieseman in regard to the importance of obtaining a solid insulation free of air voids for high-voltage generator windings. It was the intent in the paper to give the results of insulation tests for treated cloth and mica tape, and not to advocate either one for general applications. Both are satisfactory insulation materials when properly applied. In part of the test coils the mica tape was vacuum-treated before applying, and in the remaining part it was not vacuum-treated. The coils were not vacuum-treated and impregnated after the insulation was applied. No wide difference was found in the test results, and average values were used.

In Mr. Alger's comments it was stated that the stresses on the end turns would probably be the same on the high-voltage machines as on low voltage. The statement made in the paper was intended to convey that with the leads and wiring around frame, connectors, and so forth, there would be less current to handle than with lower voltage machines, and the stresses would be reduced on these parts. A slight reduction of stress would be occasioned on the actual end turns, due to the fact that greater thickness of insulation is required, and the conductors would be placed a little farther apart. It was not intended to convey the understanding that a large reduction in stresses would be obtained in high-voltage windings.

In connection with the final potential tests for high-voltage windings, the writer proposed that present A. I. E. E. rules be followed for test voltages of 50,000 and less, and for higher test voltages than 50,000 that the time of test be reduced. Mr. Alger suggested the alternative proposal of increasing the time element and reducing the magnitude of the voltage. Such tests would be a satisfactory measure of the fitness of the insulation, but it would be necessary to obtain definite agreement in regard to the magnitude of the voltage reduction.

The writer agrees with Mr. Alger's statement, in regard to Parson's 33,000-volt generator conductor design, that on the basis of *same conductor surface area* the temperature rise should not be higher than for an American design, in which open rectangular shaped slots are used. The comparison in the paper is based on conductors having the same copper section and weight. The cylindrically shaped conductor is the most uneconomical shape from the standpoint of heat dissipating surface, and in order to obtain the same surface areas as for a rectangular shaped conductor it is necessary to use appreciably more conductor section and copper weight.

In reply to Professor Douglas' question concerning the electrostatic field, as shown in Fig. 9A, it is to be noted that the insulation design has not been worked out for practical application.

Mr. Schou raised the question in regard to the built-up type of insulation. If I understood him correctly, his proposition is to apply a certain per cent of the insulation and treat the coil and then apply another percentage, and so forth. In my original paper it specifies greater attention and consideration must be given to the building of the insulation and the application to the coils. That follows directly under such procedure indicated by that statement.

The writer is also indebted to Messrs. Sporn, Williamson, Calvert, Fechheimer, and Henderson for the valuable contributory discussions of the paper.

# Double Windings for Turbine Alternators

BY PHILIP L. ALGER,* E. H. FREIBURGHOUSE,* and D. D. CHASE*
Member, A. I. E. E. Associate, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—Large turbine alternators with two similar independent armature windings have recently been proposed, to permit the electrical segregation of bus sections in large stations without loss of synchronizing power. Several such generators have been installed, or are under construction, and it now seems that they will become of paramount importance in very large future stations. This paper explains the theory, and design limitations of these double winding generators, and describes their application in systems having different types of bus connections.*

* * * * *

## I. Introduction

A VERY recent and important development in the design of large steam turbine driven alternators is the use of two electrically independent similar armature windings. By loading the windings independently, the advantages of a higher generator reactance and hence lower fault currents are obtained, while yet retaining adequate synchronizing power. Also, by connecting the windings to adjacent bus sections of a sectionalized ring bus, the sections will be effectively separated by a high "through" reactance, thus limiting the current flow on faults, while still permitting power flow between sections, by virtue of the transformer action between the two windings.

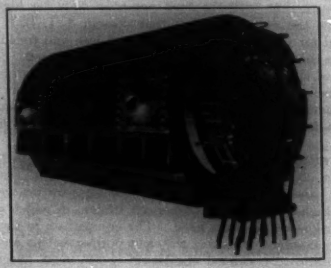

Fig. 1—Wound Stationary Armature, with Welded Frame, for Double-Winding Generator

83,333 kv-a., 1800 rev. per min., 13,800 volts

These characteristics permit the elimination of bus reactors, and a reduction in the required circuit breaker capacity, so that the double winding generator is likely to be extensively utilized in large stations of the future.

The first unit of this type to be installed is the 60-cycle, 83,333 kv-a., 13,800-volt generator, shown in Fig. 1, which has been in operation since the latter part of September 1929, in the Cahokia station of the Union Electric Light and Power Company at St. Louis. The second is the 25-cycle, 160,000-kv-a., unity power factor, 11,400-volt, generator of the New York Edison Company, which was placed in service early in October. Several others are now under construction.

Multiple circuit armatures have been commonly used for many years, to reduce the currents individual conductors are required to carry, but their circuits are not suitable for independent loading since any inequality of

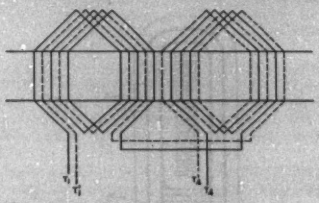


Fig. 2—Schematic Diagram of Alternate Slot Double-Winding Generator

Fractional pitch, one-phase per pole indicated for each winding

circuit currents normally gives rise to an irregular flux distribution, causing extra power losses and abnormal mechanical stresses. Only two types of winding are considered suitable for the purposes mentioned above, the alternate slot type, shown in Fig. 2, and the split belt type of Fig. 3. In the former, the two inde-

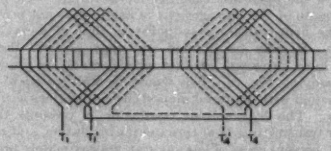


Fig. 3—Schematic Diagram of Split Phase Belt Double-Winding Generator

Fractional pitch, one-phase per pole indicated for each winding

pendently loaded circuits lie in alternate slots, with no two coil sides of different circuits lying in the same slot. In the latter, each phase belt of a single winding machine is divided into two approximately equal portions, of which one is assigned to each circuit, and the sequence of half belts in each circuit is so selected as to give perfect circuit and phase balance, while minimizing the

*All of the Engineering Department, General Electric Company, Schenectady, New York.

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29-164

number of slots carrying coil sides of different circuits. Either type of winding can be loaded unequally up to the limit allowed by armature heating, without important disturbance of the symmetry of the magnetic fields, and without introducing unusual stray losses or mechanical forces.

The alternate slot type gives perfect magnetic symmetry with unequal loading, but has its transfer reactance considerably reduced by saturation under excessive fault currents. The reactance of the split belt type is less affected by saturation, but this winding gives an appreciable dissymmetry of the magnetic field and slight extra losses with unequal loading. The latter type is recommended for general use, as it enables the minimum of reactor capacity to be used, with no real sacrifice in performance. The two machines mentioned above, however, have alternate slot windings.

The alternate pole type of winding is distinctly undesirable, as it gives low "through" slot reactance, unless approximately two-thirds pitch is used, and it gives large stray losses with unequal loading. Also, the magnetic forces on the end windings during a short circuit are much greater than with the other types of winding.

## II. Advantages of the Double Winding

The advantages in station design and operation, to which the new type of armature winding gives rise, may be grouped under the following headings:

(1) It reduces the magnitudes of the short circuit currents, which the circuit breakers are required to open under fault conditions, without increasing the number of breakers required.

(2) It maintains higher bus voltages during fault conditions.

(3) It reduces to one-half the magnitude of normal current, which the breakers and disconnecting switches must carry.

(4) It permits the elimination of bus reactors between adjacent bus sections.

(5) It reduces the capacity of generator reactors required.

(6) The decrement of the d-c. component of the short circuit current is approximately doubled, because the single winding supplying current to a short circuit has twice the resistance of a single winding machine of the same total output. On the other hand, the decrement of the a-c. component of the short circuit current is slightly reduced, because of the greater reactance of one winding, as compared with the reactance of the full output single winding machine. The increased rate of decay of the d-c. component may be of considerable importance when high-speed switching is employed.

There are certain limiting or offsetting features, on the other hand, which must be considered in evaluating the net gain due to the new double winding.

(1) It imposes certain limitations on the design of the armature winding, which are reflected in a slight increase in generator cost, without, however, affecting reliability in any manner. More connections are required than for the standard generator winding, but all are normally made on the same end.

(2) The saturation of the "through" reactance, due to excessive currents flowing between bus sections through the two windings, reduces its value for the reduction of fault currents.

(3) The kv-a. that can be transferred along the bus are limited. If the two windings are unequally loaded, the heating limits of full balanced load will be obtained in one winding with less than rated output from the generator. If, however, the ratio of loads in the two windings is kept less than 1.2, full load can be carried without exceeding the normal armature temperature rise by more than about 5 deg. cent. If one winding only is loaded, and the other is disconnected, approximately 60 per cent of rated current for the entire generator can be carried on the loaded winding. However, this difficulty due to unequal circuit loading can be overcome by means of a balancing transformer, which will equalize the current and power between the two windings, even though the bus sections may have considerably different vector voltages.

The connections of the double winding generator, and of the station buses, by which the advantages are obtained, are explained, and the advantages themselves are evaluated for each of the usual bus arrangements, in the sixth section of the paper.

These limitations will be considered in the following sections, though a consideration of the balancing of load mentioned under (3) will be reserved for discussion in a future paper, after the methods and devices required have been more fully studied.

## III. Equivalent Circuit of the Double Winding

A satisfactory double armature winding must fulfill two principal conditions:

(a) The two circuits must be capable of operating independently, or jointly, up to their heating limits, without magnetic unbalance, excessive losses, or abnormal mechanical stresses.

(b) The two circuits must be so interlinked that they can act as the two windings of a high-reactance transformer in transferring power from one bus section to the other, while yet limiting the current flow on faults.

In order to meet condition (a), it is necessary that each circuit contain coil sides under every pole, as otherwise there would be excessive magnetic dissymmetry, with unequal current loading. To meet (b), the circuits should be arranged to have as little mutual leakage flux as possible. It is also desirable, to avoid saturation of the through reactance flux leakage paths, that as many as possible of like slots be grouped together. The first condition can be met at the expense of the second, by arranging the two circuits in alternate slots, as in Fig. 2; while the second condition can be met at the expense of the first, and also at a sacrifice

with respect to condition (a) by arranging the two circuits under alternate poles. It is not convenient to arrange the winding in alternate pairs, or triplets, of like slots, because there is normally only space available for connections to approximately six phase belts per pole, and such a winding would ordinarily result in nine or more belts per pole. Neither of the two possibilities mentioned is as flexible in design as desirable, since only certain combinations of slots and winding pitches can be used. By compromising between them, and using the split belt winding of Fig. 3, approximately 80 per cent of the slots can be made to carry in-phase, or nearly in-phase, currents, while yet like slots occur in groups, and considerable flexibility is retained. For these reasons, the split belt winding is preferred for nearly all cases.

In a double winding of the alternate slot type, the end windings are so closely interlinked that the end leakage fluxes may be assumed entirely mutual, without important error. With the split belt winding, approximately one-quarter of the end leakage is considered to be purely self inductive, and the rest mutual to the two circuits, while with an alternate pole winding nearly all the end leakage is self inductive. The slot reactance of each circuit of an alternate slot winding is entirely self inductive, but only about 80 per cent of the slot reactance of a split belt winding is self inductive, the remainder being mutual to the two circuits. An alternate pole, full pitch, winding has about three-quarters of its total slot reactance mutual; but if the winding is two-thirds pitch, the slot reactance is all self inductive, the proportions of self and mutual varying linearly with pitch between these extremes.

The zigzag leakage reactance varies in the same general way as the slot reactance, though the relations are more complicated in this case. Its small value, however, does not warrant a careful analysis here. The fundamental air gap flux, due to the armature reaction of either circuit, links each circuit equally, so that it is entirely mutual.

On this basis, the theory of the double winding generator is found to be the same as that of a symmetrical three-winding transformer, which has been treated by various writers,[1, 2] and its electrical performance may be predicted by means of one of the equivalent circuits of Fig. 4. The usual values of the individual elements of the reactance are indicated on the circuits in terms of the conventional values $X_s$, $X_z$, and $X_x$ of the slot, zigzag, and end leakage reactances of the complete winding, formulas for which have been given in a previous paper by one of the present authors.[3] There are so many possible winding arrangements, especially when fractional slots per pole per phase are used, that it is difficult to make any general rule for the division of the slot reactance into its mutual and self inductive parts. By counting the numbers of slots carrying through transfer currents, that are 0, 60, 120, and 180 deg. out of phase, respectively, in the upper and lower coil sides, and adding the corresponding elements of slot reactance of each kind, it is not difficult to find the correct values for any given case.

For transient conditions, the synchronous reactance must be replaced by the transient, or subtransient, reactance, depending on whether the conditions a half second or so after, or at the instant of, a disturbance are to be considered.

The circuit of Fig. 4 is not exactly correct, because in reality there is no physical connection between the two windings, and all the interchange of currents between them occurs by transformer action. The current in one winding is, therefore, greater than the other by an

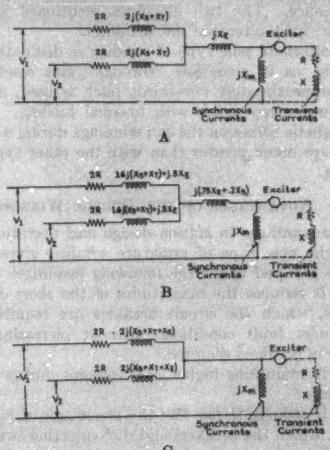


Fig. 4—Equivalent Circuits of Double-Winding Generators

A. For alternate slot winding
B. For split belt winding
C. For alternate pole 2/3 pitch winding

amount sufficient to magnetize their mutual reactance flux path, when power is transferred between windings. As this mutual reactance is large under steady state conditions (about eight times the reactance of either branch), but much smaller under transient conditions, the error due to neglecting the magnetizing current component is negligible in synchronous operation, but may be appreciable under transient conditions. In the latter case, however, it is on the safe side, as it causes the apparent through reactance to be slightly lower than the actual.

While tested values of reactance, at low currents, agree well with the values calculated in accordance with the above methods, the reactance decreases under high currents, due to saturation of the slot leakage flux

1. For references see Bibliography.

paths. There is negligible saturation when both windings carry equal and in-phase currents, since in that case the leakage paths have large areas and relatively short lengths of iron as compared with air. When the windings carry equal and opposite currents, however, as occurs in practise when current is transferred from one side of the machine to the other, the saturation may be very marked. It is, therefore, important to calculate its effects.

FIG. 5—ALTERNATE SLOT DOUBLE WINDING THROUGH LEAKAGE FLUX PATHS FOR SINGLE-PHASE LINE-TO-LINE SHORT CIRCUIT

Assuming equal incoming and outgoing transfer currents, the current distribution, and the corresponding slot leakage fluxes, on a single-phase line-to-line short circuit will appear as shown in Fig. 5, for the case of a slot 9 per pole, 8/9 pitch, alternate slot winding. With this type of winding, the leakage fluxes due to adjacent slots alternate in direction, so that the resultant effect is to make the total leakage flux pass through the root of every tooth. The four teeth in the center of the phase belt, numbers 1, 2, 8, 9, carry

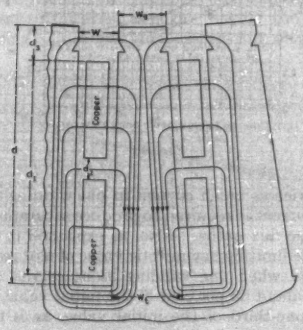


FIG. 6—DIAGRAM OF STATOR SLOT AND UNSATURATED FLUX LEAKAGE PATHS

maximum flux, those at one edge of the phase belt, numbers 3 and 4, carry, respectively, about 0.65 and 0.15 times as much, and those at the outer edge, numbers 6 and 7 carry, respectively, about 0.35 and 0.85 as much. These coefficients are based on normal slot proportions and take account of the fact that the leakage flux due to a lower coil side is about 7/3 as much as that due to an upper coil side. At ⅔ pitch, there will be only two teeth of the first type, one each of the other types, and two more of each of two intermediate types. Hence, the effect of short pitch is to reduce the amount of saturation and make it more gradual, without, however, affecting the point at which it first begins.

The actual magnitude of the flux density in the teeth of the first type, between slots carrying in-phase currents, is readily calculated from a knowledge of slot reactance theory,[8] as described in Appendix A.

The leakage flux paths in the unsaturated condition are shown in more detail in Fig. 6. As saturation of the tooth root is reached, the flux paths approximate to those in Fig. 8, under which condition the slot leakage reactance is approximately one-third as much as in the first case. As saturation continues still further, the teeth become saturated throughout their whole length, and the reactance approaches a final value, corresponding to paths entirely in air, which is about 15 per cent of the original value, but this final condition is never approached in practise.

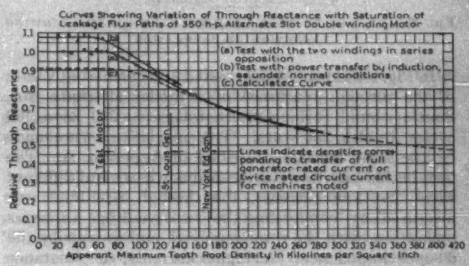


FIG. 7

## IV. TESTED AND CALCULATED VALUES OF REACTANCE

In Fig. 7 are shown test curves of the through reactance of a 350-hp., 25-cycle, 8-pole, 0.8-pitch, alternate slot, double wound motor, plotted as functions of the calculated maximum tooth density. Test (1) was made by connecting the two circuits of one phase in series opposition, with the rotor stationary, and applying a single-phase normal frequency voltage across them. R. m. s. values of current, voltage, and power were read, and the reactance so determined was plotted against the apparent maximum tooth density calculated by Equation (4) of Appendix A. Test (2) was made with one winding short circuited, and with the rotor at synchronous speed, by applying three-phase voltages to the other winding. In this case, the induced current was only about 0.9 of the impressed current, due to the magnetizing current component of the latter. The apparent primary reactance determined from this test was plotted against the density corresponding to the average of the two currents. The apparent secondary reactance, or primary reactive

voltage divided by secondary current is, of course, about 10 per cent larger. The calculated through reactance for this motor, determined by methods explained in Appendix A, is shown by curve *c* of Fig. 7. The tests confirm the saturation with increasing current, and the existence of an approximate limiting value of about 0.3 the initial, indicated by the calculations.

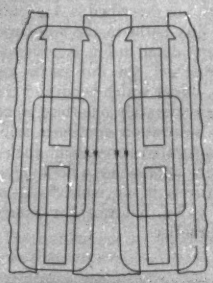

FIG. 8—DIAGRAM OF SLOT LEAKAGE FLUX AT THE LIMITING CONDITION OF SATURATION

In Fig. 9 there are shown tested and calculated values of the through reactance of a model alternate slot, double wound turbine alternator, rated 260 kv-a., 60 cycles, 4 poles, 250 volts. The calculations were made by the same method described in Appendix A. The tests in this case, however, were made in several different ways. At low currents, the through reactance was measured by connecting the two windings in series opposition, with the rotor removed, and measuring the 60-cycle impedance. At higher currents, the reactance

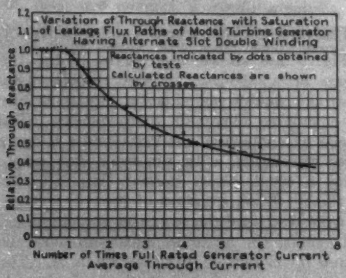


FIG. 9

was measured by operating the machine at no load at different voltages, short circuiting one of the windings, and taking oscillograms of the resulting currents and voltages. Tests were made both with the other winding opened and with the other winding connected to an infinite bus through varying amounts of reactance. The through reactance was calculated by dividing the average of the observed peak currents in the two windings into the observed peak voltage across the unshorted winding. The values so obtained agreed closely whatever point on the decrement curve of the short circuit current was taken and whatever the connection of the unshorted winding. To put the reactance values on a common base, however, it was necessary to plot them against half the algebraic difference of the currents in the two windings, since saturation of the leakage paths is produced only by the through current, and not by the in-phase components of the two winding currents.

In this case again, the tested and calculated values agree fairly well, although at very low currents the tested value of recatance is somewhat more than the calculated. This difference is ascribed to components of the zigzag leakage flux in the solid rotor, which saturate at very low currents.

As mentioned above, and as pointed out in the Ap-

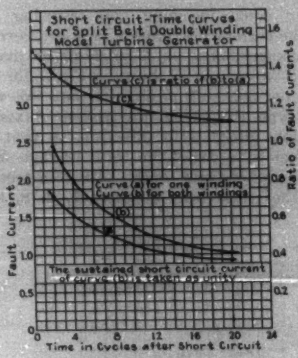


FIG. 10

pendix, twice as much current in one winding alone as through current is required to produce saturation of the slot leakage flux paths. Also, as explained in the Appendix, the limiting asymptotic value of slot reactance, approached when one winding alone carries current, should be about 63 per cent of the initial value, instead of about one-third of the initial value, as is the case when the currents in the two windings are equal and opposite. Tests were made to investigate this point, by short circuiting first one winding alone and then both windings of the model turbine generator, and comparing differences in the subtransient reactances obtained with the expected amount of additional slot reactance. The results were inconclusive, however, as the uncertainty of the test values of initial currents read from the oscillograms was too great. The subtransient reactance of any normal turbine generator decreased markedly with increase in the short circuit current, due to saturation of the rotor leakage flux

paths, so that the presence of a similar degree of saturation in the additional slot leakage reactance, when one winding of a double winding generator is short circuited, is not important. The tests showed, however, that the subtransient reactance of a single winding generator varies approximately in the ratios of 1.6 to 1.2 to 1.0, when the initial short circuit current has values of 1, 4, and 10 times normal, respectively.

So far, the test results and calculations have been confined to the alternate slot type of winding. For the split phase belt type of winding, the calculation of saturation effects is more complicated, since the flux leakage paths encircling the outer conductors of each half phase belt saturate earlier than those linking the inner conductors. In general, with a winding of approximately 5/6 pitch, the currents in the slots of adjacent half phase belts are approximately 30 deg. out of phase, so that when one winding current is a maximum the other is only 0.866 times its maximum value. Also, the slots adjacent to phase belts carrying in-phase currents in the top and bottom coil sides normally contain coil sides carrying currents out of phase by 60 deg. Hence, the total values of the currents in slots adjacent to phase belts carrying in-phase currents are normally only 0.866 times as great as the total slot currents within the phase belt. Thus, at the moment of maximum current in the phase belt carrying in-phase currents in the top and bottom coil sides, the currents in the adjacent slots are only three-quarters as great. It is thus apparent that normally 4/7 of the area of each end tooth is available for carrying leakage flux, instead of only 50 per cent of the area, as is the case for the alternate slot winding. Also, the slot leakage flux paths, which

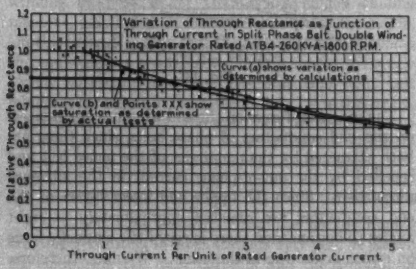


Fig. 11

pass through the end teeth of a half phase belt, cross all the intermediate slots, so that the ratio of length of iron path to length of air path is reduced by a factor equal to the number of slots in the half phase belt, as compared with the alternate slot winding.

Taking into account these factors, curve *a* of Fig. 11, of calculated through reactance against the through current for another model alternator with a split phase belt winding, was plotted. The test results shown in curve *b* agree with the calculated results to about the same degree of accuracy as was found for the alternate slot case of Fig. 9. The tests confirm the less amount of saturation for the split phase belt winding, as compared with the alternate slot winding, indicated by the calculations.

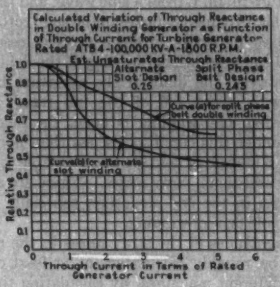


Fig. 12

In Fig. 10 are shown the results of short circuit tests on the split phase belt double winding model turbine generator. Curve *c* gives the ratio of the fault current when both windings are short circuited to that when one winding alone is shorted. It indicates that, disregarding the through current supplied by other machines, the initial fault current of a single circuit generator is roughly 1.5 times that of a double winding generator. The plotted points in Fig. 10 are the averages of the symmetrical r. m. s. currents read from oscillograms of three-phase short circuit tests taken at four different voltages, so each represents twelve observations. The actual current-time curves *a* and *b* for the different voltages varied considerably, due to saturation, but curve *c* was not noticeably affected.

Large alternators have relatively deeper slots and much higher current loadings than small machines, so that the effects of saturation become worse as the size of the machine increases. It is, therefore, unsafe to use the curves of Figs. 9 and 11 directly in practical calculations. Using the same methods as in calculating the curves of those figures, however, Fig. 12 has been prepared, which shows the expected variation of through reactance with through current for a 100,000 kv-a. generator, the upper curve representing the split belt winding, and the lower the alternate slot winding. In practise, it is to be expected that the through current on the most severe faults may be approximately three times the full generator output. The curves show that at this current the through reactance will saturate to about 0.75 of its initial value with the split belt winding, but to about 0.53 with the alternate slot winding.

## V. Effects of Unequal Loading of the Two Windings

It is important also to know how the operating characteristics of the machine vary when the two windings carry unequal currents, especially in respect to stray load losses and the magnetic forces on the end windings.

The irregular arrangement of the conductors in each winding by itself results in a considerable departure of the armature m. m. f. from a sine wave, and this in turn produces high-frequency fluxes in the solid rotor surface. These fluxes naturally produce surface losses in the rotor, and cause additional heating of the field winding. Since, however, the limit of the armature heating is reached with about 0.6 of the full rated generator current, when one winding is open, the field current required under this condition is less than normal, and so there is a margin of field heating available to be taken up by the additional stray losses. There are also additional losses in the end structure, especially with the alternate pole type of winding.

The magnitudes of the stray losses in the rotor surface can be roughly calculated, or at least compared between different machines, by calculating the r. m. s. value of all the harmonics of the m. m. f. wave. This has been done in the case of four separate machines, on which test values of the stray load losses obtained with one winding carrying current and the other open circuited are available. The test values are shown in Fig. 13, from which several interesting conclusions can be drawn.

Tests on the alternate slot wound 350-hp. synchronous motor showed no appreciably greater loss with one than with both windings for the same total current, though curve *a* of Fig. 13 shows an appreciable increase for the similarly wound model generator. This indication that the same type of dissymmetry causes greater losses with the solid steel rotor construction than with the laminated pole and copper squirrel cage construction, is confirmed by comparing curves *d* and *c* for alternate pole wound machines of these types. The sums of the squares of the calculated r. m. s., m. m. f. harmonics for the alternate slot, split phase belt, and alternate pole windings tested are equal to 0.013, 0.034, and 0.092 respectively. The increased loss of the split belt over the alternate slot winding obtained by comparing curve *b* with *a* is small, but the extra loss with alternate poles shown by curve *d* is far more than justified by the amount of its harmonics, thus confirming the conclusion that there is a large loss in the end structure in the latter case.

In the alternate pole winding, when one winding alone carries current, the end leakage flux is bunched in alternate pole pitches, creating not only local concentration of flux in the armature shields and flanges, but also eddy currents in the rotor retaining rings. The machine for which curve *d* of Fig. 13 was obtained had magnetic retaining rings and armature flanges, so that the results are pessimistic, but in any case it would be difficult to keep the end losses down with this type of winding.

The load loss of the split belt winding, with one winding carrying half the full output, is somewhat less than the normal stray load loss of the machine, so that under this condition of operation the total heating of the machine should be less at all points than when full output is carried equally divided between the windings. This conclusion has been confirmed by heat runs on the model generators, which have shown differences of only 3 or 4 deg. cent. in field temperature rise, when half output is carried on one winding, as compared with carrying one-quarter the output on each winding.

In practise, when the two windings carry unequal currents, the additional stray load loss will always be less than the values shown, so that there is no question of the suitability of the split belt type of winding in this respect.

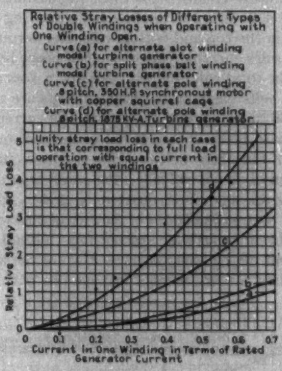


Fig. 13

The magnetic forces on the end windings are greatest on the end conductors of phase belts, since these are both attracted by the remainder of the phase belt and repelled by the out-of-phase current in the adjacent phase belt. Since the upper and lower layers of the end conductors are directed approximately at right angles to one another, there is very little magnetic force on either layer, due to the other. We may, therefore, estimate the relative forces with different kinds of windings by considering only one layer of the winding.

In general, the force on any conductor is proportional to the product of the current in that conductor by the intensity of the magnetic field at its center, due to all the other currents in the vicinity. It is a simple matter to add up the flux densities due to the neighboring conductors considered separately, and for a given current the force will be proportional to this sum. This point of view shows that the force per inch of conductor length is not affected by the winding pitch, although, of

course, the total force is greater the longer the length of end connection.

For the case of a 6 slot per pole per phase winding, the relative end winding forces in the four types of winding are compared in the following table. The left hand column gives the relative force, assuming a given current flows in one circuit, the other circuit being open. The right hand column gives the force when the same current flows in one winding and out the other. In both cases, the force with a standard single circuit winding carrying the same current is taken as unity. Three-phase currents are considered in all cases.

| Type of winding | Relative end winding magnetic forces | |
|---|---|---|
| | One winding only loaded | Windings carrying equal and opposite currents |
| Normal single circuit | 1.0 | .... |
| Same but carrying 0.7 current | 0.5 | 0.5 |
| Alternate poles | 0.95 | 1.25 |
| Alternate slots | 0.4 | 0.25 |
| Split belt | 0.6 | 1.1 |

Since the maximum through current may be safely taken as less than three-quarters of the maximum single winding current, the left hand column may be taken as an approximately correct indication of the relative forces to be met with in practise. It may be expected in practise that any double winding machine with a fault on one winding only will deliver about 0.7 as much instantaneous current as the corresponding single winding machine, so the proper comparison of maximum forces is made by taking the current in the double winding machine as 0.7 that in the single winding machine, as shown in the second row of the table. On this basis, it is seen that the relative forces to which the end windings are subjected in practise for the single circuit, alternate pole, alternate slot, and split belt windings are about in the ratios of 1 to 1.9 to 0.8 to 1.2, respectively. Clearly, the split belt winding is satisfactory from this point of view, while the alternate pole winding is definitely inferior to the other types.

## VI. Applications of Double Winding Generators

The advantages resulting from the use of double winding generators in large stations may best be shown by comparing the fault currents and the amount of protective equipment required with the usual systems of bus connections, using single and double winding generators. Five arrangements will be considered, as illustrated in Figs. 14 to 18 inclusive:

1. The standard ring bus with bus reactors (Fig. 14)
2. A ring bus with generator reactors, utilized also as bus reactors, with single winding generators (Fig. 15)
3. A ring bus with double winding generators, using alternate slot arrangement of windings (Fig. 16)

3A. A ring bus with double winding generators, using split belt arrangement of windings (Fig. 16)

4. A star bus with single winding generators (Fig. 17)
5. A star bus with double winding generators using split belt arrangement of windings (Fig. 18)

All the system diagrams shown are simplified by showing only a single bus, although a double bus arrangement is standard in the United States. The characteristics of the five systems, using 150,000-kv-a., 13,800-volt generators are compared in the accompanying tabulation, the per unit subtransient reactance of the two windings in parallel being taken as 0.113, of which 0.043 is mutual for the alternate slot case. In making the calculations for this comparison, the double bus was used throughout, and it was assumed in all cases that there were no external power ties to the system, although it is usual for several stations to be interconnected. This assumption makes the advantages shown for the double winding generator appear less than they really are, as any additional current supplied to a fault by the connected stations increases the importance of any means of limiting the current supplied by the station itself. Generator reactors, or their equivalent, have been used in all cases, in order to secure the advantages of a higher bus voltage and lower fault currents during faults in the generators themselves, or their connecting cables, and to reduce the currents supplied by the generators to external faults.

The important characteristics which affect the choice of generator and bus connections are the magnitudes of the fault currents, and the numbers and sizes of circuit breakers and reactors required to permit flexible operation and give adequate protection. Accordingly, these quantities have been calculated for each of the five systems, and are shown in the table. The first five lines of the table were compiled on the basis of unlimited ampere capacity of the circuit breakers. The 6300-ampere breakers required in three of the systems are larger than desirable, however, as most operating companies prefer to use 4000-ampere breakers, or smaller, if possible, and as the manufacturers prefer to limit the sizes to their present developed lines. The largest breakers so far built by the General Electric Company are, for the double tank per phase type, 6000 amperes, and for the single tank per phase type, 5000 amperes. The limit of interrupting duty for oil circuit breakers at present is about 2,000,000 kv-a. While larger breakers can be developed, their cost will be high, and so it is of considerable economic importance to keep the present standard sizes.

For this reason, the remainder of the table has been compiled on the basis of 4000-ampere breakers being used throughout. This considerably reduces the maximum kv-a. that can be transferred along the bus for Cases I and II, as indicated by the eighth line of the table, unless additional breakers operated in parallel are employed, as shown by lines 6 and 7. In discussing the characteristics shown for the different systems, each case will be considered separately.

*Case I.* The standard double ring bus of Fig. 14 superseded the straight bus in 1909, and is still used by most companies. Its original adoption was due to its limitation of the fault currents, and the increased system reliability it afforded. It is still considered a standard because of the flexibility it allows in transferring loads from one bus section to another. However, with the advent of generator of such large size as the 150,000 kv-a. machines considered here, the same difficulty of excessive fault currents appeared with the ring bus and its sectionalizing reactors as originally appeared with the solid bus. The table shows that the instantaneous symmetrical kv-a. delivered to a fault are nearly 2,500,000. Also, with the increasing demand for these large generating units of very high efficiency, the normal full load currents to be carried by the breakers, are becoming excessive; in the case shown 6300 amperes are required. A third important disadvantage of this system is that the generator on a faulted bus section has no synchronizing power with the rest of the system. The voltages on adjacent bus sections drop to much lower values than with the other systems, so that a bus section disturbance is really a system disturbance as well.

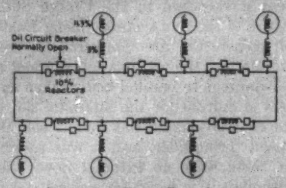


Fig. 14—Standard Ring Bus System. Case I

*Case II.* This (Fig. 15) is a modification of Case I, in which the generator is connected to the bus section between two reactors, thus making each reactor serve both as a bus and as a generator reactor. The energy of the unit is divided so that the normal voltage drop in the reactors, and the normal current carried by the breakers, are small. If it is desired to transfer the full capacity of a generator along the bus, however, the limitation of excessive current ratings, 6300 amperes for the breakers, is met with again. This system is really a half way step between systems 1 and 3.

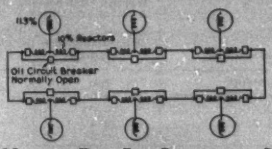


Fig. 15—Modified Ring Bus System with Standard Generators. Case II

*Case III and III-A.* In this system (Fig. 16) double winding generators are used, with each winding connected to a different bus section, so that the only power transfer along the bus is due to the transformer action

TABULATION FOR A THREE-PHASE FAULT ON THE BUS IN TYPES OF STATIONS AS SHOWN IN CASES I TO V, FIGS. 14 TO 18 OF THE COMPLETE PAPER

All Breakers and Reactors as Listed per Generator are for Double Bus Generators Rated ATB-4-150,000 Kv-a.-1800-13,800-Volts 0.85 Power Factor-6280 Amperes

| | Case I Fig. 14 | Case II Fig. 15 | Case III Fig. 16 | Case IIIA Fig. 16 | Case IV Fig. 17 | Case V Fig. 18 |
|---|---|---|---|---|---|---|
| Limit of kv-a. transfer along bus | 150,000 | 75,000 | 15,000 | 15,000 | 150,000 | 75,000 |
| No. of breakers per generator | 8 | 6 | 6 | 6 | 6 | 10 |
| Ampere rating of oil circuit breakers | 6,300 | 6,300 | 4,000 | 4,000 | 6,300 | 4,000 |
| No. of reactors required | 3 | 2 | 2 | 2 | 2 | 4 |
| Rating of reactors | 6,300 | 6,300 | 4,000 | 4,000 | 6,300 | 4,000 |
| Preferred arrangement, limiting all breakers and reactors to 4000-ampere rating | | | | | | |
| No. of breakers required | 16 | 12 | 6 | 6 | 12 | 10 |
| No. of reactors required | 6 | 4 | 2 | 2 | 4 | 4 |
| Limit of kv-a. transfer along bus | 95,000 | 20,000 | 15,000 | 15,000 | | |
| No. of breakers per generator | 10 | 6 | 6 | 6 | | |
| Ampere rating of breakers | 4,000 | 4,000 | 4,000 | 4,000 | | |
| No. of reactors required | 4 | 2 | 2 | 2 | | |
| Ampere rating of reactors | 4,000 | 4,000 | 4,000 | 4,000 | | |
| Instantaneous symmetrical kv-a. to fault | 2,470,000 | 1,860,000 | 1,370,000 | 1,216,000 | 1,900,000 | 1,200,000 |
| Sustained kv-a. to fault | 965,000 | 780,000 | 580,000 | 580,000 | 830,000 | 660,000 |
| Instantaneous r. m. s. symmetrical amperes | 103,000 | 69,500 | 57,000 | 51,000 | 79,500 | 50,000 |
| Sustained fault amperes | 41,200 | 32,500 | 24,300 | 23,500 | 34,800 | 37,700 |
| Percentage instantaneous voltage on faulted bus | 0 | 0 | 0 | 0 | 0 | 0 |
| Percentage instantaneous voltage on bus next to fault | 51 | 71 | 89 | 92 | 78 | 88 |
| Percentage instantaneous voltage on 2nd bus from fault | 74 | 91 | 99 | 99 | | |
| Percentage instantaneous voltage on 3rd bus from fault | 80 | 96 | 99 | 99 | | |
| Percentage instantaneous voltage on synchronizing bus | | | | | 65 | 80 |
| Percentage sustained voltage on faulted bus | 0 | 0 | 0 | 0 | 0 | 0 |
| Percentage sustained voltage on bus next to fault | 25 | 40 | 54 | 58 | 48 | 60 |
| Percentage sustained voltage on 2nd bus from fault | 39 | 59 | 79 | 81 | | |
| Percentage sustained voltage on 3rd bus from fault | 43 | 65 | 86 | 87 | | |
| Percentage sustained voltage on synchronizing bus | | | | | 40 | 54 |
| Instantaneous sym. kv-a. to synchronizing bus fault | | | | | 3,420,000 | 3,420,000 |
| Sustained kv-a. to synchronizing bus fault | | | | | 1,200,000 | 1,200,000 |
| Instantaneous r. m. s. sym. amps. to synchronizing bus fault | | | | | 143,000 | 143,000 |
| Sustained r. m. s. sym. amps. to synchronizing bus fault | | | | | 50,000 | 50,000 |

between the two windings of a single generator. Generator reactors of 10 per cent are used in series with each winding, but as these only carry normal currents of half the full generator rating, the drop in these reactors is only 5 per cent at full load. In calculating the fault current, the slot reactances of the two windings were reduced to the equivalent value of reactance as obtained from the saturation curves of the generators

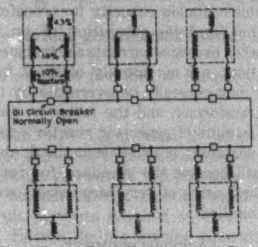


Fig. 16—New Ring Bus System with Double-Winding Generators. Case III

with the corresponding current which would flow, in accordance with the discussion in Part III of the paper, but the favorable effect of reduced saturation of the subtransient reactance of the rotor due to the lessened fault currents of the double winding generator was not taken into account.

The slot reactance of the generators next to the fault in Case III was reduced to 57 per cent of its original value for the first instant of fault and for the sustained conditions a saturation factor of 70 per cent was used.

In Case III-A, generators with split belt windings, the slot leakage reactance was reduced to 85 per cent of the original unsaturated value for the instantaneous fault conditions and to 90 per cent for the sustained fault conditions on the generators next to the fault. Saturation did not affect the remainder of the units as the fault current was of such a small magnitude that the units did not saturate.

The obvious disadvantage of this system is the limitation of the kv-a. transfer along the bus. However, as the current in the two windings of a fully loaded generator can safely be divided in the ratio 45:55, there is actually 30,000 kv-a., or 20 per cent, extra capacity available on each bus section, so long as the adjacent bus sections are not overloaded. With the generators operating at their most efficient load, about 75 per cent of rating, either winding can be loaded to 60 per cent of the full generator capacity. Thus, the available transfer power is still considerable, and is fully comparable with that of Case II, when 4000-ampere breakers are used.

The equipment required for this system is much less expensive than for the first two systems, even when they are limited to 4000-ampere breakers and their kv-a. transfer capacity is correspondingly reduced. As compared with Case I only six breakers and two reactors of 4000-ampere capacity are required per generator for a double bus system, instead of 10 breakers and 4 reactors of the same size. As compared with Case II, the same number of breakers and reactors of the same current carrying capacity are required, but the interrupting duty on each breaker is much less for this third case than for either of the first two cases. In the cases which have been calculated, the breaker duty is reduced to about half that required for Case I, or three-quarters of that for Case II. This means that in many cases a double winding generator of the largest size can be installed in an old station, without changing the switching equipment, whereas the use of a single winding generator of equivalent size would require the complete rebuilding of the system and the installation of larger breakers.

Besides this advantage of reduced cost of equipment, this double winding generator system results in greatly increased system reliability. For, even though the voltage on a faulted bus falls to zero during a three-phase short circuit, the connected generators remain in step with the rest of the system, since there is sufficient synchronizing power between the other windings of the generator directly affected, and the rest of the system, to maintain synchronism. This has been verified by factory tests, taken on two small model double winding generators without reactors, which correspond to a more severe condition than normal. Under the same fault conditions for Case I, the generator on the faulted bus section goes out of synchronism, and the adjacent bus section voltages fall to such low values that much

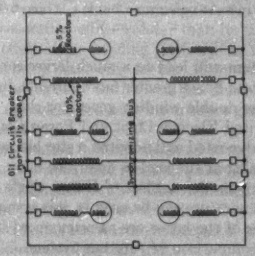


Fig. 17—Star Bus System with Standard Generators. Case IV

load is dropped, and the whole system is seriously affected.

The voltages maintained on the bus section near the fault are much higher in this case than for either of the first two cases. Comparing Cases III, III-A, and I, the adjacent bus sections have, respectively, instantaneous voltages of 89, 92, and 51, and the third section from the fault has 99.5 instead of 80 per cent instan-

taneous voltage. The sustained voltages, which are not reached if the breakers open properly, are equally in favor of the double winding generator system. Thus, this system effectively limits fault disturbances to one bus section.

*Cases IV and V.* At first sight, there does not appear to be much advantage of the double winding generator (Fig. 18) over the standard generator (Fig. 17), when applied to a star bus system, since the numbers and continuous ratings of breakers and reactors required are nearly the same in the two cases. However, the table shows that the interrupting duty of the breakers in Case V is about one-third less than in Case IV, which results in a material saving.

Also, the system stability is greater in the former case, as higher bus voltages are maintained, under fault conditions. In either case, a fault on the synchronizing bus would cause the system to fall apart, so that there is no choice between them in this respect. When one unit is taken out of service, the necessary rearrangement

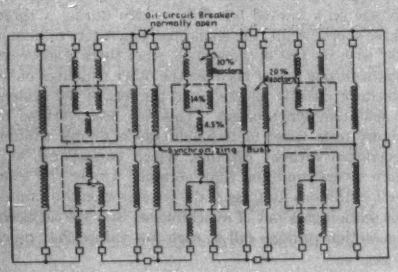


FIG. 18—STAR BUS SYSTEM WITH DOUBLE-WINDING GENERATORS. CASE V

of the system will lead to a much larger concentration of power, and hence greater fault currents, in the single than in the double winding generator case.

The United Electric Light and Power Company has recently advocated and adopted a star bus system with synchronizing at the load as described in an A. I. E. E. symposium on the subject.[4] Either single or double winding generators can be used in this system, but the advantages of the latter are as pronounced in this case as in the comparison of ring bus systems. It will not be necessary to discuss this aspect of the subject here, because the matter was fully presented by Mr. E. E. Chilberg in his discussion of the papers of the symposium just mentioned.

## VII. CONCLUSIONS AND ACKNOWLEDGMENTS

Consideration of the data presented in the paper leads to these conclusions.

1. The double winding generator can conveniently be applied in large power stations, using any of the usual systems of bus conections, with resulting large advantages in reduced cost of equipment, lower fault currents, and more effective isolation of faults.

2. The best type of double winding for ordinary purposes is the split belt design, shown in Fig. 3. When ample generator reactor capacity is installed, however, the alternate slot type of winding may be preferable, due to its slightly lower stray losses, and less end winding magnetic forces with unequal loadings.

3. The principal limitations of the double winding generator, due to its low capacity for transfer of power along the bus, and the saturation of its "through" reactance, when excessive currents are transferred under fault conditions, are not usually of great importance. The former may generally be overcome by means of a balancing transformer, and the latter by the use of a reasonable amount of generator reactor capacity.

4. It is, therefore, probable that the double winding generator will become the standard for future power stations, where units of very large size (over 100,000 kv-a.) are installed.

### ACKNOWLEDGMENT

The authors acknowledge the material assistance rendered them by Mr. T. F. Barton, whose original thought led to the developments described, Messrs. R. H. Park and D. H. Harms, who contributed many helpful suggestions, and Mr. A. H. Wing, who managed most of the tests.

## Appendix A

### CALCULATION OF SATURATION FACTORS FOR SLOT REACTANCE

Considering the case of equal and opposite currents in the two circuits of an alternate slot winding:

Let the total r. m. s. current per slot be $I$ amperes, and the slot and tooth dimensions in inches be as shown in Fig. 6. Then, the maximum leakage flux crossing the slot due to the upper coil side, per inch of axial length, is:

$$\phi_1 = \frac{3.19\, I\, \sqrt{2}}{2\, W} \left( d_2 + \frac{d_1 - d_2}{4} \right) \text{lines,} \qquad (1)$$

and that due to the lower coil side is:

$$\phi_2 = \frac{3.19\, I\, \sqrt{2}}{2\, W} \left( d_2 + \frac{3\,(d_1 - d_2)}{4} + d_2) \right) \text{lines.} \qquad (2)$$

Their sum is:

$$\phi = \frac{3.19\, I\, \sqrt{2}}{2\, W} (2\, d_2 + d_1) \text{ lines.} \qquad (3)$$

Since the flux passing through the tooth root is twice that crossing the slot, the flux density at the bottom of the tooth is:

$$B = \frac{3.19\, I\, \sqrt{2}\, (2\, d_2 + d_1)}{W\, W_t} \text{ lines per sq. in.} \qquad (4)$$

Normally the width of tooth at the gap is about 1.2 $W$, the ratio of $2\,d_2 + d_1$ to $d$ is about 1.1, and the ratio of $W_s$ to $W$ is about 1.7, so that (4) may be simply expressed in terms of the normal r. m. s. amperes per inch of periphery, $\Delta$, the ratio of actual to normal circuit current, $K$, and the ratio, $d/W$, of slot depth to width, by:

$$B = 7.0\,K\,\Delta\,\frac{d}{W}\text{, approximately, lines per sq. in.} \qquad (5)$$

For large turbine generators of normal design, $\Delta$ is about 1600 amperes per inch of periphery, and $\frac{d}{W}$ about 7.

As saturation will begin when $B$ exceeds 100,000 Equation (5) indicates that the incidence of saturation in large turbine generators will normally be at about 1.2 times normal circuit current transferred. The actual circuit currents required on the St. Louis and New York Edison double winding generators to produce a maximum density of 100,000 lines per sq. in. at the tooth roots in the center of the phase belt are 1.51 and 1.16 times normal, respectively.

Since the current loading, $\Delta$, was only 780 for the test motor of Fig. 7, it required 3.0 times normal circuit current to produce 100,000 lines per sq. in. maximum density. The calculated through reactance, without saturation, for the motor was only 0.91 of its test value, of which 0.84 was slot and 0.07 zigzag reactance. The extra amount was probably due to end leakage not mutual to the two windings, as it only corresponds to about 0.2 of the total end leakage.

When saturation occurs with increasing current, the through reactance does not diminish toward zero, but approaches a new limit corresponding approximately to the leakage when the teeth are cut off at the roots and the core is removed. In this limiting case, the leakage paths are symmetrical at the top and bottom, as shown in Fig. 8, so that the through slot reactance is reduced approximately as the ratio

$$\frac{2\left(\frac{d_2}{4} + \frac{d_1}{24}\right)}{d_2 + \frac{d_1}{3}} = 0.35\text{, approximately.} \qquad (6)$$

Taking the excess of test above calculated through reactance as non-saturating, due to its air paths, the calculated limiting value of reactance for this particular case is (0.304) (0.91) + 0.09 = 0.37 of its initial value, a value which agrees fairly well with the indicated limit of the test curve. At extreme value of current, the teeth would saturate still further, and the reactance would approach the limit of a complete air path, about ⅓ of this first limit, but such a final limit is probably of no practical interest.

These results indicate that it is necessary to determine rather carefully the saturation factor to be applied to the calculated through reactance of a large generator, so that the amount of reactance actually available for current limitation may be found. It would not be sufficient without examination to use the curve of Fig. 7 for a large machine, since the ratio of lengths of flux path in iron and in air will vary with the size of machine. Before attempting to predict the effective reactances of a large generator, a reactance curve will be calculated to match the test curve of Fig. 7. The method employed in this calculation involves the following assumptions:

1. The effect of saturation is considered to be the inter-position of a series reluctance in the path of the total slot leakage flux, without altering in any way the relative distribution of flux across the slot depth. Actually, the concentration of the iron reluctance at the tooth root will decrease the relatively ineffective portions of the flux crossing the lower part of the slot more than the rest, so that the assumption makes the calculated effect of saturation greater than the true effect.

2. The total ampere turns consumed in the iron corresponding to the m. m. f. of one slot are taken equal to those for the full tooth root density existing over the length of one tooth. Actually, the flux traverses two teeth with varying density, but calculations indicate that the integrated ampere turns over the whole path are about equal to those given by this assumption.

3. The saturation factor for the actual alternating current is taken to be the same as that for a direct current equal to the maximum a-c. value. Actually, the change of wave shape due to reactance will make the effective saturation correspond to a somewhat lower direct current, so that this assumption should make the calculated saturation effect greater than its true value.

4. The effect of the winding pitch will be neglected, calculations being made only for the center teeth of the phase belts, which have the highest flux densities. This also makes the calculated saturation effect greater than the true amount.

5. The saturation factor is assumed to apply only to the excess of the calculated reactance above its limiting value given by Equation (6). The calculated reactance for the test motor is thus determined to be (0.28 + 0.63 $K_s$) times its unsaturated test value, where $K_s$ is the saturation factor, less than unity.

On this basis, the effect of saturation is to increase the reluctance $R$, of the slot leakage flux path for a maximum a-c. flux density, $B$, from the value given by Equation (3):

$$R = \frac{2\,W}{3.19\,(2\,d_2 + d_1)} \qquad (7)$$

to

$$R = \frac{2\,W}{3.19\,(2\,d_2 + d_1)} + \frac{2\,(d_1 + d_2)\,F}{B\,W_s} \qquad (8)$$

where $F$ represents the magnetizing ampere turns per inch of tooth for a d-c. flux density of $B$ lines per sq. in.

The reactance reduction factor is there given by the ratio of (7) to (8), or is

$$K_s = \frac{1}{\dfrac{1 + 3.19\,(d_s + d_1)\,(2\,d_s + d_1)\,F}{W\,W_s\,B}} \qquad (9)$$

For the particular case of the test motor this becomes:

$$K_s = \frac{1}{1 + \dfrac{70\,F}{B}} \qquad (10)$$

The ratio of the reactance determined from (10) by the method outlined under assumption (5) to the unsaturated test value is shown by curve $c$ on Fig. 7. The tests indicate somewhat greater saturation than expected, but they also show an excess of the unsaturated test above the calculated value of reactance, so that good agreement is obtained over most of the range.

A further point to check in this connection is the saturation of the generator subtransient reactance when a short circuit occurs on one winding only. In this case, the flux density at the tooth roots for the same circuit current is only half what it is when the two windings carry equal and opposite currents, since the flux crossing each slot now has the full area of one tooth available. On this account, the saturation curve for the slot leakage reactance of a single circuit should be similar to that of Fig. 7 for the through slot reactance, except for a doubling of the horizontal scale.

However, the limiting value approached by the slot reactance of one circuit as saturation increases is about 0.63 times its unsaturated value, instead of only 0.35 as in the other case. This follows because the reluctance of the path across an empty slot, which the leakage flux takes when the tooth roots are saturated, is represented by

$$\frac{W}{3.19\,(d_1 + d_s)} \qquad (11)$$

whereas the reluctance of the path across a slot carrying current is from (7):

$$\frac{2\,W}{3.19\,(2\,d_s + d_1)} \qquad (12)$$

The reciprocal of the sum of (11) and (12) is approximately 0.63 times the reciprocal of (12) above, for normal slot proportions. This indicates that the saturation factor given by (10) should be applied to only 37 per cent of the single winding slot reactance.

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## Discussion

**C. M. Laffoon:** There are several points in connection with these different types of double windings which should be given further consideration. In connection with the first, or alternate-slot type of winding, it is gratifying to see that the authors now recognize the fact that the through reactance coefficient is materially reduced by saturation under faulty conditions. This effect of saturation was discovered by L. A. Kilgore last January, and its effect on the through reactance was discussed in a paper presented by the writer at the April, 1929, meeting of the Empire Gas and Electric Association at Buffalo. This question was discussed again by the writer in a paper presented before the meeting of the Association of the Edison Electric Illuminating Companies at Philadelphia on May 17, 1929. These effects were again discussed in an article on "Developments in Generators and Systems as They Affect System Stability," by Messrs. Kilgore and Powers, *Electric Jl.*, October 1929.

In the case of the split-phase type of winding in which the two windings are in alternate groups of slots, there is no general disagreement with the conclusions given in the paper from a qualitative standpoint. The advantages of *this type* of double winding were also mentioned by the writer in the above mentioned paper, which was presented at the meeting of the Association of Edison Electric Illuminating Companies in May, 1929. A turbine generator having a double winding of this type was built in 1915 by the company with which the writer is connected. This machine, which was rated at 3200 kv-a., 178 volts, 6-phase, 60-cycle, 2-pole, 3600-rev. per min., had two independent windings, and each independent winding supplied power to a separate rotary converter. The windings of each pole were arranged in six groups and connected to give two independent circuits. The voltages of the two windings were necessarily out of phase, due to the fact that it was a two-pole machine and each winding was required to be in two parallels on account of the voltage magnitude. However, it was well known at that time that the voltage could have been brought in phase if the voltage had been such as to require the series connection, instead of the parallel connection.

In the case of the third type of winding in which the phase groups of alternate poles are connected in series, it is necessary to use a coil throw of approximately 2/3 to 5/6 pitch, in order to obtain high through reactance. With one winding only, in operation, the estimated values of the 2nd and 4th order harmonics in the stator demagnetizing m. m. f. are relatively large and indicate high additional losses when operating under unbalanced load conditions. The authors have eliminated this type of winding on the basis of excessive losses under unbalanced loads and high stresses on the end turns under short-circuit conditions. The writer does not feel that this conclusion is justified from the actual test results which have been obtained on a 7500 kv-a., 6600-volt, 2-pole, 60-cycle, 3600-rev. per min. generator. This generator was provided with two windings of this type, and the

coil throw was 62.5 per cent. The following tests were made on this machine.

(a) Temperature tests when carrying different values of unbalanced loads.

(b) Locked saturation tests.

(c) Losses under sustained short-circuit conditions.

(d) Instantaneous short-circuit tests.

In obtaining the thermal performance of the machine when operating under unbalanced load conditions, a series of temperature tests was made with 50 per cent of the machine's rated load on one winding and 50, 37.5, 25, 12½, and 0 per cent loads respectively on the other winding. The results from these tests are shown in Fig. 1. In no case does the temperature of either the field or armature windings exceed that reached when operating at full rating, with equal loads on both windings. Another test run was made with 60 per cent of the machine's rated load on one winding and 40 per cent on the other. In this case, the field temperature rise was 8 deg. cent. higher, and the stator temperature rise 15 deg. cent. higher than when carrying full rating with balanced loads. If the load division were 55 and 45

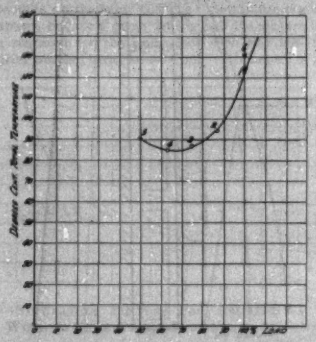


Fig. 1—Temperature Tests with Unbalanced Zero Power-Factor Loads on Double Winding Generator with Alternate Poles in Series

1. 50 per cent load on *A* winding—50 per cent on *B* winding
2. 50 per cent load on *A* winding—37.5 per cent on *B* winding
3. 50 per cent load on *A* winding—25 per cent on *B* winding
4. 50 per cent load on *A* winding—12.5 per cent on *B* winding
5. 50 per cent load on *A* winding—0.0 per cent on *B* winding
6. 60 per cent load winding—40 per cent on *B* winding

per cent respectively, it is estimated from these test results that the increase in the temperature rise for both the stator and rotor would not exceed 5 deg. cent. It is also estimated that this machine should deliver 60 per cent of its rating with one winding only in operation, and not exceed the guaranteed temperature on the rotor and no higher temperature rise than with any other type of winding for the stator.

It is agreed that the stresses on the end turns are greater with this type of winding under single-winding short-circuit conditions, because the width of the phase group is greater. However, when the short-circuit tests were made on the 7500-kv-a. machine at full voltage, no observable distortion occurred in the end windings, and it is not anticipated that any unsurmountable difficulties would be encountered in bracing the end turns of windings of this type. Fig. 2 shows the currents delivered by this machine under short-circuit conditions. The curve indicated by *A* is for the machine with both windings in parallel; the curve indicated by *B* is for one winding only; and the curve indicated by *C* is for a short circuit on one winding and the power maintained on the other winding. The currents are expressed in terms of symmetrical r. m. s. values.

These test curves show that there is low coupling between the windings under transient conditions, and there is a high through reactance not appreciably affected by saturation.

The through reactance coefficients obtained from locked tests checked very closely with the calculated values under unsaturated and saturated conditions, and confirmed the results obtained from instantaneous short-circuit tests.

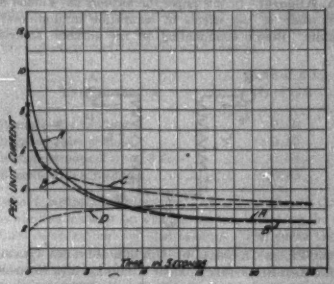


Fig. 2—Sudden Short Circuit Test on 7500-Kv-a. 3600-Rev. per Min.; Double Winding Generator. Alternate Poles in Series

*A*. Both windings in parallel
*B*. One winding only
*C*. One winding short circuited and power maintained on the other
*D*. Winding connected to power supply

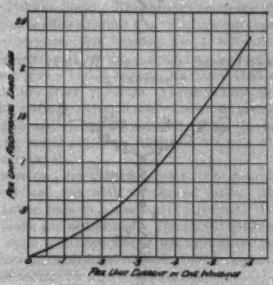


Fig. 3—Sustained Short Circuit Losses

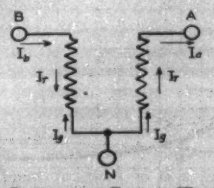
On 7500-kv-a., 3600-rev. per min., double winding generator. Alternate pole in series

The additional losses when operating under sustained short-circuit conditions with one winding only are shown in Fig. 3. It is true that the additional losses are relatively high for large loads on one winding only, but with the machine operating with a maximum allowable unbalanced load of approximately 10 per cent, the additional load losses would not be excessive. In view of the fact that an appreciable part of the additional losses occurs in the end zones, it is felt that they are susceptible to reduction by using different kinds of material in the construction of these parts. In order to evaluate properly the importance of the additional losses, it is necessary to treat each generating station and system on the basis of its own load characteristics and possible unbalanced loads on individual generator windings.

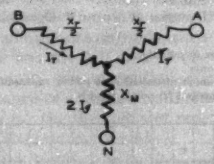
The general conclusions based on analytical and test results indicate that the alternate-pole type of double winding is a very satisfactory winding and should be given consideration for application in which double winding generators are required.

The authors of the paper conclude that the alternate-slot and split-phase types of windings are the only practical windings for commercial applications. My conclusion is that the split-phase, or alternate groups of slots, and the alternate-pole type of double windings are the most desirable types of double windings for commercial applications.

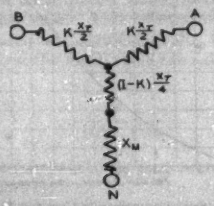
**L. A. Kilgore:** In this paper the authors have made an extensive study of the effects of saturation in double-winding generators. Before commenting on the authors' analysis the writer would like to present briefly what is believed to be a more accurate analysis.




Single-Phase Diagram of Double Winding Generator Showing Assumed Directions of Currents and Components of Currents




Equivalent Circuit of Double Winding Generator—Unsaturated




Equivalent Circuit of Double Winding Generator Showing Effects of Saturation

Fig. 4

Under fault conditions the currents in the two windings are in opposite directions. It is very convenient to divide the actual currents into two components, one flowing through the machine and the other out of the machine. The through component of current will be equal and opposite in the two windings and the other component currents will be equal and in the same direction in the two windings. Defined in this manner the through component is the average of the two winding currents assumed to be flowing in opposite directions, and the other component is half the difference.

The reactance to the flow of through current is reduced by saturation because the currents flow in opposite directions in adjacent slots or groups of slots, thus magnetizing the teeth radially. The reactance to the other component of current is practically unaffected by saturation, since the currents flow as in a normal single winding machine.

The effects of saturation may be taken into account in short-circuit calculations by changing the equivalent circuit as shown in Fig. 4 herewith. As the authors have stated the effect is to reduce the through reactance by a factor $K$. However, the authors have not mentioned another effect which can not be neglected. Saturation increases the mutual reactance due to the reluctance of the saturated tooth in the path of the leakage flux; and for complete saturation the reactance is nearly all mutual. This may be accounted for by adding $\frac{1-K}{4}$ times the through reactance to the common leg.

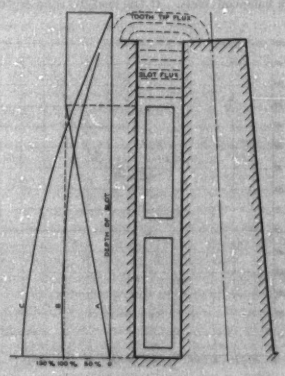



Fig. 5—Slot and Tooth Diagram Showing Radial Densities of Slot Flux in Tooth

*A.* Density of flux crossing slot
*B.* Density of slot flux giving radial in the tooth
*C.* Slot flux in tooth section

The saturation factor $K$ may be calculated from the machine constants and the saturation curve of the stator iron. For short-circuit calculations it is convenient to plot $K$ as a function of through current, which we have defined as the average of the currents flowing in opposite directions in the two windings.

*Calculation of Saturation Factor.* The method used in calculating the saturation factor $K$ was similar to that given in the paper, except that other appreciable factors such as air paths in parallel with the iron, and wave distortion were taken into account.

However, the writer disagrees on one significant factor. The authors have considered a limiting value of reactance about 0.35 the unsaturated value, and have applied the saturation factor $K$, to the remaining 0.65. This limiting value was based on the assumption that the effect of saturation is as if the teeth are cut off at the roots and the core removed. The authors then calculated the limiting value considering only the reluctance of the slot, and assuming infinite permeability for the tooth itself.

Fig. 5 shows the actual flux going radially in the tooth of a large 4-pole double-winding machine. It will be seen that the tooth taper offsets the increase in flux going radially so that the densities are nearly uniform through the bottom half of the

tooth. For the case worked out the average density for bottom half is 98.5 per cent of that at the base when saturation begins. For higher currents the density at the center would undoubtedly be higher than at the base.

It is apparent then that for 2- or 4-pole machines at least there is no limiting value of reactance determined by cutting-off the teeth at the base. The real limiting value can be approximated by assuming the effect equivalent to cutting out the bottom half of the tooth. This would give a limiting value about 0.035 instead of 0.35.

The curves of Fig. 6 show saturation factors for a 150,000-kv-a., 4-pole turbine generator connected in the several ways which have been described. The values for the alternate-slot type were calculated as has been outlined above. The points marked with a circle are test points from sudden short circuit on a model generator with an alternate-slot type of double winding. These tests indicate definitely that the degree of saturation is about that calculated, and that there is no apparent limiting value of about 0.35.

*Alternate Groups of Slots.* A curve of saturation factors for alternate pairs of slots may be constructed from the curve for alternate slots on the same machine. Saturation begins at the same current, but for a given density half the ampere turns per slot are required for the iron, since each slot now furnishes magnetizing ampere turns for only one tooth instead of two.

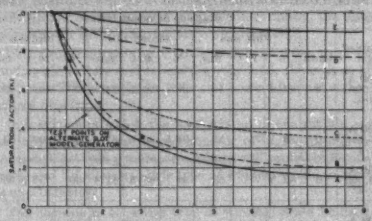



FIG. 6—SATURATION FACTORS FOR 150,000-KV-A. DOUBLE WINDING GENERATOR. FOUR POLES—60 SLOTS

Versus through current for:
*A.* Alternate slots
*B.* Alternate pairs of slots
*C.* Alternate groups of 2 and 3
*D.* Alternate poles
*E.* $K$ *vs.* total generator current for single winding machine

The through current times $K$, ($I_T K$), is proportional to the slot flux and consequently tooth density; and $(1 - K) I_T$ is proportional to magnetizing ampere-turns for the teeth. Then for the same densities

$$K' I_T' = K I_T$$

or

$$I_T' = \frac{K I_T}{K'}$$

$$(1 - K') I_T' = \frac{(1 - K)}{2} I_T$$

or

$$K' = \frac{2K}{1 + K}$$

For alternate groups of slots (more than two) only the end slots of a group supply magnetizing ampere turns to the teeth between the groups. The ampere-turns available across the middle slots are greater than the end slots by the amount of the magnetizing ampere-turns required for the iron. This causes an increased interlinkage with the middle slots. A saturation-factor curve may be constructed from the curve for alternate slots in the same way as for alternate pairs of slots but taking into account the increased interlinkage with the middle slots. Since only the flux of the end slots is affected appreciably by saturation, a portion of the reactance is unaffected. The slots per group less two is a measure of the part unaffected. It may readily be seen that with three or more slots per group considerable improvement in saturation factor can be obtained.

Taking half the conductors of a phase belt as one group gives the winding which the authors have termed the split-phase belt winding. Using each phase belt as a group of conductors gives the maximum slots per group a minimum saturation effect. This type has been termed alternate poles in series.

In order to compare the several types of windings consider the values of $K$ from the curve of the 150,000-kv-a. machine with a through current of 2.5 times rated current.

| Type of winding | Value of $K$ for $I_T = 2.5$ |
|---|---|
| Alternate-slot winding | 0.40 |
| Alternate pairs of slots | 0.43 |
| Alternate groups of 2 and 3 slots | 0.54 |
| Alternate poles in series | 0.85 |

The above saturation factors might be compared with that for a single-winding machine on a similar system by taking the value at 4 times rated current for the machine. The curve shows a value of 0.96 for a winding pitch of exactly 2/3; however, at any other fractional pitch this factor would be nearer unity.

From this comparison it is evident that a large reduction of through reactance can be expected on an alternate-slot winding with 15 slots per pole. It might be well to note that saturation effects occur at lower current values for machines with a larger number of slots per pole. Alternate pairs of slots show little improvement. Alternate groups of slots show considerable gain. Alternate poles in series show relatively little reduction in reactance.

*Alternate Poles in Series.* The through reactance of the alternate-pole type is affected much less by saturation than the other types. Furthermore, this winding has a self-inductive belt leakage and only part of the end-winding leakage is mutual. These factors give a higher through reactance than can be obtained with the other windings. Consequently this type of winding with the same external reactance would give least short-circuit current and system disturbance, or on the basis of the same current would require a minimum amount of generator reactors or none at all.

The authors consider this type distinctly undesirable because of additional load loss with unbalanced loads. Mr. Laffoon has shown actual tests on a machine of this type. It is possible that these losses can be reduced. The choice between alternate poles with some additional loss or the split-phase belt winding with the necessary additional reactors depends upon the average amount of unbalance for a given application.

**R. E. Powers:** The outstanding purpose of providing alternators with double windings is to secure a combination of generators, supplying a given load, that will have low reactance to the normal flow of power current, but will have high reactance to the flow of fault current. The double-winding generators so far considered have been affected by the saturation of the slot leakage reactance path, due to the flow of through current, and consequently their effectiveness has been reduced.

To minimize the detrimental action of saturation within the unit itself, and to provide the necessary limiting reactance, heavy generator reactors have been utilized in the individual generators leads. The addition of generator reactors inherently reduces the fault current that can flow, consequently minimizing the saturation of the unit, the combination of generator reactors and alternator inherent reactance being sufficient to reduce the short-circuit currents to the required value.

The ideal type of double-winding generator, from a short-

circuit standpoint, is one in which the "through" reactance is high and in which saturation of the leakage path is not present to any marked degree, making the use of external reactors unnecessary, the inherent reactance of the unit alone limiting the current to the required value.

Mr. Kilgore has shown that the effects of saturation are considerably less in a double-winding generator designed so as to secure the individual windings by connecting alternate poles in series than in any of the other types so far considered at the value of through currents encountered in actual practise. The saturation factor for a given 150,000-kv-a. double-winding alternator with the winding arranged in alternate slots is 0.39, whereas with the windings arranged on alternate poles the saturation factor was increased to 0.85 when carrying 2.5 per unit through current.

The comparison of saturation factors for the two windings was made on the basis that the same stator frame was used and that new windings, the best suitable for each type, were used. It might be pointed out that some variation in the ratio between saturation factors may be expected as the generator design proportions are changed.

Fig. 7 herewith shows a comparison of results secured from short-circuit studies on various types of double-winding generators when connected in a ring bus, or synchronized through the load network. The double-winding alternate-pole generator has an unsaturated through sub-transient reactance of 53.2 per cent, and an over-all sub-transient reactance of 15 per cent. The alternate slot and groups of slots type unit had a subtransient through reactance of 50 per cent and an over-all subtransient reactance of 15 per cent.

The comparison of the performance of double-winding units of various types, when connected in a ring bus, was made on the basis that equal initial currents were to be secured. Saturation of each unit was taken into consideration and faults were taken from full load. In order to secure equal initial currents, external reactors of 9.6 and 6.2 per cent respectively must be added in series with the alternate-slot and grouped-slot double-winding generators, and 15 per cent to the standard generators, in order to equal the performance of the unit with alternate poles in series. The instantaneous symmetrical current was limited to 55,000 amperes. However, it will be noticed that the sustained value of short-circuit current varies from 24,700 amperes to 29,000 amperes, depending upon the type of unit used. The combination using alternate poles in series to secure the double winding has the highest instantaneous and short-time voltage on all buses. The sustained voltage on the first and second bus is also highest for the alternate-pole type. However, the sustained voltage on the third bus is highest for the unit that has the lowest saturation factor. The unit with the lowest saturation factor requires the greatest values of external reactance and consequently the circuits which are unaffected by saturation have a greater total reactance, resulting in a different distribution of currents and voltages.

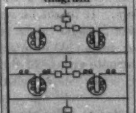
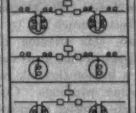
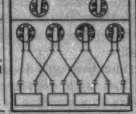
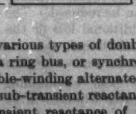
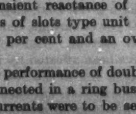
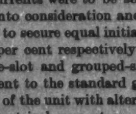
The results of analysis on standard units using combination generator and bus reactors, are shown on line 4.

In all of the analyses shown on line 1—5, back feed was not taken into consideration.

In the last two sections of the chart are shown the results of analyses made on a system using alternate-pole double-winding units synchronized through the load network. In case I the reactance between the internal voltage of the unit under consideration and internal voltage of all other units in parallel was set at 60 per cent; case II at 40 per cent.

FIG. 7

THREE-PHASE FAULT ON BUS SECTION. SHORT CIRCUIT VALUES BASED ON 7-150,000-KV-A., 13,800-VOLT GENERATORS
SHORT CIRCUITS APPLIED UNDER FULL LOAD CONDITIONS

| System and constants | Single line diagram | Short circuit currents and kv-a. | | | Voltage on adjacent busses | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | First bus | | | Second bus | | | Third bus | | |
| | | Inst. symmetrical | One-tenth second | Sustained value | Fault | 0 | 0.1 | Sus. | 0 | 0.1 | Sus. | 0 | 0.1 | Sus. |
| Double-winding generators. Alternate poles in series. No reactors |  | 55.000 A. 1,310,000 Kv-a. | 43.000 A. 1,030,000 Kv-a. | 24.700 A. 590,000 Kv-a. | 0 | 91.4 | 80 | 59 | 99 | 96.5 | 84 | 100 | 100 | 93.3 |
| Double-winding generators. Alternate groups of slots. 6.2 per cent reactors |  | 55.000 A. 1,310,000 Kv-a. | 41.600 A. 995,000 Kv-a. | 25.000 A. 597,000 Kv-a. | 0 | 86 | 75 | 57 | 98.5 | 96.5 | 81 | 100 | 100 | 94.7 |
| Double-winding generators. Alternate slots. 9.25 per cent reactors |  | 55.000 A. 1,310,000 Kv-a. | 42.100 A. 1,010,000 Kv-a. | 25.600 A. 615,000 Kv-a. | 0 | 82.5 | 71 | 53 | 99 | 95.5 | 81.4 | 100 | 99.5 | 95.5 |
| Standard machines. 15 per cent reactors |  | 55.000 A. 1,310,000 Kv-a. | 47.600 A. 1,140,000 Kv-a. | 29.000 A. 694,000 Kv-a. | 0 | 70 | 67.3 | 50.5 | 92 | 86 | 68.5 | 96.5 | 92.6 | 83 |
| Double-winding generators. Alternate slots. No reactors |  | 97.000 A. 2,320,000 Kv-a. | | | 0 | 54 | | | 91.2 | | | 100 | | |
| Double-winding generators. Alternate poles in series. Synchronized at load. Reactance from internal voltage of one machine to all others in parallel. 40 per cent = Case I |  | 33,400 A. 795,000 Kv-a. | 28,400 A. 676,000 Kv-a. | 17,400 A. 405,000 Kv-a. | 0 | Faulted gen. bus | | | Unfaulted gen. bus | | | All other busses | | |
| | | | | | | 0 | 0 | 0 | 91 | 71 | 47.5 | 96 | 93.5 | 88 |
| 60 per cent = Case II | | 41,200 A. 981,000 Kv-a. | 36,600 A. 871,000 Kv-a. | 24,650 A. 585,000 Kv-a. | 0 | 0 | 0 | 0 | 87 | 66 | 46 | 93.7 | 90 | 81 |

In both cases, the instantaneous symmetrical fault current was decreased from the base current of 55,000 amperes used in comparison in items 1—5 to 33,400 amperes and 41,200 amperes respectively. The chart shows sustained values of voltage on all other buses of 88 per cent and 81 per cent, which would appear to be low in comparison with the systems shown in lines 1—5 of the table. In the system synchronized at the load, the system comprises the reactance between units and the results shown on the table take back-feed into consideration and represent the actual values of current and voltage incident to a given fault, whereas back-feed is not taken into consideration in the comparison in lines 1—5; its effect would be to lower the voltage on adjacent buses, the reduction depending upon the amount of external interlacing between the bus sections.

A study of Fig. 7 indicates clearly that the alternate-pole type double-winding generator has considerable advantage from a short-circuit standpoint. Generators of 150,000 kv-a. can be connected into a bus system, either ring bus or synchronized at the load, and standard oil circuit breakers in the class already de-

veloped, can be used without external generator or bus reactors which undoubtedly will result in switch house simplification and a reduction in cost.

The authors have shown that the alternate pole in series type of double winding unit has increased stray losses with unbalance in load current carried by the individual windings. The test results shown by the authors in Fig. 13, and by Mr. Laffoon in a slide are secured by loading one winding only, the other being unloaded. During normal operation, it is not expected that a unit will be run with 60 per cent of the generator output on one winding, and no load on the other. I believe it would be fair to assume that the maximum unbalance between windings would be 20 to 30 per cent with an average unbalance considerably below that figure, on the order of 10 to 15 per cent. Under such operating conditions, the additional stray losses will not be excessive. In units utilizing external generator reactors, the kilowatt loss in the reactors is no small item. The loss in the 9.2 per cent reactor and 6.2 per cent reactor used in the alternate slot and grouped slot units is approximately 70 and 50 kw. respectively. The loss in external generator reactors is of a constant nature, that is, it is present at all times irrespective of unbalance, whereas the increased stray losses are a function of unbalance.

Undoubtedly, the double-winding unit will find its greatest application in metropolitan areas where considerable energy is transmitted at generator voltage. Consequently, numerous feeder positions will be available. With a flexible bus arrangement similar to that used in many stations today, the output of the generator circuits can be fairly well balanced.

With proper interlacing of the feeders in a system using double-winding generators synchronized at the load, the output of each winding will inherently be balanced and additional stray losses will not be a factor.

In a system in which the total output of the station is taken out through a relatively small number of high-capacity feeders, unbalance between generator windings will probably be of a high order, and the alternate-pole type of winding would undoubtedly be unsatisfactory.

The decision as to which type of winding could be used for a given application will depend upon the general system layout, bus arrangement selected, probability of continued unbalance between windings, capitalization of losses, and valuation of space within the switch house.

The curves shown in Fig. 10 of the paper bring out a very important point, and that is that under short-circuit conditions, the double-winding generator delivers less current to the fault with consequent smaller reaction of the armature on the field. Under such conditions, the internal voltage of the generator decays at a much slower rate.

In Fig. 2 of Mr. Laffoon's discussion are shown terminal short circuits on a standard generator and a double-winding generator in which one winding only is shorted, the other winding being connected to an infinite bus. Under such conditions, the net armature demagnetization is a function of the difference of the currents in the two windings and consequently considerably reduced over what it would be in a standard unit when both windings were shorted simultaneously.

The double-winding generator gives in effect the results of a single-winding unit with a very high short-circuit ratio and opens up the possibility of designing large double-winding generators with short-circuit ratios on the order of 0.85 to 0.9, and securing the same rate of decay of internal voltage as is secured in the present designed unit with higher short-circuit ratios.

**D. D. Chase:** Mr. Powers presents a chart showing the fault conditions where double-winding generators of the three types (alternate-slot, split-phase-belt, and alternate-pole) were used. The generator with the alternate-pole winding had 2/3 pitch, which gives the maximum self inductance between the two windings, and hence the highest possible through reactance, due to the fact that no bars of different windings are ever in the same slot. However, if about 80 per cent pitch is used, as is desirable and usual for large 1800-rev. per min. machines, the two windings will have nearly half their conductors in the same slots, thus cutting the initial through reactance to about 60 per cent of that for the alternate-slot cast. The lower initial reactance in this case, therefore, cancels the gain from reduced saturation, and leaves the alternate-pole winding with the net disadvantage of inferior performance under unequal loading.

When the number of slots per pole is reduced, the three types of winding become more nearly alike in their characteristics, and it is evident that when there is only one slot per pole per phase, the alternate-slot and alternate-pole windings become identical, and the split-belt type becomes impossible. In general, the fewer slots there are per pole, the higher the inherent reactance is, so that the type to be used is a matter of convenience, rather than importance, when there are less than 4 slots per pole per phase. However, we do not agree with Mr. Laffoon's statement that the split-belt type is limited to cases where the pitch is between 2/3 and 5/6.

The question was raised whether it was necessary to have generators which would operate with unbalanced loads. Most turbines are designed so that the most efficient point of operation is near 2/3 load, and it is, therefore, a very common practice to operate at about this load condition. Of course, there are some base-load stations where the turbines are operated at full capacity, because the station is much more efficient than any of the others, and the best over-all efficiency is thereby secured. However, the base-load station of today becomes the peak-load station of tomorrow, and hence it is soon very apt to be operating at reduced loads. If it is possible to design a generator so that one winding can be loaded to 60 per cent of its rating, when the other winding is unloaded, it is very desirable to do so, as it simplifies operation considerably by eliminating the balancing of loads on the various bus sections.

There are many power companies who operate all of their stations at approximately ¾ load, as all have approximately the same efficiency. In this way, the turbines are run at the best operating point, the equipment is not stressed to full capacity, and there is a reserve supply of power in every station to take care of sudden increase of load or loss of other power supply.

In this connection, the recent load division of the 160,000-kw., 25-cycle, double-winding generator is of interest. This unit has been in operation only a short time and has been operated already with a load of 90,000 kw. on one winding and 30,000 kw. on the other. The unit has also been carrying 80,000 kw. load on one winding with no load on the other.

**E. H. Freiburghouse:** It was not until 1927, when T. F. Barton pointed out their advantages, that the use of double-winding generators for limiting fault currents and maintaining system stability was considered. Just what type of winding should be used for this purpose is largely a matter of judgment. Originally, we did not give the question of saturation of the leakage paths as much consideration as it deserved, believing that the use of adequate reactors and the retention of the best characteristics for unequally loaded operation were desirable. Lately, the tendencies to still further concentrate large amounts of power on each bus and to limit reactor capacity have led us to recommend the split-belt winding in place of the alternate-slot winding, thus securing less saturation at the expense of slightly inferior performance with unequal loading.

We do not recommend the alternate-pole type of winding, for the reasons that it is distinctly inferior to the other types in respect to stray losses, heating, and stresses, when unequally loaded.

We know that the subtransient reactance of a single-winding generator, as well as that of a double-winding machine, varies greatly in inverse relation to the fault current. From a study of the many short-circuit tests we have made upon standard machines we feel quite certain that saturation of the subtransient reactance is much greater in most cases than that indicated by Curve *E*, Fig. 6, of Mr. Kilgore's discussion.

Mr. Kilgore's ideas on the calculation of saturation are sound and well expressed, and it is interesting to see the results he has reached from a somewhat different standpoint. It should be noted that Curve *C* of his Fig. 6, corresponding to alternate groups of 2 and 3 slots per belt, shows considerably less saturation than Curve *B* for alternate pairs, thus confirming the conclusion that for the usual split-belt winding of a large machine with about 4 slots per belt the saturation is about as shown in our Fig. 12.

Another reason for desiring to have a generator which can operate with unbalanced load is shown by the present Cahokia Station layout. When it is advisable to take a bus out of service for cleaning, the other winding of the generator can continue to carry load to its capacity. If the generator could not operate under these conditions, the unit would have to be shut down, as there is no way of transferring the winding from the bus which is to be cleaned to another bus.

# A 40,000-Kw. Variable-Ratio Frequency Converter Installation

BY E. S. BUNDY,[1] A. VAN NIEKERK,[2] and W. H. RODGERS[3]

Associate, A. I. E. E. Associate, A. I. E. E. Associate A. I. E. E.

*Synopsis.—Part I of this paper describes the installation of two 20,000-kw., adjustable load, variable-ratio, frequency converters interconnecting the 25-cycle and the 60-cycle systems of the Niagara, Lockport and Ontario Power Company at Lockport Substation about twenty miles from Niagara Falls and Buffalo, N. Y. It also explains the function of the various machines, points out the more important features of the control, and relates a few interesting incidents in the past eighteen months of operation.*

*Part II describes and explains the characteristics of such a converter and, more intimately, the operation and design of the component apparatus, using rather generally known and understood analogies, comparisons, and simple physical conceptions without any mathematical analyses or difficult theoretical treatment.*

* * * * *

## Part I

THE Niagara, Lockport and Ontario Power Company was organized in 1906 for transmitting and distributing power in the western and central parts of New York State. The power was generated and transmitted at 25 cycles. Some of the larger customers were distributing companies and municipalities having 60-cycle distribution systems, and in some cases 60-cycle generating equipment. As a result of the difference in frequency between the transmitted power and the distribution systems, several installations of frequency converters were made, each with reserve capacity for emergency use.

In addition to several existing synchronous-synchronous frequency converters, it was decided in 1924 to install two 6000-kw. variable ratio converters at the eastern end of the 25-cycle system, making possible interconnections with the 60-cycle systems of the Northern New York Utilities Co. and Adirondack Power Co. and at the same time providing 60-cycle power for the Syracuse Lighting Company whose frequency converters were loaded nearly to capacity.

The two frequency converters were installed at Altmar, N. Y., where a 110-kv. connection was made to the Northern New York Utilities System and a double circuit 110-kv. line was constructed to Syracuse, N. Y. where connections were made to the Syracuse Lighting Co. and the Adirondack Power Co. systems.

In 1925, a third 6000-kw. variable-ratio converter was installed at Jamestown, N. Y., in order to provide a means of interconnecting the 25-cycle system with the 60-cycle system of the Penn Public Service Corporation.

In 1927, in order to consolidate the 60-cycle sections of the system and to supply the additional requirement of 60-cycle power to those customers distributing at this frequency, 60-cycle, 110-kv. circuits were provided connecting the eastern and western ends of the system. At the same time two 20,000-kw. variable-ratio frequency converters were ordered for installation at Lockport, which is about in the center of both the 25- and 60-cycle systems.

The two 20,000-kw. converters have now been in service for about eighteen months, serving as the main interconnection between the 25- and 60-cycle systems.

The 25-cycle power system has an installed generating capacity of about 1,000,000 kv-a., of which the Niagara Falls Power Co., the Buffalo General Electric Co., and the Hydro-Electric Power Commission of Ontario system are parts. The 60-cycle power system has an installed generating capacity of about 600,000 kv-a., of which the Niagara, Lockport and Ontario Power Co., the Northern N. Y. Utilities Co., the Mohawk-Hudson Power Corp., and the New England Power Co. systems are parts.

The load on these 20,000-kw. sets is inherently adjustable independently of the generating stations and can be maintained constant at any desired load regardless of variations in the frequencies of the two interconnected power systems, provided these variations do not exceed the range for which the set has been designed, *i. e.*, from 98 per cent to 101 per cent of the nominal 25:60 frequency ratio.

Within this frequency ratio range, the converters are completely reversible and can transmit their rating of 20,000 kw. in either direction.

The main synchronous machine and the main induction machine of each frequency converter are capable of operating as a synchronous and an asynchronous condenser respectively, at a capacity of 20,000 kv-a. zero power factor (over-excited), but not simultaneously. When operating as a condenser, the induction machine is asynchronously excited through its rotor by the regulating machines.

This part of the paper is intended to describe the equipment as installed and to review some of the outstanding events during its operation. It is believed such a description will be of interest inasmuch as these equipments constitute a major advance in interconnection apparatus from considerations of both type and

1. Niagara, Lockport & Ontario Power Company, Buffalo, N. Y.

2. Designing Power Engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

3. Central Station General Engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

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29-154

capacity. The design of the equipment is somewhat unique and the capacity of each set is between three and four times greater than that of any previously installed frequency converter of similar type.

Each 20,000-kw. converter consists of the following machines:

MAIN SET (all machines direct and rigidly connected):

One 24-pole synchronous machine, rated 25,000 kv-a., 0.8 power factor (over-excited), 20,000 kw., 12,000 volts, 1200 amperes, three-phase,

FIG. 1—TWO 20,000-KW. VARIABLE-RATIO FREQUENCY CONVERTERS

The two direct connected units in the foreground are those of the double unit regulating machine. The third machine is the main induction machine and in the background is the main synchronous machine. In the left foreground are the accelerating resistors

60 cycles, 300 rev. per min. without exceeding observable temperature rises of 60 deg. cent. on the stator (armature) and 80 deg. cent. on the rotor (field) as measured by embedded detectors and the change in resistance respectively.

One 10-pole wound rotor induction machine, rated 23,000-kv-a., 0.95 power factor (over-excited) 23,000 hp. 12,000 volts, 1110 amperes, three-phase, 25 cycles, 300 rev. per min., without exceeding observable temperature rises of 60 deg. cent. on both stator (primary) and rotor (secondary) as measured by embedded detectors and thermometers respectively.

One overhung shunt wound d-c. generator, for exciting the field of the 25,000 kv-a. synchronous machine, rated 165 kw., 250 volts, 660 amperes, 300 rev. per min.

One double unit three-phase a-c. commutator machine, for exciting the secondary (rotor) of the 23,000 kv-a. induction machine, the two units connected in series and each rated 1925 amperes, three-phase, 375 kv-a., 112.5 volts, 0.5 cycles.

AUXILIARY SYNCHRONOUS EXCITER SET (Machines direct connected):

One synchronous exciter, for exciting the rotor of the 750-kv-a. double unit a-c. commutator machine rated 350 kv-a., 130 volts, 900 amperes, three-phase, (6 leads) 25 cycles, 750 rev. per min.

One synchronous driving motor, rated 80 hp., 1.0 power factor, 440 volts, 87 amperes, three-phase, 25 cycles, 750 rev. per min.

One d-c. generator, for exciting the fields of the synchronous exciter and driving motor of this set, rated 17.5 kw., 115 volts, 150 amperes, 750 rev. per min.

Fig. 1 is a view showing the two adjustable-load, variable-ratio frequency converters as installed. Fig. 2 is an elevation drawing of one of the main sets showing the physical arrangement of the machines and their foundations. Fig. 3 is a diagram indicating the mechanical and electrical interconnection of the apparatus comprising a set. The captions accompanying the individual figures are explanatory.

The stator winding of the 25,000-kv-a. synchronous machine provides the sole connection of the converter set to the nominal 60-cycle power system. Due to the inherent "non-slip" characteristic of synchronous machines, its rotor and therefore the entire rigidly coupled rotating part of the main set operate in exact synchronism with the actual frequency of the nominal 60-cycle system. In other words, the speed of the main set which includes the rotor of the main induction machine is solely determined by the actual frequency of the power system energizing the synchronous machine stator and is independent of the frequency of the power system energizing the induction machine stator.

The stator winding of the 23,000-kv-a. induction

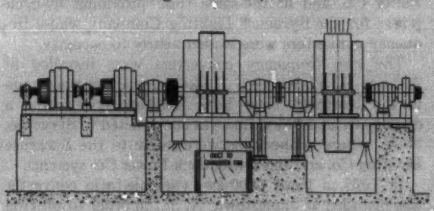

FIG. 2—AN ELEVATION DRAWING OF A MAIN SET

To the left are the two units of the regulating machine, then the main induction machine, the main synchronous machine, and to the right the d-c. exciter for the main synchronous machine

machine is connected to the nominal 25-cycle power system and its stator flux rotates in synchronism with the frequency of this power system. The non-synchronous, "shunt" speed-torque characteristics of an induction machine allows "slip" between its stator flux and rotor speed. Consequently this induction machine is the part of the frequency converter that provides the "loose" coupling between the two power systems so as to accommodate the variations in frequency or departures from the nominal 25:60 frequency ratio.

The double unit regulating machine and the auxiliary synchronous exciter set constitute the load adjusting equipment for the converter set. These machines change the speed-torque characteristic of the wound rotor induction machine.

The regulating machine is the means whereby three-

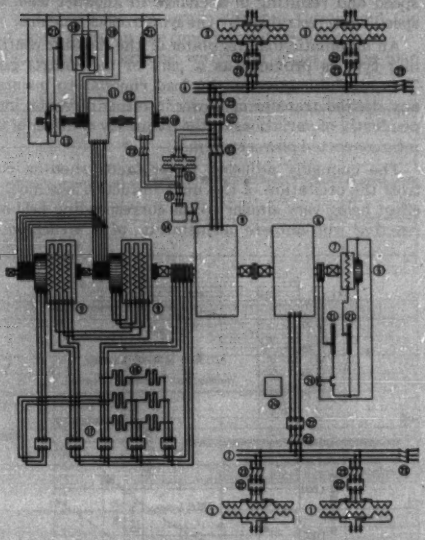

FIG. 3—CONNECTION DIAGRAM OF VARIABLE-RATIO FREQUENCY CONVERTER

A fundamental diagram of the set is shown in Fig. 7

1 Transformer: 12,000-kv-a., 110/12-kv., 60 cycle
2 60-cycle bus.
3 Transformer: 12,000-kv-a., 63.6/12-kv., 25-cycle
4 25 cycle bus
5 Main unit: 300 rev. per min.
6 25,000 kv-a., 60-cycle synchronous machine
7 165-kw., d-c. exciter
8 23,000-kv-a., 25-cycle induction machine
9 375-kv-a., regulating machine unit
10 Auxiliary unit: 750 rev. per min.
11 350-kv-a., 25 cycle synchronous exciter
12 80-hp., 25-cycle synchronous motor
13 17.5-kw., d-c. exciter
14 60-hp., 25-cycle induction motor (exhauster fan)
15 Transformer: 3 × 50-kv-a., 12/0.44-kv., 25-cycle
16 Starting resistors
17 Oil circuit breakers for starting
18 Load rheostat
19 Power factor rheostat
20 Automatic load regulator
21 Field rheostat
22 Oil circuit breaker
23 Disconnect switch
24 Field circuit breaker

phase, alternating voltages at slip frequency and of adjustable magnitude and phase relationship are induced in the rotor circuit of the main induction machine, thereby raising or lowering the "shunt" speed-torque characteristic as desired.

The synchronous exciter of the auxiliary set excites both units of the regulating machine and is the medium controlling the voltages induced by them. This synchronous exciter is essentially a three-phase, 25-cycle synchronous generator except that it has two field windings, one controlling the load component of the induced voltage and the other, the power factor component. In the "load field" is a motor operated potentiometer type rheostat providing reversible excitation, and in the "power factor field" is an ordinary motor operated rheostat. By manipulation of the excitation of this synchronous exciter, load and power factor control of the 23,000 kv-a. induction machine is obtained. These two simple and reliable rheostats are the sole controlling devices.

The design of these load adjusting machines will be described in Part II of this paper.

The main set consists of five machines with five rotors rigidly connected together and running at a nominal speed of 300 rev. per min., the actual speed being determined by the actual frequency applied to the stator of the main synchronous machine. This rotating part is supported in six pedestal bearings as indicated in Fig. 2. One structural steel bed-plate supports the frames of the main machines and four pedestal bearings; a separate structural bed-plate supports the frames of the two regulating units and two pedestal bearings. The operation of the set has been completely successful with this mechanical arrangement.

Space and bedplate accommodations have been provided for the axial shift of all machine frames so as to facilitate uncovering the individual rotors in case air-gap repairs should be needed.

Both ends of each of the three separate rotor phases of the main induction machine are brought out to individual collector rings. The locked rotor secondary voltage per phase is 4080 volts and the current at rated load is 1925 amperes per phase.

All machines are self-ventilated except the 23,000-kv-a. induction machine. Because of the small air-gap economically inherent in an induction machine and the lack of any appreciable fan effect of the smooth drum rotor, the ventilation of this machine is provided by a separate turbo-conoidal exhauster fan having a capacity of 84,000 cu. ft. of air per minute at a static pressure of 2½ in. of water. This fan is driven by a 60-hp., 725-rev. per min., squirrel-cage induction motor; is located in a ventilating chamber in the basement connected to the lower discharge chimney of the main induction machine; and discharges the warm air through a screened opening in the station wall.

The regulating machine was built in two units in order to keep the design, particularly that of the commutator, within conservative and reliable limits. Results are more than gratifying. The commutation of these units is black under all conditions. After eighteen months of operation with only normal atten-

tion, the commutators are in excellent condition and the brushes are brightly polished over their entire face. The brush life promises to be two or three years at least.

The 80-hp., 750-rev. per min., synchronous motor driving the auxiliary exciter set and the 60-hp., 4 -pole, squirrel-cage motor driving the exhauster fan are both supplied with 440-volt, three-phase, 25-cycle power through auxiliary step-down transformers, which are connected directly to the stator leads of the main induction machine. Both motors are started at rated voltage simultaneously with the energizing of the induction machine stator.

In starting the converter, the main induction machine is used as a wound rotor induction motor with secondary accelerating resistors in each of the three separate rotor phases. The acceleration is in three steps accomplished automatically under the control of a motor driven drum type relay. Full speed is reached in less than 90 seconds and the maximum inrush is about 10,000 kv-a.

The converter cannot be started unless the two regulating machine units are disconnected from the rotor circuit of the large induction machine; the second and third accelerating breakers are open; the two rheostats controlling the excitation of the synchronous exciter are in the minimum excitation position; and the motor driven accelerating relay is in the starting position. These things being all correct, starting of the converter is initiated by merely turning one control switch. This closes the first accelerating breaker, which is automatically followed by the closing of the main breaker in the primary leads of the main induction machine, and the starting of the motor driven accelerating relay. The ventilating fan and the auxiliary exciter set are brought up to speed at the same time that the main induction machine stator is energized. After a period of about 35 seconds, the motor driven relay closes the second accelerating breaker and 30 seconds later the third accelerating breaker which short circuits the rotor of the main induction machine. About 20 seconds later, by which time the main set is completely accelerated, the motor driven relay closes the two breakers connecting the regulating machine units to the rotor circuit of the main induction machine provided the auxiliary exciter set is up to synchronous speed. As soon as both breakers connecting the regulating machine to the rotor of the main induction machine have closed, the three accelerating breakers open, leaving the collector rings of the induction machine connected to the regulating machine units only. This entire sequence is automatically and positively provided and fully insured by interlocking.

After the foregoing has been accomplished the main synchronous machine may be manually synchronized with the nominal 60-cycle bus and connected to it. Synchronizing is done in the normal way, the speed of the converter being adjusted by manipulation of the load rheostat. This affects the speed for synchronizing just as does manipulation of the governor of a prime mover and is equally simple. After the converter is connected to both power systems, manipulation of the load rheostat continues to have the same effect as manipulation of the governor of a prime mover driving an alternator, both tending to force or retard the rotor speed and resulting in a change in kilowatt load, the speed being restrained by the synchronous machine.

An automatic load regulator of the rheostat controlling type is provided as a part of the control gear. This regulator governs the load rheostat to maintain any desired transfer of power in either direction independently of variations in the frequency of either of the interconnected power systems.

The manually adjusted power factor rheostat controls the excitation of the main induction machine, its effect being very similar to the corresponding field and reactive volt-ampere adjustment of a synchronous

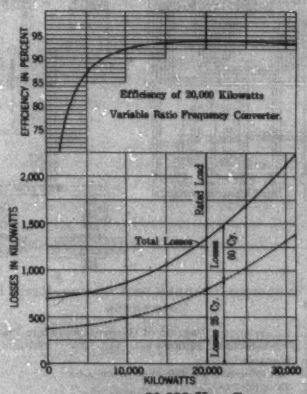


Fig. 4—Performance of the 20,000-Kw. Converters under Maximum Loss Conditions

machine. Normal operation of the induction machine is at 0.95 power factor over-excited.

In case of intentional or automatic opening of the oil circuit breaker in the primary leads of the main induction machine, all devices automatically reset to the proper re-start position except the load and power factor rheostats which must be re-set manually. A re-start can be made within ten seconds after an interruption.

Electrically operated "latched-in" oil circuit breakers are used throughout. These breakers have demonstrated their reliability fully, there having been not one instance of improper operation since installation.

The control board for the two sets is located in a quiet, well-lighted room about 100 ft. distant from the machine room. The board is of the frameless, dead-

front, stretcher-level-steel type and supports all controlling, protective, and metering devices.

The main machines are differentially protected. Overload protection is provided on the supply transformers. Each converter unit is served by two three-phase, 12,000-kv-a., water-cooled inertaire type transformers on both 25 and 60 cycles.

Fig. 4 shows the converter efficiency throughout the load range based on the conditions of greatest loss.

Fig. 5 shows a graphic wattmeter chart of the load

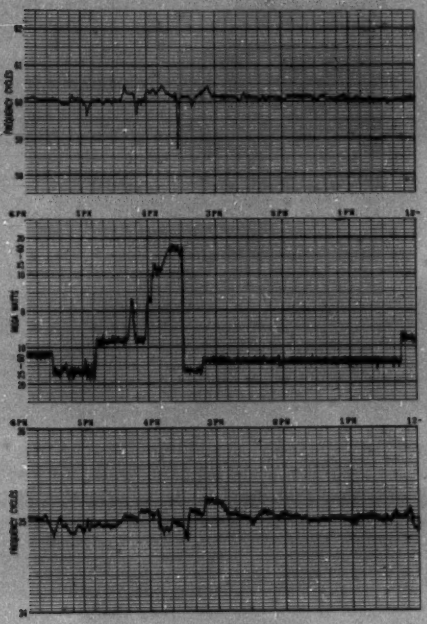

Fig. 5—Simultaneous Load Transfer and 25-Cycle and 60-Cycle Frequency Records

The top chart shows frequency of the 60-cycle bus; the middle chart shows megawatts, and the bottom chart shows frequency on the 25-cycle bus

on one converter when regulated by means of the automatic load regulator and simultaneous frequency records of the 25-cycle and 60-cycle systems. That part of the wattmeter curve below the center zero line represents a power flow through the converters from the 60-cycle to the 25-cycle system and that part above the zero line represents a conversion of power from the 25-cycle to the 60-cycle system.

The scale of the wattmeter is 25,000 kw. each side of the zero center line and it will be noticed that at 3:30 p. m. the load reversed through the converter changing from 17,000 kw. in one direction to 17,000 kw. in the opposite direction. This resulted from the loss of generating capacity on the 60-cycle system, which made it necessary to supply the deficiency from the 25-cycle system. Coincident with this power disturbance, the frequency of the nominal 60-cycle system decreased materially (to 58.7 cycles) but the nominal 25-cycle system evidenced no very appreciable reaction due to the relatively small change in power on this system, particularly from considerations of the 25-cycle system inertia.

Since installation both units have been in practically continuous operation. In the flood season, the surplus power from the 60-cycle system is supplied to the 25-cycle system through the converters. During the low water season, part of the 60-cycle system load is carried from the 25-cycle system through the converters. During the first 12 months operation *80 per cent* of the power through the converters was converted from 60 cycles to 25 cycles and *20 per cent* was in the opposite direction.

## Part II

This second part of the paper will discuss a little more intimately the operation of a variable ratio frequency converter of the type described in the first part with particular reference to the relationship and the combined performance of its induction and load regulating machines.

The fundamental characteristics of a variable ratio converter can be rather simply evidenced by comparing it with the better known synchronous-synchronous type of converter.

The synchronous-synchronous type of set operates as a rigid tie between the interconnected power systems, in so far as the ratio of the system frequencies must be absolutely constant. If, for any reason whatever, the frequency of one of the systems has a tendency to change, a change in power flow through the set will result. The effect of this is to counteract the tendency of the one system to change frequency, by loading the system whose frequency tends to be high and unloading the system whose frequency tends to be low, until any tendency to depart from the exact frequency is equalized. In order to prevent the transfer power demands caused by the frequency variation tendencies from exceeding the maximum capacity of the interconnecting machines, it is obvious that the synchronous-synchronous set must have a certain minimum rating, determined by the capacities of the systems to be interconnected; otherwise normal changes in system conditions may cause pull-out of the set.

Fig. 6 illustrates the load conditions of two systems, and the effect of a synchronous-synchronous interconnection. In this figure the governor characteristics of the prime movers for a given setting are shown; at the left for station No. 1, at the right for station No. 2. The load is plotted from 0 along the horizontal axis.

The vertical axis gives the frequency in per cent of its nominal value. Let the points $P_1$ and $Q_1$ determine an initial load condition. The station loads are $P_1 R_1$ and $Q_1 R_1$, the system loads are $P_1 S_1$ and $Q_1 S_1$, and the load on the set is represented by $R_1 S_1$. Assume the load on system No. 2 increases; then new load conditions are established, as indicated by the points $P_2$ and $Q_2$. It is apparent that the frequency of the systems has decreased slightly and that the load increase of system No. 2 is partially supplied by station No. 1, thus increasing the load carried by the frequency converter. There is only one way to bring the system frequencies and the power transferred by the set back to their initial values—by setting the governors of station No. 2 for a higher load, so that the load distribution will now be determined by the points $P_1$ and $Q_1$.

This demonstrates the following well-known fact: the power flow through a synchronous-synchronous converter can be adjusted solely by changing the

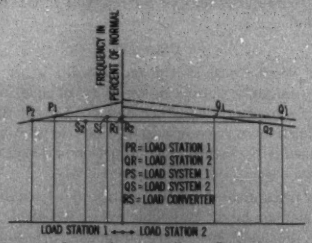


Fig. 6—Chart Showing Load Division

settings of the governors in the generating stations. If a substation contains more than one synchronous-synchronous set, the total load of the sub-station is likewise adjusted, although frame shifting devices make it possible to distribute this load between the individual frequency converter units as desired.

The arrangement of the variable ratio converter is essentially indicated by Fig. 7, consisting of a synchronous machine with d-c. exciter, a wound rotor induction machine, and a rotor excited commutator machine (regulating machine) with its separate exciter set.

The characteristics of the converter are very similar to those of a motor-generator set consisting of a synchronous machine coupled to a shunt wound d-c. machine with field adjusting rheostat. In both cases the speed of the set is determined by the frequency of the power system to which the synchronous machine is connected and the load transferred by the set is adjustable by load regulating equipment. For the synchronous-d-c. set the load is controlled by manipulating the field rheostat of the direct current machine; for the variable ratio converter, by varying the excitation of the regulating machine.

Fig. 8 shows speed-load characteristics representative of both a variable ratio converter and a synchronous-d-c. motor-generator set. These are "shunt" characteristics indicated with sufficient accuracy by a straight line for each setting of the load adjusting device. The load is plotted along the horizontal axis. To the right

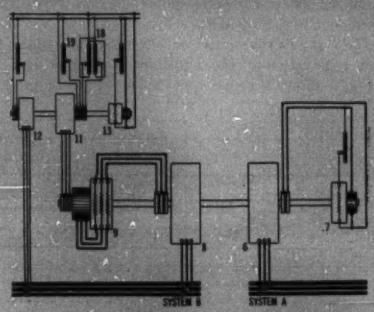


Fig. 7—Fundamental Diagram of the Variable-Ratio Frequency Converter

The reference numbers correspond to those in the complete wiring diagram shown in Fig. 3

| | |
|---|---|
| 6 | Main synchronous machine |
| 7 | Main d-c. exciter |
| 8 | Main induction machine |
| 9 | Load regulating machine |
| 11 | Synchronous exciter |
| 12 | Auxiliary synchronous motor |
| 13 | Auxiliary d-c. exciter |
| 18 | Load rheostat |
| 19 | Power factor rheostat |

of point $O$ the adjustable machine (induction or d-c. machine) is motoring and to the left generating. The speed of the set is plotted along the vertical axis. As shown, for any setting of the load adjusting device,

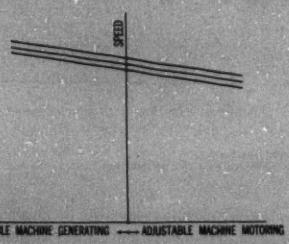


Fig. 8—Speed Load Characteristics of Converter and Motor Generator

decreasing speeds result inherently in decreasing generator-load or increasing motor-load.

Changing the setting of the load adjusting equipment results in practically a parallel displacement of the sloping "shunt" characteristic and with each setting there is a corresponding no-load speed. Within the

range covered by such a "family" of characteristics as provided by the design of the regulating equipment the set can be adjusted so as to carry any desired power flow (in either direction) at any speed. A load regulator provides automatic manipulation of the load adjusting apparatus so as to maintain a constant load in spite of speed variations.

In the case of a variable ratio frequency converter, the vertical axis of Fig. 8 must express the ratio of the synchronous speeds of the synchronous and induction machines instead of the rotational speed of the set. This is because the load transferred by the set will be entirely determined by the speed relationship between the rotor and the flux of the induction machine for each setting of the load regulating equipment. Variations

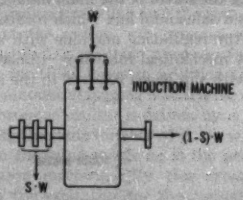


Fig. 9—Diagram of Induction Machine

| | Line power ($W$) is positive | Line power ($W$) is negative |
|---|---|---|
| Slip ($S$) is negative. Induction machine operates above synchronism. | (1) Shaft power $(1 - S)\ W$ is positive. Induction machine operates as motor. Rotor power $S\ W$ is negative. Regulating machine operates as generator. | (2) Shaft power $(1 - S)\ W$ is negative. Induction machine operates as generator. Rotor power $S\ W$ is positive. Regulating machine operates as motor. |
| Slip ($S$) is positive and less than unity. Induction machine operates below synchronism. | (3) Shaft power $(1 - S)\ W$ is positive. Induction machine operates as motor. Rotor power $S\ W$ is positive. Regulating machine operates as motor. | (4) Shaft power $(1 - S)\ W$ is negative. Induction machine operates as generator. Rotor power $S\ W$ is negative. Regulating machine operates as generator. |

in the frequencies of either one or both of the interconnected power systems will change this speed relationship, the ratio of the synchronous speeds being proportional to the frequency ratio. Assume for instance that the frequency impressed on the synchronous machine remains constant, and the frequency impressed on the induction machine varies; then the load will vary with the ratio of the synchronous speeds although the speed of the set remains the same.

The shunt characteristics of the variable ratio converter have a very slight slope. This means that, without load adjustment, small variations in frequency ratio will cause large changes in the load transferred by the converter, and thus the variations in frequency ratio will be partially but not entirely counteracted. In the case of the synchronous-synchronous converter, as has been stated before, any tendency to depart from the exact frequency ratio will be wholly counteracted by a change in the load transferred.

Except for its load reversibility, a variable ratio set is closely analogous to a synchronous generator driven by a prime mover, the induction machine with its load adjusting apparatus simulating the prime mover with governing equipment. In either case the operating characteristics of the synchronous machine are similar and in no way peculiar. Hence, the following will be restricted to a discussion of the induction machine and the load adjusting apparatus as they provide the essential and interesting characteristics of an adjustable load variable ratio converter.

The wound rotor induction machine as represented by Fig. 9 will be considered first. Let $W$ represent the line power which may be input to (positive) or output from (negative) the primary of the machine. Neglecting the losses of the machine, this power will partly appear at the shaft in the form of mechanical power and the remainder will be converted by transformer action to the secondary or rotor winding and appear at the collector as electrical power. The relative values of these two components of the line power are determined by the speed relationship of the flux and the rotor, or in other words, by the slip of the machine. Letting $S$ represent the slip, the shaft power is equal to $(1 - S)$ W and the collector power to $S\ W$. Collector power must be either absorbed or supplied by external equipment. The sign of $W$, and the value and sign of $S$ determine the operating possibilities of the induction machine and regulating apparatus as given in the table accompanying Fig. 9.

For instance, an induction machine with a constant resistance in its rotor circuit will run at synchronous speed at no-load. If loaded, its rotor will slip positively or negatively so that the rotor power ($S\ W$), which must provide the ohmic losses in the rotor circuit and is dissipated entirely as heat, will be positive. Therefore, under this operating condition only cases 2 and 3 of the table are possible, showing that the machine can run only as a motor below synchronism and only as a generator above synchronism.

However, if an active source of energy, such as a so called "regulating machine" is inserted in the rotor circuit of the induction machine, its rotor power ($S\ W$) may be negative as well as positive, regardless of whether the slip is positive or negative.

The fundamental operating principles of such a regulating machine will be explained as follows: Assume that a wound rotor induction machine, with its stator energized and its rotor circuit open, is operated at some definite speed. Then the frequency and voltage appearing at the rotor leads will be proportional to the slip. If an external voltage of the same slip frequency, and equal and opposite to the internal

rotor voltage is applied to the collector, no current will flow in the rotor circuit, due to the voltage balance, and the conditions in the main induction machine remain unchanged. Increasing or decreasing the magnitude of the external voltage will cause a flow of rotor current in phase or in phase-opposition with this voltage so that the ohmic drop will maintain the voltage balance. The product of internal rotor voltage and current represents the rotor power ($S\,W$); that is, the main induction machine now carries a corresponding load ($W$). In this way the main induction machine may be forced to carry various desired loads, by adjusting the magnitude of the external voltage applied to its collector, irrespective of the slip.

The above describes the effect of an external voltage in phase or in phase-opposition with the internal rotor voltage. Similarly, if the external voltage is given a component in phase-quadrature with the internal rotor voltage, it will result in a quadrature component of rotor current which inherently will be neutralized by a corresponding reactive current component in the primary of the induction machine. In other words the quadrature component of the external voltage applied to the collector will influence the power factor of the primary, but not the energy load carried by the machine. From this it is obvious that control of the external rotor voltage (regulating machine voltage) in quadrature directions provides a means of adjusting the watt and wattless components of the primary current. For the sake of simplicity the foregoing explanation intentionally neglects the effect of the reactance and the primary resistance of the induction machine. The principal influence of these factors is to cause a small phase shift in the internal rotor voltage, depending on the load, thus changing slightly its relationship with the in-phase and quadrature components of the external voltage. As a result the in-phase component will affect to some extent the power factor and the quadrature component the energy load of the machine. With low slip values these effects are immaterial.

External rotor voltages of the required characteristics as previously outlined can be obtained from a suitably designed regulating machine and by its use the operating range of the induction machine will be enlarged so as to include all four operating possibilities of the table accompanying Fig. 9.

For the machine arrangement being considered, the regulating machine is directly coupled to and is wound for the same number of poles as the main induction machine. The regulating machine has a uniform air-gap and evenly distributed windings on stator and rotor. The stator has a three-phase, two-layer winding with 60-deg. phase belts and 180-deg. coil throw. The rotor is very similar to an ordinary d-c. armature and has a two-layer lap winding with 180-deg. coil throw connected to a commutator. The current is collected from the commutator by three sets of brushes spaced 120 electrical degrees apart, which form the three commutator phases and are connected to the three stator phases as shown by Fig. 10. The turn ratio of the stator and rotor windings is chosen so that these two windings exactly compensate each other provided the brushes are in the proper position on the commutator. This means that any system of three-phase currents flowing through the combination of series connected stator and commutator phases cannot create any magnetic flux because the stator and rotor ampere-turns neutralize each other completely.

The magnetic flux required in the machine is created exclusively by a third winding of the three-phase type which is evenly distributed on the rotor and is connected to a collector. This exciting winding is energized by a source having a frequency exactly equal to that of the line energizing the stator of the main induction machine and produces a sinusoidal flux which rotates relative to the rotor of the regulating machine with synchronous speed against mechanical rotation. Consequently the flux rotates with slip speed relative to the stator and a

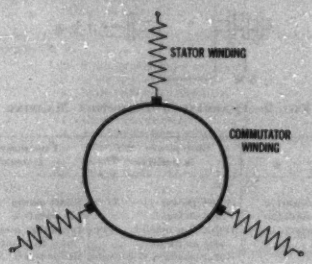


Fig. 10—Fundamental Diagram of Main Circuits of Regulating Machine

three-phase voltage having a frequency at all times equal to the frequency appearing at the collector of the main induction machine is induced in the combination of series connected stator and commutator phases. The magnitude of this voltage is proportional to the flux intensity and the rotational speed of the machine.

Referring again to Fig. 7, assume that the leads between the collector of the main induction machine and the stator terminals of the regulating machine are disconnected. Then at the collector of the induction machine a three-phase voltage appears which has a magnitude and frequency proportional to the slip, and a three-phase voltage of the same frequency exists at the terminals of the regulating machine. By properly adjusting the magnitude and phase of the collector voltage of the regulating machine, its stator terminal voltage can be made equal and opposite to the collector voltage of the induction machine. Then if the main secondary circuit is closed no electrical change will occur and by in-phase and quadrature adjustments of the regulating machine collector voltage the main induction

machine can be forced to carry the desired energy and wattless loads.

The regulating machine operates either as a motor or as a generator converting the electrical power at its stator terminals into mechanical power at the shaft or *vice versa;* no power is transferred to or from its exciting winding. This will be more readily understood if it is realized that the flux in the regulating machine is due entirely to the current in the exciting winding and, therefore, will be in phase with this current. However, the voltage induced in the exciting winding will be in quadrature with the flux and consequently with the exciting current. Hence the exciting current will be wattless current, lagging relative to the voltage impressed on the collector of the regulating machine, except for a small watt component supplying the copper losses in the exciting winding and the core losses. It is apparent that the source (synchronous exciter) energizing the regulating machine needs to furnish only a little energy for these losses in addition to a considerably greater amount of lagging wattless for excitation.

The synchronous exciter is driven by a synchronous motor, having the same number of poles, whose stator is connected to the same source as is the primary of the main induction machine. By this arrangement the frequency of the excitation for the regulating machine will always be correct. The synchronous exciter is essentially a three-phase synchronous generator with a distributed field winding in two separate circuits each connected to individual collector rings. When energized by direct current the two circuits of the field winding create two magnetic fields at 90 deg. with each other, which induce the two in-quadrature components of the exciting voltage needed for the regulating machine. A definite phase relation must exist between these voltage components and the primary voltage of the main induction machine; this is properly established experimentally and fixed permanently by setting the coupling between the synchronous exciter and its driving motor before the converter is put into service.

The two component fields of the exciter are designated as "load field" and "power factor field," this nomenclature expressing their purpose in controlling the energy and reactive loads respectively of the main induction machine. A rheostat of the potentiometer type controls the excitation of the load field; this "load rheostat" is actuated normally by the automatic load regulator. The field rheostat for the control of the power factor field is of the ordinary series type, as the small slip of the main induction machine makes reversal of the power factor field current unnecessary. The d-c. excitation for the synchronous exciter and its synchronous driving motor is supplied by a small d-c. generator. These three machines constitute the auxiliary set of Fig. 7.

To explain more simply the functioning of the regulating machine its exciting winding has been represented as being a separate winding on the rotor. Normally this winding is common with the commutator winding, resulting in an arrangement very similar to that on the rotor of a synchronous converter.

The excitation of the regulating machine could be obtained more directly through a static voltage transformation (with ratio and phase angle control) from the power system to which the stator of the main induction machine is connected. However, the use of an auxiliary synchronous exciter set to supply this excitation results fundamentally in a main induction machine which is more stable at time of system disturbances as its rotor excitation is, within the pull-out torque of the synchronous motor driving the auxiliary set, practically independent of system voltage. Furthermore, load and power factor field adjustment by means of rheostats is very reliable and simple and compares favorably with ratio and phase angle control of the excitation voltage through complicated transformer equipment or by means of exciters having commutator brush shifting mechanisms.

Fig. 11—Phase Wound Rotor of the 23,000-Kv-a. Induction Machine

In the foregoing pages the fundamental arrangement and operating characteristics of a variable ratio frequency converter of the type installed in the Lockport Substation have been discussed in some detail. The following is intended to show the actual construction and appearance of the more interesting parts of the Lockport converters and to point out the departures from the simplified arrangement of Fig. 7.

The rotor of the main induction machine is shown in Fig. 11. The coils were completely formed and insulated before being put in place in the half closed slots. Both ends of each of the three rotor phases are connected to individual rings of the six-ring collector, this phase separation being advantageous in connection with the construction of the regulating machine in two units.

Fig. 12 shows the stator of a regulating machine unit. The coils of the three-phase stator winding are embedded in fully closed slots. In the top of the slots is a

high resistance squirrel-cage winding for damping high harmonic fields which might disturb commutation.

Fig. 13 is a view of the rotor of a regulating unit. The coils are connected to the commutator bars through high resistance leads in order to minimize the circulating current in the coils undergoing commutation. The banding on the front of the commutator

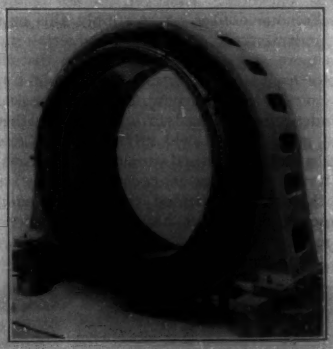

Fig. 12—Stator of a Load Regulating Machine Unit

covers involute cross connections between commutator bars. The excitation leads from the rotor winding connect to a six-ring collector.

The auxiliary exciter set is shown by Fig. 14. The center machine is the synchronous exciter with the six leads of the three separate stator phases in the fore-

Fig. 13—Rotor of a Load Regulating Machine Unit

ground. To the left are the two pairs of collector rings for the load and power factor fields. To the right is the coupling used to adjust the phase angle relationship between the synchronous exciter and the synchronous driving motor. At the extreme left is the small d-c. exciter.

Attention has been called to the application of a double unit regulating machine and to the use of three separated phase windings on the main induction rotor and in the synchronous exciter stator of the Lockport converters. The diagram exemplifying the rotor connections involved by this arrangement appears in Fig. 15. In the center of the diagram are represented the three separated rotor phases of the main induction machine; at either side is the rotor winding of a regulating unit. The diagram is bipolar; heavy lines represent windings, and small circles indicate the location of the collector taps. For the sake of simplicity the stator (compensating) windings of the regulating units have been omitted.

Tracing through each main rotor phase it is seen that one phase lead terminates on the commutator of the left unit and the other lead of the same phase on the

Fig. 14—The Auxiliary Synchronous Exciter Set

commutator of the right unit at points which electrically are diametrically opposite. The stator phases of the synchronous exciter are not shown, although their connections to the rotor windings of the regulating units are shown by the six collector taps $R_1 - R_4$, $R_2 - R_5$, and $R_3 - R_6$ corresponding to the exciter phases 1 - 4, 2 - 5, and 3 - 6.

The three collector phase taps $R_1$, $R_2$, and $R_3$ are spaced 120 electrical degrees apart; the phase belts between $R_1 - R_4$, $R_2 - R_5$, and $R_3 - R_6$ do not cover 180 electrical degrees but are less than a full pole pitch. This chording of the phase belts necessitates six collector taps but it minimizes the magnitude of harmonic fluxes created by the exciting current which would be detrimental to commutation. The two three-phase commutator winding systems, excited in parallel and connected in series through the main rotor phases, are electrically equivalent to the winding system of one

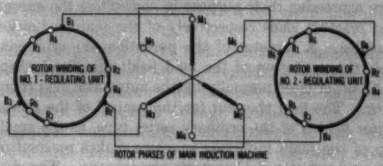


Fig. 15—Fundamental Connection Diagram of Main Rotor Circuits

rotor excited machine with six commutator phases instead of three.

It is interesting to consider the various factors affecting the selection of the most suitable arrangement of a variable ratio converter. The induction machine

may be built for either one of the systems to be interconnected; however, one of the systems may have advantages which should be recognized in individual cases. For instance, if the converter is to interconnect a three-phase and a single-phase system, it usually will be more desirable to connect the induction machine to the three-phase and the synchronous machine to the single-phase system. If the converter is to interconnect two three-phase systems, the induction machine should be connected to the system offering the most favorable conditions for the design of the load regulating equipment which generally is the lower frequency system. The number of poles of the main synchronous and induction machines are preferably chosen so as to obtain equal or nearly equal synchronous speeds at nominal frequencies in order to minimize the slip of the induction machine and consequently the rating of the regulating apparatus. For instance, if the converter is to interconnect a 25-cycle and a 60-cycle system, and is to have the synchronous machine on the 60-cycle end, the following speeds and pole combinations can be chosen.

| Speed rev. per min. | Synchronous machine poles (60 cycles) | Induction machine poles (25 cycles) | Slip induction machine (at nominal frequencies) |
|---|---|---|---|
| 720 | 10 | 4 | +4.00% |
| 514 | 14 | 6 | −2.86% |
| 360 | 20 | 8 | +4.00% |
| 300 | 24 | 10 | 0% |

The fourth column gives the slip of the induction machine at nominal frequencies (positive slip indicates under-synchronism and negative slip over-synchronism).

Variable ratio frequency converters will be fittingly selected for application where the operating economy or convenience of load adjustment at the converter justifies their somewhat higher cost and slightly lower efficiency. There will be other instances where necessity dictates the use of such converters in order to provide a sufficiently reliable connection between systems. It is impossible to specify generally the system conditions requiring variable ratio converters. In determining the proper type and size of any form of interconnecting equipment not only the capacity of the systems but also the general and specific capacity of the other metallic and electro-magnetic connections within a system should be considered. Recent experience with automatic frequency regulators reveals the fact that normal frequency fluctuations can be controlled within very close limits by load regulation of a surprisingly small percentage of system capacity. From this fact it is apparent that the normal tendencies of two interconnected systems to depart from a constant frequency ratio can be counteracted by at least a correspondingly small transfer of load from one system to the other. Actual operating experience has shown that two power systems may be connected together successfully by synchronous-synchronous frequency converters having a capacity of only ten per cent of the capacity of the smaller system. Where the capacity of the desired interconnecting apparatus is less than ten per cent some uncertainty exists regarding the suitability of the more rigid types of converters and the application of variable ratio converters should be carefully considered.

## Discussion

**P. W. Robinson:** The presentation of this paper following those of Mr. Encke and Mr. Burnham last year at the New Haven meeting is indicative of the growing demand for large conversion units for load transfer between power systems. In the meantime, a 20,000-kw. variable-ratio set with Scherbius type of load regulating machine has been delivered to the Buffalo General Electric Co., and two more of the same capacity are under construction for the Union Electric Light and Power Co. for installation at their Page Avenue substation in St. Louis. An interesting feature of the latter installation is that the induction units of the sets, which are to be located at considerable distance from a main generating station, are to be so controlled as to make the reactive kv-a. respond to system voltage. Thus a Scherbius-controlled induction motor, in addition to controlling load transfer, will be used to minimize line voltage variations by regulation of the reactive kv-a. it supplies to or draws from the power system. A further interesting development in connection with the control of these sets is that starting motors will be used to bring them to approximately the synchronous speed of the induction unit and this unit is excited through its rotor by the Scherbius machine before its primary is connected to the power system. This arrangement makes it possible to use a starting motor with a more suitable secondary voltage than can be used on the main induction unit, thus eliminating high-tension switching apparatus in the secondary circuit for starting and reducing the size of the secondary control. Further important advantages are that the induction of high secondary voltage in the main induction unit and the strains incident to connecting the unexcited primary to the line are both avoided.

The most important difference between the type of set described in the paper and the Scherbius controlled set is that in the former the excitation for the regulating machine is unaffected by variations in system voltage, while in the latter case it is proportional to the system voltage. The constant voltage supply enables the induction machine to transfer more power to the system in case of voltage disturbances, up to the limit of pull-out torque of the synchronous machines. Precautions must be taken, however, that this maximum power limit is not exceeded.

As a result of the supply of excitation for the Lockport set at line frequency, a total of 350 kv-a. exciter capacity is required, while the excitation for the Scherbius control set of the same rating for Buffalo, being supplied at slip frequency, amounts to only 14 kv-a.

**A. Van Niekirk and W. H. Rodgers:** Mr. Robinson's discussion is of interest and value, being expressive of a slightly different point of view. In that connection it may be of equal interest to mention some of the pertinent considerations which influenced the design of the Lockport Converters.

A starting motor is logically used as an expedient where the inrush kv-a. incident to the starting of a converter (or condenser) is paramount and cannot be limited otherwise to an acceptable value. There may be other cases where a starting motor will offer economic advantages, for instance where the locked rotor voltage of an induction machine is very high. However, with the Lockport converters, the design is such that using the main induction machine for starting requires only a moderate and acceptable current inrush (corresponding to 10,000 kv-a.).

Furthermore the rotor voltage of the induction machine (4080 volts per phase) is not so high that a starting motor could have offered any economic advantages.

In this connection it should be realized that the fill-factor of the rotor slot for the 4080-volt winding will not be appreciably smaller than the slot fill-factor for a 500-volt winding, because the heavy rotor copper straps of a machine of this size require a certain minimum insulation thickness in order to obtain a coil insulation which is sufficiently strong from mechanical considerations.

The use of a starting motor results in the addition of another direct-connected machine; it increases the constant losses; and makes bearing oil pressure starting equipment necessary. Moreover, the main induction machine is inherently more reliable than a short-time rated starting motor and this fact is particularly momentous in connection with the importance of this interconnecting equipment.

It is most unusual to hear advocated that it is advisable to avoid the strains incident to connecting an unexcited induction machine to the line; it is common practise to start wound-rotor induction motors of even the highest ratings directly, using suitable secondary control. This method is generally successful, and has been during the 18 months of regular operation of the Lockport converters. When a starting motor is used, this motor will be started by the same method; however, the strains incident to energizing its stator will be relatively higher than for the main induction motor if used for starting, because the short-time rated starting motor will be of less sturdy construction.

Further it should be emphasized that to connect the induction machine primary to the line, after exciting the rotor winding by the regulating equipment, does not necessarily require a starting motor. It can be much more reliably accomplished by starting with the main synchronous machine in combination with a starting transformer in cases where the converter can or must be started from the synchronous end.

The kv-a. ratings of the a-c. exciters for the Lockport and Scherbius types of converters are not at all indicative of the comparative physical size, complexity, or performance of these exciters. As a matter of fact, the 350-kv-a. Lockport exciter is no larger over-all than the 14-kv-a. Scherbius exciter; the former is an ordinary synchronous machine of simple construction rather than a frequency converter with commutator and complicated brush-shifting mechanism.

It is gratifying to hear that due acknowledgment is made of the inherent superiority of regulating machine excitation derived from a source less directly affected by system voltage disturbances than is the case where this excitation is proportional to system voltage.

# Theory of a New Valve Type Lightning Arrester

BY J. SLEPIAN[1], Fellow, A. I. E. E. R. TANBERG,[1] Associate, A. I. E. E. and C. E. KRAUSE[1] Associate, A. I. E. E.

*Synopsis.—Theory and experimental data are given on the properties of discharges confined to small holes, such as the pores of a naturally porous material. The characteristics of these discharges are such that they are well suited for utilization in a valve type lightning arrester.*

## I. The Valve Type Arrester

A VALVE type lightning arrester is an apparatus which passes current freely for impressed voltage in excess of a certain value, and which ceases to carry current almost completely for impressed voltage less than a certain other value. If the impressed voltage is increased continuously from a low value, that voltage at which current begins to be passed freely is called the breakdown voltage. After the breakdown voltage is exceeded, if the voltage is decreased continuously, the arrester will generally continue to pass current relatively freely until a lower value of voltage is reached at which discharge of current substantially ceases. This voltage at which current flow nearly stops, we shall call the cut-off voltage of the valve arrester.

The cut-off voltage of a valve arrester is usually not sharply defined, since a small current may flow down to zero voltage. For practical purposes, however, it is that voltage at which the current flow is so small that it may be readily interrupted by a simple series spark-gap structure on alternating current. The breakdown voltage of the arrester is not necessarily the largest voltage which may appear across the arrester. The characteristic of the arrester may be such that to pass several hundred or a thousand amperes, the voltage may rise to a value greater than the breakdown voltage. The largest voltage which appears across an arrester during a normal discharge we shall call the maximum voltage of the arrester. The ratio of this maximum voltage to the cut-off voltage, we shall call the voltage ratio of the arrester.

It is evident that the voltage ratio of a valve type arrester determines its protective value on an electrical system. For the cut-off voltage must be proportioned to the normal working voltage of the system, and then the maximum voltage of the arrester will determine the stress which the system insulation will receive during lightning. The characteristics of electrical insulation under impulse voltages are such that a properly applied arrester with voltage ratio of two or three will give almost perfect protection. A valve arrester with a voltage ratio of ten or more will have little protective value.

A valve type arrester must change from a good conductor to a relatively good insulator over a moderate change of voltage. The field of discharges in gases would seem to offer the best possibilities for the realization of these characteristics. Examination of the field reveals, however, that although valve effects are generally present, their voltage ratio is not sufficiently low to be useful except in a few special cases or arrangements.

To illustrate this, consider a simple spark-gap, one cm. long, between spheres or planes in air at normal pressure and temperature. The breakdown voltage is 30,000 volts. After breakdown, its properties are that of a one cm. arc shown in Fig. 1.[2] Here we see that the

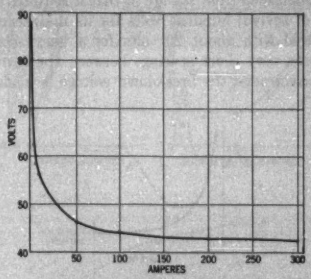


Fig. 1—Characteristic of a One Cm. Long Arc, Copper Electrodes

minimum voltage capable of maintaining the discharge is very low, of the order of about 40 volts, and that this minimum occurs for very large currents. Hence, the cut-off voltage of such a spark-gap used on systems capable of delivering large current would be 40 volts, and the voltage ratio would be 750. If the electrical system is not capable of delivering large currents, the voltage for maintaining the arc will be greater, but even if the current is limited to 10 amperes, the arc voltage will still be only 56 volts, and the voltage ratio will be 535.

It is clear from this example that the volt-ampere

1. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.*

2. Plotted from equations of Nottingham. *Phys. Rev.*, 28, 1926, p. 764.

characteristic of the discharge which follows breakdown must be studied to determine the lowest voltage which will maintain the discharge under given conditions. This will be the cut-off voltage of the arrester constructed utilizing this type of discharge. It is also clear that types of discharge must be sought which require a high voltage for their maintenance. In this

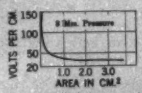


Fig. 2—Gradient in Positive Column in Discharge in Nitrogen with Current Density of 0.26 Amperes, Cm.² in Tubes of Varying Cross—Sectional Area

way the cut-off voltage may be brought up to the order of magnitude of the breakdown voltage, and thus a low-voltage ratio may be obtained.

In the autovalve arrester,[3] for example, by the use of electrodes of relatively high resistivity, the discharge is constrained to remain in the form of a glow instead of being permitted to take the form of an arc which is the more usual form at atmospheric pressures. The glow is distinguished from the arc in that it requires a minimum of several hundred volts for its maintenance as compared with about 20 volts for a very short arc. By using very short spacings between the high resistivity electrodes, the breakdown voltage is made to be

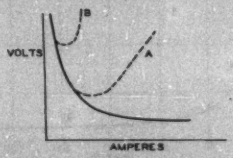


Fig. 3—Volt-Ampere Characteristic of Discharge in the Open and in Holes of Different Sizes

also only several hundred volts, and thus a very low voltage-ratio is obtained.

## II. Electrical Discharges in Holes and Fine Capillaries

Another method of obtaining a discharge which requires for its maintenance a voltage comparable with that required to initiate the discharge has been discovered. It has been found that the voltage required to maintain a discharge can be raised to high values by confining the discharge to narrow passages with insulating walls. This is well known in the case of discharges in Geissler tubes, where the gradient required by the positive column at constant current density varies inversely with the diameter of the circular glass tube as shown in Fig. 2.[4] The reason for this lies in the fact that ions are lost from the discharge principally by recombination on the walls of the tube, and the ratio of the wall perimeter to the tube section increases as the diameter decreases. Not only is the gradient increased by confining the discharge, but the volt-ampere characteristic may be changed from a falling one to a rising one.

In Fig. 3, the heavy line indicates the volt-ampere characteristic of a discharge in the open at atmospheric pressure. The dotted curve *A* indicates that of a discharge confined to a circular hole. For small currents, where the natural section of the discharge is less than that of the hole, the walls of the hole have little influence upon the discharge, and the voltage is the same as that for a discharge in the open. When the discharge fills the hole, however, the voltage is increased and the curve *A* departs from the solid curve. With further increase of current, the confining action of the hole becomes so great that the voltage increases with increasing current. Curve *B* in Fig. 3 indicates the effect of a smaller hole. The departure from the solid curve

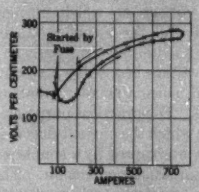


Fig. 4—Characteristic of Discharge in 0.178 Diameter Hole in Soapstone

for the discharge in the open occurs at smaller current and higher voltage.

From these curves we are led to believe that for discharges confined to holes at atmospheric pressure there is a minimum voltage which occurs at a relatively small current, and that with smaller holes this minimum voltage is greater, and occurs at smaller currents. This is confirmed by the work of R. C. Mason who has plotted the volt-ampere characteristic shown in Fig. 4 of a discharge in a 0.178 cm. diameter hole in soapstone, the discharge being started by a fine fuse wire, and the current and voltage values measured from an oscillogram. The existence of a minimum voltage gradient of considerable magnitude and occurring at a small value of current is brought out in this curve. Mason has also obtained data showing that the minimum voltage gradient is increased as the size of the hole is decreased. In Fig. 5, the crosses indicate the minimum voltages observed by Mason for discharges in slots with soapstone walls of varying width. These

3. J. Slepian, Trans. of A. I. E. E., XLV, 1926, p. 169.

4. W. Matthies and H. Struck, *Handb. d. Physik*, Vol. XIV, p. 274.

discharges were started by fine fuse wires in a 60-cycle circuit and oscillograms taken of current and voltage. The circles in Fig. 5 indicate the results obtained by the authors for very narrow slots between glass plates. These discharges were started disruptively by application of very high voltage, and a cathode ray oscillogram was taken of the volt-ampere characteristics.

## III. Discharges in Naturally Porous Materials

The data of Fig. 5 show that to obtain minimum discharge voltage gradients of the order of several thousand volts per cm. at atmospheric pressure and thus of an order of magnitude beginning to be comparable with breakdown voltage gradients, the passages to which the discharges are confined must have sections with linear dimensions less than 0.001 cm. With such small dimensions, the current carried by a passage with the voltage gradient maintained at breakdown value will be

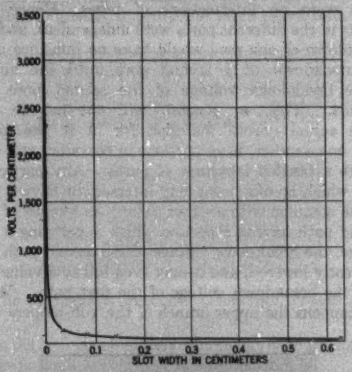


Fig 5—Minimum Voltage Gradient for Discharges in Slots

very small. For lightning arrester purposes, therefore, it will be necessary to use a very large number of these very fine passages in parallel. It would not be practical to construct or assemble directly such a multitude of fine passages or channels. Materials can be made, however, which are naturally permeated by fine pores, whose sections are of the required dimensions.

In Fig. 6, for example, is given a cathode ray oscillogram showing the course of the voltage with the time, for a discharge from a condenser through a piece of red building brick, 7 mm. thick. Breakdown occurred at about 22,500 volts. The voltage then dropped sharply to about 10,000 volts, and then dropped slowly to about 5000 volts, where it remained nearly stationary as the current decreasd. This indicates that most of the pores had minimum discharge voltages or cut-off voltages of about 5000 volts. In terms of gradients, breakdown occurred at 32,000 volts/cm. and cut-off for most of the pores at 7100 volts/cm. The brick appeared to be uninjured by the discharge and the experiment could be repeated, reproducing the oscillogram and thus indicating that the discharge had passed only through the pores of the brick without affecting the solid material.

Before showing volt-ampere oscillograms of discharges through porous materials, it will be well to

Fig. 6—Discharge through Piece of Red Brick

consider what characteristic may be expected from consideration of the volt-ampere characteristic of a single fine hole as shown in Fig. 3. In Fig. 7A, the full curve shows the static volt-ampere characteristic of a dis-

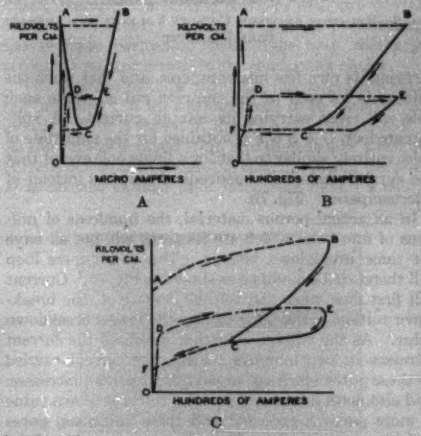


Fig. 7—Characteristics of Discharges in Five Holes

charge in a very fine long hole. Breakdown occurs at $A$, and the minimum or cut-off voltage is shown at $C$. If the voltage impressed along the hole is raised to the breakdown point $A$, and then held at this value, the current will at once build up to that corresponding to $B$, which is the other intersection of the horizontal through $A$ with the static characteristic. If the voltage is now lowered, the current will decrease following the curve $BC$ until the cut-off point $C$ is reached. If now the voltage is lowered only slightly, and held constant, the

discharge can no longer be maintained, and the current decreases rapidly to zero along the line $C\,F$. Raising the voltage to the breakdown value and then lowering it, thus causes the loop $O\,A\,B\,C\,F$ to be traced.

If now a hundred million fine holes, each having identically the characteristic of Fig. 7A, are used in parallel, it is clear that when the voltage is raised to the breakdown value each individual hole will break down

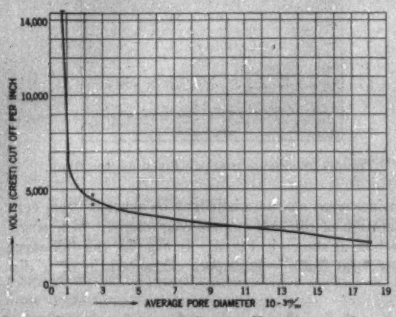


Fig. 8—Relation between Cut-off Voltage and Average Pore Diameter

carrying its own few microamperes, and that when the voltage is lowered to the common cut-off value each hole will cease carrying its minute current. A volt-ampere loop $O\,A\,B\,C\,F$ is obtained for the multitude of holes entirely similar to that for a single hole except that the current scale is in hundreds of amperes instead of microamperes. Fig. 7B.

In an actual porous material, the hundreds of millions of fine holes which are its pores will not all have the same breakdown voltage. The volt-ampere loop will therefore be modified as shown in Fig. 7C. Current will first flow when the voltage reaches $A$, the breakdown voltage of the pores having the lowest breakdown value. As the voltage is further increased the current increases in two manners. First, the current carried by those pores which are already broken down increases. And also, with increase of voltage, the breakdown value of more pores is exceeded and these additional pores begin to carry current. Thus, the upper portion of the volt-ampere loop slopes upward as in Fig. 7C.

The pores of an actual porous material will also not all have the same minimum or cut-off voltage. This will cause the lower branch of the volt-ampere loop to be modified as in Fig. 7C. As the voltage is lowered from the point $B$, the current decreases because the current in each pore decreases. When the point $C$ is reached, some of the pores stop carrying current altogether because their cut-off voltage has been reached. Along the portion $C\,F$ more and more of the pores cease carrying current, and at $F$, the cut-off of the last pore is reached.

Regarded as a lightning arrester, the breakdown voltage of the porous material is the breakdown voltage of the pore having the lowest breakdown, and the cut-off voltage of the porous material is the cut-off voltage of the pore having the lowest cut-off.

It may be concluded, therefore, that finely porous materials will have high cut-off voltages.

This is confirmed in the curve of Fig. 8, which shows the cut-off voltage for four porous materials, determined by cathode ray oscillograms. An average pore diameter for these materials was estimated by Mr. B. S. Covell by a determination of the pore volume, and from the rate at which a fluid under pressure flowed through the materials.

In the derivation of the volt-ampere characteristic shown in Fig. 7C it was assumed that the pores were all distinct, and that although they might not be at all straight, they ran more or less parallel paths so that there were no intersections of pores. Hence, the events in the different pores were independent, and the breakdown of one pore would have no influence upon the breakdown of a second pore until the appropriate breakdown voltage of the second pore was reached. This, in general, will not be the case in an actual porous material, for in it the pores cross one another, have portions in common, and constitute a tangled labyrinth of paths. Any particular path which breaks down may intersect or have a portion in common with another path. As a result of this second path having a portion which is carrying a discharge, the breakdown voltage of the second path will be greatly lowered, and it may even fall to a value less than the breakdown voltage of the first path. When this happens the upper branch of the volt-ampere loop

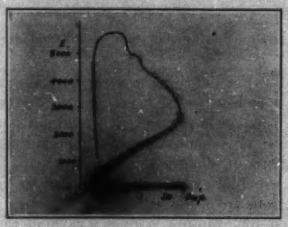

Fig. 9—Discharge through Piece of Brick

may slope downwards instead of upwards. This effect will be most pronounced in coarsely porous materials.

This is well brought out in the cathode ray oscillogram for a discharge through a 6.3 mm. thick piece of brick shown in Fig. 9. The breakdown of some of the pores, so lowered the breakdown voltage of the other pores, that the voltage fell with increasing current. The actual course of the upper branch of the volt-am-

pere loop, when it is falling in this way will now depend on the characteristics of the circuit supplying the current. The lower branch of the volt-ampere loop for this piece of brick is of the nature predicted in Fig. 7C.

## IV. Discharges in Slightly Conducting Porous Materials

By confining the discharge following breakdown to very fine channels it is possible as we have seen to raise greatly the minimum voltage for maintaining the discharge, and thus greatly improve the valve effect. To obtain a voltage ratio sufficiently low to make a good valve type lightning arrester, however, calls for a material with pores of an exceedingly great degree of fineness. The authors have found that by incorporating small amounts of conducting material such as lampblack or powdered metal in the porous material the breakdown voltage is considerably reduced while the cut-off voltage is unaffected. In this way it is possible to greatly improve the valve effect, and to reduce the stringency of the requirement as to the fineness of the pores.

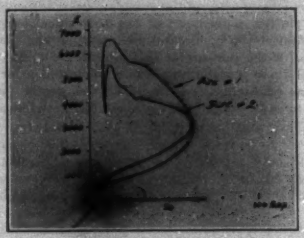

Fig. 10—Discharge through Insulating Porous Disks

Fig. 10, for example, shows cathode ray oscillograms of volt-ampere loops of porous disks 5.0 cm. in diameter and 3.2 mm. thick which were practically free from conducting material so that their resistance when measured at 1000 volts was about 2000 megohms. Fig. 11 shows the characteristics of a similar disk but containing a small amount of carbon so that its resistance when measured at 1000 volts was 30,000 ohms. Comparing the two oscillograms, we see that the addition of the carbon had only a very slight effect upon the lower or cut-off branch of the loop, whereas it greatly lowered the upper or breakdown branch, thus greatly improving the valve effect.

The way in which the finely divided conducting material causes the breakdown voltage to be lowered is readily pictured. The conducting particles are distributed through the porous material, and are too few in number to form many conducting paths through the material. The few continuous chains of conducting particles through the material account for the conductivity at low voltage (30,000 ohms in the disk of Fig. 11).

Besides these continuous chains, there will be some chains of conducting particles which are not completely continuous but have tiny breaks in them. When the voltage impressed on the piece is raised to a few hundred volts those chains which have single tiny breaks will begin to carry current, a discharge occurring across the tiny break in each chain. The current in this discharge is kept small by the high resistance of the fine chain leading up to the break. As the voltage is further raised, chains of conducting particles with two or more breaks begin to carry current. Thus, the porous material becomes permeated with these tiny discharges across the minute breaks in the conducting chains.

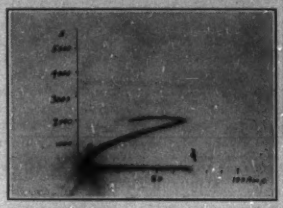

Fig. 11—Discharge through Slightly Conducting Porous Disks

The presence of these tiny pilot discharges will cause the breakdown in the various pores to be lowered very greatly. This is shown in Fig. 7A by the loop $O\ D\ E\ F$. As the voltage is raised from zero there is now a leakage current due to the conducting chains. When the point $D$ is reached enough pilot discharges have formed to cause the fine hole to break down as a whole. The current then increases to the value at point $E$ on the rising part of the volt-ampere curve for a discharge in the hole. If the voltage is now lowered, at $C$ the cut-off voltage for the hole, the current will drop to the leakage value at $F$. The effect of the addition of conducting material is shown also in the loops $O\ D\ E\ C\ F$ in Figs. 7B and 7C.

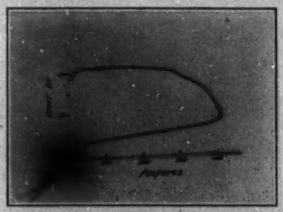

Fig. 12—Discharge through Disk with Eight Per Cent of Aluminum Powder

It will be noticed that the current taken by the hole

at the breakdown voltage is lessened when the conducting material is added. Hence, with a multiplicity of holes in parallel for the discharge of a given current more holes will participate, as is clear from Figs. 7B and 7C. Thus the duty on each hole resulting from the mechanical stress due to the pressure developed by the discharge is lessened since both the voltage and the

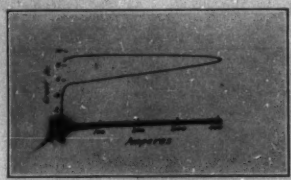

Fig. 13—Discharge through Disk with 12½ Per Cent of Aluminum Powder

current are lowered. This is a very important advantage obtained by the addition of the conducting material. The tendency to shatter or puncture observed in insulating porous material when subjected to very heavy discharges was almost completely eliminated by the addition of the proper amount of conducting material.

The amount of conducting material added to the porous material must of course be properly chosen if desirable lightning arrester characteristics are to be obtained. If too little is used, the breakdown voltage will be high in comparison with the cut-off voltage, and the material will also tend to shatter or puncture.

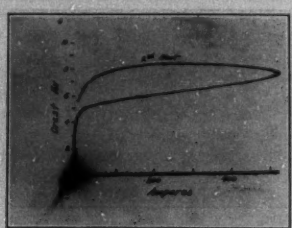

Fig. 14—Discharge through Disk with 20 Per Cent of Aluminum Powder

If too much is used the large leakage current will cause the cut-off to be vague and impose too great a duty on the series spark-gap.

As an example, the results obtained with a series of disks made of a special clay with varying amounts of aluminum powder may be mentioned. When the aluminum was less than 4 per cent of the weight of the disk, the breakdown voltage was very high, in fact so high that on test the discharge usually passed over the edge of the disk rather than through the pores. With the aluminum weight from 4 per cent to 37 per cent, quite good volt-ampere loops were obtained, with sharp cut-off. When the aluminum content exceeded 37 per cent the leakage current became so great as to quite obliterate the cut-off. Figs. 12, 13, and 14 show the progressive change in volt-ampere characteristics with increasing aluminum content.

## Conclusions

The theory and experimental work described above show that there are good possibilities for the development of a valve type arrester utilizing discharges confined to fine pores of a naturally porous material. In a later paper, the authors hope to show how these possibilities have been realized.

## Discussion

**Edward Beck:** The authors have described a new principle which permits the construction of valve type arresters of a new form. The development of lightning arresters incorporating this new principle has passed out of the theoretical stage. About 3000 arresters of the confined-discharge type have been placed in the field for the purpose of accumulating service experience. The first of these installations was a modest one for 2300-volt service made on August 1, 1928. This was quickly followed by others for the same and higher voltages until both line and station

Fig. 1

type arresters have been installed on circuits operating on lines up to and including 110 kv. A 132-kv. station installation will be completed this month.

The standard autovalve arrester was based on the theory that a valve, that is, a voltage-limiting device with a cut-off or valve-closing voltage at the crest value of the arrester's rating, lends itself to the construction of an ideal arrester. The many years of service experience with the autovalve arrester have established the validity of this belief. This valve principle is retained in the new arrester, which might be considered to be born of the

autovalve arrester. However, the performance, although it resembles that of the autovalve, is secured in a radically different manner by the construction worked out by the authors of the paper.

The insulating and supporting structure and series gaps in the new arrester follow the tried and established design of the autovalve.

The reduction in size and weight and the greater convenience of installation which this new arrester principle will permit is indicated by the accompanying illustration. We may look for the day when lightning arresters will be suspended from the towers and station structure, thereby eliminating the space requirement now necessary in the station for lightning arresters.

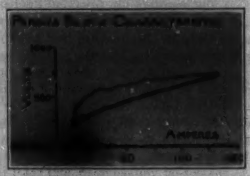


Fig. 2—Volt-Ampere Curve on 3-Inch Diameter Disks Containing 17 Per Cent Aluminum

With over 2500 arrester-years of service experience, the performance of these new arresters has been highly satisfactory, particularly when it is borne in mind that 1929 produced one of the most severe lightning seasons experienced in several years. Equipment and insulator strings protected by the confined discharge arresters have been singularly free from lightning damage and the ruggedness of this arrester principle has been definitely indicated by these field trials.

**K. B. McEachron:** The authors state that in the autovalve arrester "the discharge is constrained to remain in the form of a glow" . . . which is "distinguished from the arc in that it requires several hundred volts for its maintenance." As I pointed out in my discussion of Dr. Slepian's 1926 A. I. E. E. paper referred to, the autovalve arrester does not maintain a voltage of several hundred volts when the current decreases to small values. In my discussion I showed the first cathode ray oscillograms to be taken on the autovalve arrester showing that at low-current values the potential was less than 100 volts. Using volt-ampere curves given by Atherton in the April 13, 1929 *Electrical World*, a voltage of 170 volts per gap is obtained which included the $I\ R$ drop in the disks. Just what this resistance drop may represent in volts is not known, but all of the available data which I am familiar with indicate about double the glow voltage at the time of breakdown and about one-half the glow voltage at the time of sealing. This statement applies to disks in contact so that the spacing is small. It would seem therefore that the autovalve arrester uses the glow principle rather more imperfectly than the authors' statement indicates.

The discussion of the use of restricted passages in a lightning arrester structure is very interesting and represents a valuable contribution. This method of obtaining satisfactory arrester operation, *i. e.*, comparatively low breakdown and high sealing voltage, was disclosed by Percy Thomas in U. S. Patent 882,218 issued in 1908. This patent provides for a large number of conducting particles giving a large number of independent discharges in parallel but constructed so that each path would prevent follow current. Porosity is not discussed in the patent but seems to be a necessary characteristic to give desired discharge.

In Figs. 12, 13, and 14 cathode ray oscillograms are shown indicating the effect of increasing the aluminum powder content. The cut-off potential for the 8 per cent powder in Fig. 12 is approximately 2.5 kv. and about 5 kv. for 12½ per cent and for 20 per cent aluminum as shown in Figs. 13 and 14. It would be interesting to know if all of these tests were made on the same size disks and if the aluminum powder was the only variable.

I have been doing some work along the same line as the authors but have not obtained results quite as good as those given in the paper. Fig. 2 herewith, shows the results obtained from a porous structure containing 17 per cent aluminum powder. The tests indicate that the characteristic obtained is due in some measure to contact conditions at the surface of the electrode and porous material. I wonder if the authors have evaluated the contact effect. It would be of interest in this connection to know whether or not the authors have succeeded in maintaining the characteristic in thick sections or if the porous material will have to be kept in the form of thin disks in order that proper performance may be secured.

The tests which I have made indicate a considerable degree of instability, especially at large current values of the order of 1000 amperes or more. Perhaps a better balance between pore size and amount of conducting material will improve the situation.

In general any characteristic depending on the breakdown of air will exhibit time lag. The greater the rate of application of potential the greater will be the breakdown potential. It can be stated as a general rule that any volt-ampere characteristic which shows a loop in which the current decreases at a lower voltage than it increases will indicate a possibility of time lag. The authors' comment on what they have found with regard to the time lag of porous materials will be helpful.

In connection with materials for lightning arresters I shall describe at the Winter convention a resistance material called thyrite, which has been developed in Pittsfield. Thyrite is a true resistance and as shown in Fig. 3 herewith, has a volt-ampere characteristic which shows no loop whatever as its characteristics do not depend on the breakdown of any gas. For a given applied potential a current will flow which does not depend on the previous history of the discharge nor on whether the discharge is large or small. The d-c. resistance at a given potential is exactly equal to the resistance under transient conditions for the same current or potential, even though the transient may rise to its crest in a millionth of a second or less.

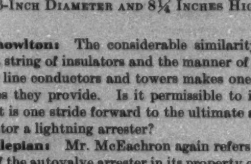


Fig. 3—Characteristic Volt-Ampere Curve for Thyrite 6-Inch Diameter and 8¼ Inches High

**A. E. Knowlton:** The considerable similarity of the new arrester to a string of insulators and the manner of direct attachment to the line conductors and towers makes one wonder what opportunities they provide. Is it permissible to infer that this development is one stride forward to the ultimate aim of making every insulator a lightning arrester?

**Joseph Slepian:** Mr. McEachron again refers to the lack of perfection of the autovalve arrester in its property of constraining the discharge through it to remain in the form of a glow rather than to take the form of an arc. This lack of perfection is admitted. In fact in the design of the arrester this lack of perfection is the one factor which determines the resistivity to be used in the autovalve disks. In my 1926 paper I say "the resistivity of the electrode material must be made only high

enough to take care of surface in homogeneities and the partial contacts due to bridging particles." Also in my closing discussion to that paper I say, "there is a low-voltage part during the last 50 amperes of the discharge which is undoubtedly due to vague contacts and lining up of particles in the gap by the intense field." These quotations recognize the appearance of agents which cause current to flow at less than glow voltage. Proper design of the arrester is able to reduce the effects of these agents in the arrester, itself, but so far has not been able to affect the important place which they have in Mr. McEachron's discussions.

Mr. McEachron refers to the pioneer work of Percy Thomas described in his U. S. Patent 882,218. The arrester described in this patent apparently did not utilize the properties of discharges confined to very fine pores which are described in this paper. This Thomas arrester was manufactured by the Westinghouse Elec. & Mfg. Co. following the specifications of the patent and sold under the name of type M. P. arrester. The discharge element of this arrester is certainly porous, and when tested at sufficiently high voltage does show the characteristics of a rather poor arrester of the pore-discharge type. The reason for this poor performance is lack of sufficient fineness of the pores, and lack of sufficient uniformity of the fineness of the pores. Neither of these requirements is mentioned in the Thomas patent. The material used was also not suitable mechanically to withstand the effects of repeated discharges in fine pores. To obtain these discharges in the pores of the type M. P. arrester it was necessary to apply voltages many times that of the electric lines for which the arrester was designed. This again shows that complete discharges through the pores were neither contemplated nor obtained. The Thomas arrester undoubtedly depended for its action upon tiny sparks across breaks in chains of conducting particles very much as described in the third and fourth paragraphs of Section IV of the paper presented.

Regarding the comparison of Figs. 12, 13, and 14 with respect to cut-off voltage, the records show that for Fig. 12, due to the high breakdown voltage, there was a partial flashover making the position of the cut-off voltage uncertain. The tests corresponding to the three figures were made with disks of the same size, and so far as possible with the same pore size. To eliminate the effect of imperfect contacts, the faces of the disks were coated with metal by the Shoop spray process.

We have found no particular instability in our porous materials at high currents, although I suppose there is some limiting current at which the material would shatter or be damaged in some way. In the laboratory we send discharges of thousands of amperes through porous blocks with no noticeable change in the material. We have in service 66 arresters of this new type on a short length of 66-kv. line. This line formerly flashed over seven-disk insulator strings quite frequently, so that it is quite safe to say that the arresters are receiving discharges of more than one thousand amperes. So far, no arrester has failed.

I cannot agree with Mr. McEachron that there is any necessary relation between time lag and the area of the loop in the volt-ampere characteristics. The sphere-gap, for example, is generally credited with being the fastest of discharge devices, and for moderate overvoltages, has a time lag of only a fraction of a microsecond. Nevertheless its volt-ampere characteristic has a tremendous loop. Thus, the 1-cm. spark-gap referred to in the paper has a loop which reaches from the breakdown voltage of 30,000 down to the cut-off voltage of 40, and yet if the electrodes are moderately large spheres, this spark-gap will have very little time lag. The time lag of the discharge through porous materials has been found to be very short. Data on this will be given in the future.

The similarity in appearance and size of the new arrester to a string of insulators leads Mr. Knowlton to inquire as to the possibility of replacing insulator strings by arresters. If the mechanical strength of the arrester case can be made sufficiently great, I see no reason why this should not be feasible.

# Low-Voltage A-C. Networks
## of the Standard Gas and Electric Company's Properties

BY R. M. STANLEY[1] and C. T. SINCLAIR[2]

Fellow, A. I. E. E. Member, A. I. E. E.

*Synopsis.—The low-tension a-c. network utilizing secondary network protectors has been adopted by five properties of the Standard Gas and Electric Company for service in areas of high-load density. The system has been applied to cities of the second class and smaller, although load density in certain cases is high. Each individual installation was made after a specific study of conditions involved.*

*Underlying principles on which all of the designs are based are: (1) Primary supply at generator voltage (11 kv. or 13 kv.), (2) Omission of feeder regulators, (3) Simplified transformer vault design with barrier wall between primary and secondary equipment, (4) High-reactance transformers, usually inherent, (5) Use of secondary network protectors, (6) Three-phase four-wire secondaries, (7) Use of 250,000 cir. mil. secondary mains (or smaller) forming a solid grid without fuses.*

*The operating experience of the installations made thus far has justified their application. The use of the system in other areas will be considered in future planning.*

* * * * *

THE low-tension a-c. network has come into general use for distribution in the medium sized and larger cities. There are two general reasons for this: first, the high standard of service rendered, and second, the economies resulting.

The high standard of service, both from a standpoint of continuity and regulation, is in a broad sense the result of the principle of a secondary grid fed by a number of primary feeders. Primary faults are isolated by automatic switching. Secondary faults clear themselves. Hence, a failure of either portion of the system does not affect the service rendered.

As there is a strong tendency toward higher voltages, the regulation of the primary feeders is usually negligible. The regulation of the secondary grid is good because of the parallel paths and multiple feeds at the intersections of the grid. These principles are well known and have been discussed at length through the medium of the technical press.

The economies resulting from the application of network principles usually lie in the elimination of the substation by utilizing the generation voltage. Saving is further made in substation operating forces. Improvement in system efficiency is often apparent by use of higher distribution voltage and saving in transformer core loss during light load periods.

Great improvements have been made in network equipment in the past few years and failures of switches to operate correctly are now very infrequent. This is strikingly evident from the fact that out of over 34,000 service operations of the switches installed on the Pittsburgh network only 18 or about 0.05 of 1 per cent were not correct. Service was unaffected by these incorrect operations.

### Networks of Standard Gas and Electric Properties

Five of the larger properties of the Standard Gas and Electric group have adopted the low-voltage a-c. network for distribution in the business district of the cities served, namely Minneapolis, St. Paul, Oklahoma City, Louisville, and Pittsburgh.

The same general plan is being followed in all of these installations. All are of the three-phase four-wire type serving (with the exception of Minneapolis) both power and light from the same secondary mains. The Minneapolis network has separate power and light mains, resulting from an early development, but is essentially a three-phase four-wire system. All are to be served eventually at generator voltage from the generating station, although in some cases a lower voltage feed from a substation will be used for the first step to utilize an existing primary system, until the load in the district develops sufficiently to warrant replacing it with one at a higher voltage.

### Type of Load

The type of load found in the business districts of these cities is typical of that found in larger cities. A number of large office buildings, department stores, etc., are scattered throughout the district, the greater part of which is, however, covered with comparatively small buildings housing small shops.

The power load in these cities is chiefly motors, driving elevators, refrigerating machines, printing presses, etc., and the relation between power and light in the load in each city is as follows:

| | Light | Power |
|---|---|---|
| Minneapolis | 70% | 30% |
| St. Paul | 60% | 40% |
| Oklahoma City | 60% | 40% |
| Louisville | 52% | 48% |
| Pittsburgh | 56% | 44% |

The load densities in these cities is as follows:

| | | |
|---|---|---|
| Minneapolis | 34,000 | kv-a. per square mile |
| St. Paul | 52,000 | " " " " |
| Oklahoma City | 47,000 | " " " " |
| Louisville | 20,000 | " " " " |
| Pittsburgh | 90,000 | " " " " |

1. Byllesby Engr. & Mgt. Corp., Chicago, Ill.
2. Byllesby Engr. & Mgt. Corp., Pittsburgh, Pa.

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In Oklahoma City and St. Paul the areas supplied by networks are at present small, and therefore the load density is higher than might be expected for cities of this class. In Minneapolis and Louisville the areas covered by networks are larger and therefore the load density is lower.

In Pittsburgh, however, where the area supplied by the network is approximately equal to that in Louisville and Minneapolis, the density is very much higher due to the greater development of the district and the larger number of high office buildings, department stores, etc.

The reasons for the adoption of the network were generally the same. The cities had outgrown their old distribution systems and a very considerable expenditure would be required to expand or change them sufficiently to be able to continue to meet the requirements of the rapidly increasing loads. Decision to adopt networks were reached only after careful studies of local conditions, each case being decided entirely upon its own merits.

## Design Features

In the design of all the networks certain broad principles were followed. These are as follows:

(a) Primary supply at generator voltage.
(b) Omission of feeder regulators.
(c) Simplified transformer vault design.
(d) High-reactance transformers, usually inherent.
(e) A system with secondary network protectors.
(f) Three-phase four-wire secondaries.
(g) Use of 250,000-cir. mil, secondary mains, and smaller, forming a solid grid without fuses.

(a) Supplying the network at generator voltage from generating stations eliminated substation construction. In certain cases feeders were also run from substations for added flexibility or as an initial step. In other cases use was made of the existing 4-kv. substation capacity for network purposes.

(b) It was decided to omit feeder regulators where possible after an analysis of the system voltage conditions was made. When higher voltages are used for distribution the primary voltage drop is usually not a limiting factor, except where very long cable runs are necessary. Where the network supply voltage can be varied throughout the day feeder regulators may be omitted, especially if the primary cable runs are relatively short.

(c) A simplified vault design has been developed with a material reduction in the amount of cable work required and a fireproof barrier wall separating the primary and secondary equipment. This design is described in detail later in this paper.

(d) Transformers with 10 per cent reactance are generally used. This reactance is preferably made inherent. Subsequently in the paper a discussion of the value of this transformer design will appear.

(e) The system utilizing network protectors was adopted because of the increased measure of protection afforded to the low-voltage network and to service from the network, since this protective device is nearest to the network. By its use segregation of potential trouble in transformer vaults, in transformers themselves, in primary and secondary connections in transformer vaults is accomplished.

(f) The three-phase four-wire secondary offers a universal system whereby power and lighting loads can be served from the same secondary mains. There have been some objections to 199 for power voltage, but these have been met by the use of boosters when difficult situations were encountered.

(g) Relatively small secondary mains, 250,000-cir. mil and smaller, were adopted as a result of cable burning tests which indicated that larger cables were more difficult to clear in event of a secondary fault. When required, two sets of mains can be installed each in a separate duct. This, of course, requires an additional duct, but these ducts are frequently available because of the elimination of numerous cables on systems being replaced. Secondary grids are not fused and expensive servicing of fuses eliminated and cost of fuse boxes saved.

Information on the important features of the networks is given in Table I. Further details on some of the points are given in the following paragraphs under the headings of the different cities.

## Minneapolis

Formerly, Minneapolis transformers with isolated secondaries were supplied by 4-kv. looped feeders. When the secondaries of these transformers were interconnected to form a network, it was decided to supply additional transformers to be connected to this network by 13-kv. radial feeders. This decision was made as a result of an extensive study of the relative costs and merits of 4-kv. and 13-kv. systems, which showed that the cost of 13-kv. radial feeders for a load increase of 12,000 kv-a. would represent a considerable saving when compared with the cost of 4-kv. feeders and 13/4-kv. substations. Fig. 1 shows the Minneapolis network area.

The Minneapolis network has a number of distinctive features. It is the only one of the group which does not supply both power and light loads from the same secondary mains and which is fed by both 13.8- and 4-kv. banks in parallel. At the present time there are 17 of the former and 23 of the latter. The reactance of the 13.8-kv. transformers is 5 per cent and that of the 4-kv. 3½ per cent. External reactors are installed in the secondary circuit. Some trouble has been experienced during low load periods when the secondary voltage supplied from the 4-kv. systems is higher than that supplied from the 13-kv. system, resulting in some of the network protectors opening and shifting load on the secondary cables.

The 4-kv. bus at Clinton Substation which feeds the 4-kv. network feeders is regulated and corrects for

TABLE I

GENERAL CHARACTERISTICS OF STANDARD GAS & ELECTRIC NETWORKS

| Subject | Minneapolis | St. Paul | Oklahoma Gas & Electric Co. | Louisville Gas & Electric Co. | Duquesne Light Co. |
|---|---|---|---|---|---|
| Area of network present, sq. mi. | 0.57 | 0.125 | 0.10 | 0.50 | 0.50 |
| Present load in network area, kv-a. | 19,300 | 6,500 | 4,700 | 10,000 | 45,000 |
| Kv-a. per sq. mi. | 34,000 | 52,000 | 47,000 | 20,000 | 90,000 |
| Load on network, end of 1929, kv-a. | 9,100 | 1,500 | 5,800 | 2,300 | 22,000 |
| Percentage light and power | Light 70<br>Power 30 | Light 60<br>Power 40 | Light 60<br>Power 40 | Light 52<br>Power 48 | Light 56<br>Power 44 |
| Number of transformer banks | 13.2 kv. 3 $\phi$—18<br>13.2 kv. 1 $\phi$— 1<br>4 kv. 1 $\phi$—23 | 4 kv. 1 $\phi$—20 | 13.2 kv. 3 $\phi$— 9<br>13.2 kv. 1 $\phi$—21 | 13.2 kv. 3 $\phi$—16 | 11 kv. 3 $\phi$—102<br>11 kv. 1 $\phi$— 43<br>4 kv. 1 $\phi$— 43 |
| Ratio installed capacity to peak load | 2 to 1 | 3 to 1 | 1.6 to 1 | 2.04 to 1 | 2.68 to 1 |
| Primary voltage | 13,200<br>4,000 | 13,200<br>4,000 | 13,200 | 13,200 | 11,000<br>4,000 |
| Number of primary feeders | 2 at 13.2 kv.<br>2 at 4 kv. | 3 | 3 | 2 | 7 at 11 kv.<br>8 at 4 kv. |
| Source of supply | 2 substa. | 2 substa. | 1 substa. | Gen. sta. | 11 kv. gen. sta.<br>4 kv. 2 substa. |
| Feeder regulators | None | Regulators[1] | None | None | None |
| Secondary voltage[2] | Lt. 115/199<br>Pr. 230[1] | 120/208 | 120/208 | 115/199 | 115/199 |
| Secondary grid | Fused | Sectionalized by fuses[3] | Solid | Solid | Solid |
| Transformer sizes kv-a. | | | | | |
| 13.2 kv. 3 $\phi$ | 500 & 300 | .... | 300 | 300 & 500 | .... |
| 13.2 kv. 1 $\phi$ | 150 | .... | 100 | .... | .... |
| 11.0 kv. 3 $\phi$ | .... | .... | .... | .... | 500 |
| 11.0 kv. 1 $\phi$ | .... | .... | .... | .... | 100 |
| 2.4 kv. 1 $\phi$ | 200, 150, 100 | 100 | .... | .... | 100 |
| Voltage rating of transformers | 13,800–120/208<br>2,400–120 | 2,400–120 | 13,800–120/208 | 13,200–115/199 | 11,500–120/208<br>2,400–120 |
| Transformer impedance | 5% inherent + 5% external reactance shunted by fuse | 4% inherent | 10% inherent | 10% inherent | 10% inherent on 11 kv<br>4% inherent + 6% external reactance on 4 kv. |

Notes:—

1—Three single-phase regulators on each feeder; compensators not interconnected. These regulators were in use on the old radial system.

2—All secondaries are three-phase, four-wire except the power secondary in Minneapolis which is three-phase, three-wire connected through auto-transformers.

3—To be operated with sectionalizing fuses until sufficient short-circuit current is available to make the fuses unnecessary.

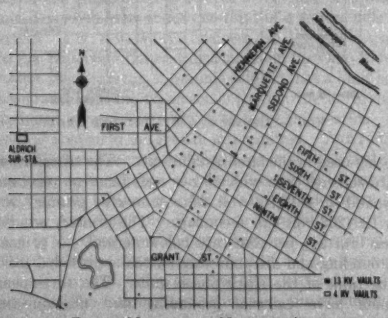


FIG. 1—MINNEAPOLIS NETWORK AREA

variation in system voltage only. The regulators are blocked in one position depending upon the load and voltage so that the load will divide properly between the 4-kv. and 13.8-kv. banks.

The secondary grid is of 500,000 cir. mil. paper insulated lead covered cables. Three-conductor cables were used on the initial step, but single conductor 250,000 cir. mil has now been adopted as standard.

Open type network protectors are used and line type transformers on the 4-kv. system. The 13.8-kv. transformers are the subway type.

All 13-kv. vaults have a fire wall between the transformer and network protector. Some of the 4-kv. vaults have an asbestos board enclosure around the transformers, but others have no separation.

## St. Paul

The St. Paul area is shown in Fig. 2.

Prior to 1929 the a-c. distribution system in this section consisted of a number of radial feeders (some at 2.3 kv. and others at 4 kv.) supplying a comparatively large number of small capacity transformer vaults. Emergency primary service was provided by bringing two feeders into each vault. Each vault supplied its

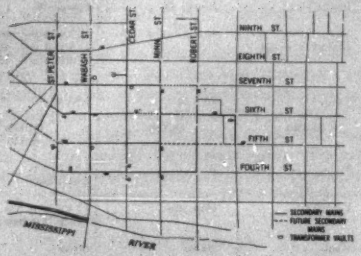


Fig. 2—St. Paul Network Area

own definite load and no provision was made for emergency service in case of failure of a transformer or a secondary cable.

With the rapid increase in the demand for a-c. service in this section it had become evident that some radical changes in the system must soon be made to provide more reliable service for the downtown buildings. Among other things it was certain that larger capacity vaults must be built, and that they must be provided with entrances accessible at all times. The existing vaults were nearly all located in the basements of buildings and were accessible only through the buildings, which often resulted in delays in gaining entrance. These requirements led to the decision to replace a number of small vaults with a few larger capacity vaults, each located under a sidewalk, independent and isolated from adjacent buildings and accessible through hatchways placed in the sidewalk.

Furthermore, the primary system was not uniform. With the exception of the downtown district the old 2.3-kv. system had been eliminated and the 4-kv. system had been substituted.

A study indicated that since rebuilding was necessary, the secondary network offered the most economical and satisfactory solution.

Another factor influencing this decision was the fact that very satisfactory progress had been made during past few years in substituting a-c. service for d-c. service in the downtown district. It is expected that with the reliable service which a secondary network is capable of providing, the reduction in the total d-c. demand will be sufficient to warrant the elimination of certain conversion equipment when it reaches the end of its useful life.

While the initial network step is supplied by 4-kv. primaries, the ultimate design calls for 13-kv. primary supply. The secondary grid is of 250,000-cir. mil single conductor cable, although some 500,000-cir. mil cable is used. Due to the low values of short circuit current obtaining on the initial step, the secondaries are sectionalized by fuses. This is a temporary measure.

The later vaults conform to the newer principles of design in using the barrier wall design.

## Oklahoma City

In Oklahoma City, until the adoption of the network, the distribution system was entirely overhead. When it was decided to place the system underground, the network was adopted as being best suited to local conditions and the type of system most easily expanded to meet increased loads.

The Oklahoma City network, Fig. 3, utilizes single conductor 2/0 primary street mains. It is supplied by three primary feeders from a regulated bus at the Broadway Substation. Individual feeder regulators are not used.

The majority of vaults have a single compartment in which both primary and secondary equipment is installed. The later vaults, however, have been designed with a barrier wall and all future installations will follow this design.

A bank of three single-phase units was installed in the first vaults to be built, but three-phase units are

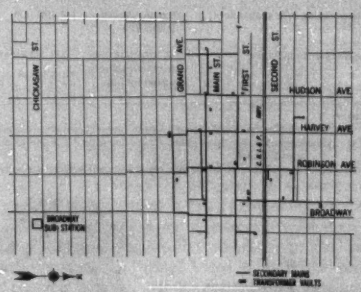


Fig. 3—Oklahoma City Network Area

being used in the later installations. The transformers are subway type with 10 per cent inherent reactance wound for a 13,800-volt delta connected primary, and a 120/208-volt star secondary. The primary winding has four 2½ per cent taps below normal. A primary grounding and disconnecting switch is provided inside the tank of the single-phase units. The three-phase units have external grounding and disconnecting switches in the high-voltage terminal chamber.

Network switches are of the subway type, and 1200-ampere capacity. There are 10 of the solenoid type, and 20 motor operated, 15 of the latter having trip free mechanism.

Braided cable is used between the transformer and network switch on the newer installations, although the older jobs were made with lead covered cable.

Both primary and secondary cables if lead covered, are supported on cable racks with an insulator between the sheath and the rack. The braided cable is supported by porcelain cleats.

The secondary grid is formed of single conductor 500,000-cir. mil lead covered paper insulated cable. Three cables and a 500,000-cir. mil bare neutral are installed in one duct. They are not fireproofed in either the vault or the manhole.

Boosters are installed for power loads, when required. Not more than 1 per cent of the 220-volt load has required auto-transformers. As there are no very high buildings in the city, no serious elevator problems have arisen.

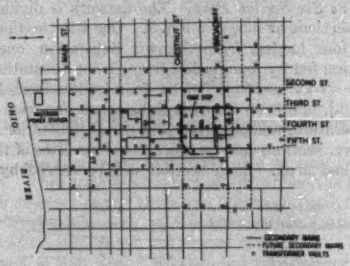


Fig. 4—Louisville Network Area

## Louisville

In Louisville the principal business district is centered about the intersection of Fourth Street and Broadway, and covers an area about one-third of a square mile in extent. Fig. 4 shows the business district with respect to the Waterside Generating Station on the Ohio River. About two years ago it became evident that a limit had been reached in the expansion of the distribution system designed several years before to serve this section. A radical change in the system was required. As a result, a detailed engineering study was made of the situation, considering a number of possible methods of serving the section. These included a 4-kv. radial system fed in one case from the Waterside Generating Station, and in another from a new downtown substation, a 13-kv. radial system from Waterside, a 4-kv. low-voltage a-c. network fed in one case from Waterside and in another from a downtown substation, the extension of the existing system, and a 13-kv. network fed from Waterside. The relative costs of the system studied are of interest.

| | Type of system | Relative cost based on three 5-yr. construction programs including carrying charges |
|---|---|---|
| 1. | 4-kv. radial from existing substation | 1.10 |
| 2. | 4-kv. radial from new substation (disconnecting switch transfer) | 1.34 |
| 3. | Same as 2 except (oil switch transfer) | 1.41 |
| 4. | 13-kv. radial from generating station | 1.86 |
| 5. | 4-kv. network from substation (same as 1) | 1.23 |
| 6. | 4-kv. network from new substation (same as 2) disconnect transfer | 1.40 |
| 7. | Same as 6 except oil switch transfer | 1.44 |
| 8. | 13-kv. network with 250,000 cir. mil (sec. mains) | 1.00 |

By disconnect transfer is meant that the station was designed for transferring the circuits from one bus to the other by disconnecting switches. The alternate was by oil switch transfer.

The study is based upon detailed estimates of each system in its entirety. It was assumed that an increase to 30,000 kv-a. in load could be expected over a fifteen-year period. Losses and operators salaries are included in addition to the actual cost of the money.

It was found that a low-voltage a-c. network fed at generator voltage from Waterside would be the most economical system in the ratio shown. The system closest in cost is 10 per cent higher and was not considered comparable with the network from a standpoint of reliability of service, ease of operation, expansion, and feasibility of construction in the streets.

The secondary system of the Louisville installation is three-phase four-wire 115/199 volts. The general network plan covers an area of a little more than half a square mile, although the initial step covers a somewhat smaller area. The primary supply is at 13 kv. directly from the Waterside Generating Station. The transformers are 300 kv-a. with 10 per cent inherent impedance, in barrier vaults described later. The secondary mains are 250,000 cir. mil although existing mains of smaller size are used where possible. No regulators are used in the primary feeders.

The cutover was accomplished by the construction of a small number of vaults forming a small network. The load was then cut over to this network and new vaults added gradually.

## Pittsburgh

The business district of Pittsburgh lies between the Allegheny and Monongahela Rivers immediately at their confluence. The area covered is one-half square mile but is triangular. Fig. 5 shows this area with respect to the rivers, and Fig. 6 shows the detail of the business district. The two principal generating stations, Colfax and Brunot Island, are shown and the 66-kv. ring bus connecting them.

Before the installation of the network, the business district in Pittsburgh, Fig. 6 was fed by 4-kv. three-phase radial feeders from three substations located near the three corners of the district. Duplicate throw-over service, necessarily involving an interruption, was supplied to most of the customers by feeders from different substations from which they were normally fed. In addition to the 4-kv. system many customers were still

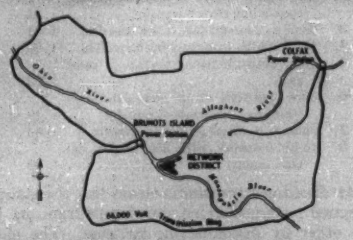


Fig. 5—Showing Relative Location of Network and Sources of Supply

served from the remnants of older systems eventually to be discontinued. These included one-, two-, and three-phase, 2300-volt systems and a small d-c. radial system. No d-c. network was ever installed in Pittsburgh.

The downtown substations were fed primarily by 11-kv. feeders from the Brunot Island Generating Station located on the Ohio River about three miles downstream. Another generating station at Colfax about fifteen miles up the Allegheny River is tied to the Brunot Island station through a 66-kv. transmission ring around the city. A few 22-kv. feeders from ring substations also fed into the downtown substations.

In 1926 the 4-kv. equipment in the downtown substations was loaded to its safe capacity. A number of large buildings was planned for immediate construction about this time, which indicated a considerable increase in new business load in addition to the normal growth in the existing load. A very considerable increase in 11-kv. and 4-kv. substation (Stanwix) equipment would have been required to serve this additional load satisfactorily. This major extension of the substation would have meant additional transformer capacity with necessary bus extensions and oil circuit breaker equipment. The cost of such an extension would have been large. Further expenditures would have been required for additions to the 4-kv. distribution system. Duplication of services in the downtown section had caused such congestion in the duct lines that new duct construction was necessary unless concerted effort was made to clear existing ducts.

Studies of cost of service in the Triangle were made as follows: first, extending existing 4-kv. radial system; second, a-c. network fed at generator voltage direct from Brunot Island Generating Station.

The results of these studies indicated clearly that a very considerable saving would result from the adoption of the network fed from the generating station with a material improvement in service to customers. It was also found that by taking all of the load over on to a network the number of old cables removed would be greater than the number of new cables required, with a net gain in spare ducts, making new duct construction unnecessary.

*Secondary Voltage.* A three-phase four-wire network operating at 115/199 volts and fed by a large number of comparatively high reactance banks was adopted for the Pittsburgh District.

The lighting voltage had been standardized in Pittsburgh at 115 volts and most of the motors in use were of the 220-volt type. A star connected system with 115 volts to neutral would be satisfactory for lighting but would supply only 199 volts for the motors. This is, however, within the 10 per cent low limit guaranteed by the manufacturers for satisfactory motor operation.

*The Six-Section Plan.* The network is divided into six sections as shown in Fig. 7. One 4-kv. section is fed by four feeders from Stanwix Substation, one 4-kv. section fed by four feeders from Grant Substation, and four 11-kv. sections fed by four feeders from Brunot Island, one from Stanwix Substation, one from Grant Substation, and one from 13th Street Substation. The 11-kv. sections take in more than four-fifths of the networked area. Each section will be served by three

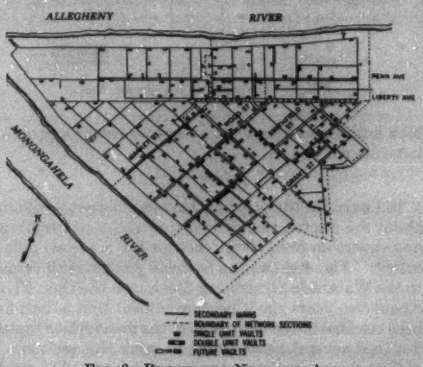


Fig. 6—Pittsburgh Network Area

feeders. This is the smallest number that it is thought safe to install. Any one of these feeders may be taken out of service and held out indefinitely without overloading the other two. It was decided that no one feeder should serve more than two sections. The minimum number of feeders required to satisfy these conditions (*i. e.*, 4 sections, 2 sections to a feeder, 3 feeders to a section) is six. Actually seven have been installed,

but the seventh, an existing 4/0 cable from 13th Street, is required only for added flexibility. It is used for the fourth transformer bank in a few large customers' installations. Without this feeder two of the banks in these vaults would have to be fed from the same feeder.

The feeders have been arranged in such a manner that any one of the four sections may be completely de-energized by disconnecting the three cables feeding it

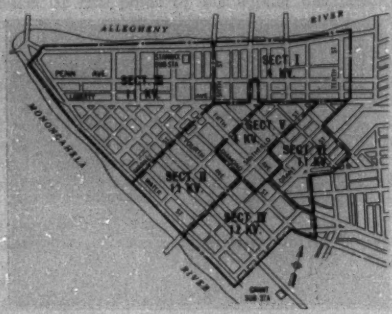


Fig. 7—Map Showing Six Sections of Pittsburgh Network

without affecting more than one cable in any other section. Thus with a minimum of six cables it is possible to de-energize any three and still have two left to carry the load in each of the three other sections. The remaining cables will not be overloaded.

A total of 190 banks of 300-kv-a. transformer capacity will supply the district upon the completion of the 1929 construction program. Approximately two-thirds of these are to be 11-kv. units. The majority of these are in single-unit vaults, but there is quite a number of vaults with two and some with three and four units.

*Primary System.* The 4-kv. primary feeders consist of 3-conductor 500,000-cir. mil sector shape copper, paper insulated lead covered cables. Primary mains consisting in some cases of the same size cable and in others of 250,000 cir. mil depending upon the number of vaults to be connected, radiate from the feeders. The feeders operate in parallel from the same bus at the substation.

The 11-kv. primary feeders consist of 3-conductor, 500,000-cir. mil sector shape copper, paper insulated lead covered cables.

The 11-kv. mains from the feeder are either 3-conductor, 500,000-cir. mil or 3-conductor, 4/0 cable, depending upon the number of vaults to be served.

*Floods.* An unusual characteristic in Pittsburgh, which must be taken into consideration in the design of an underground system, is the frequency with which serious floods occur. A rise in the river of 20 ft. above the normal stage is not unusual, and a rise of 15 ft. is sufficient to flood basements in the Triangle. Drains are, of course, useless at such times and pumps are of value only in retarding the rise of water in the basements. The flood stage takes in about one-half of the area of the Triangle. All electrical equipment installed underground within this portion must be of the submersible type. The vaults are consequently designed to operate indefinitely when completely filled with water.

*Transformer Vault Design.* The single-unit vaults consist of two compartments, usually without a connecting door. The transformer is located in one compartment and the network switch and other secondary equipment in the other. This design is shown in Fig. 8. Access to each compartment is generally through a separate opening in the sidewalk. Where permits for two openings cannot be obtained, a fireproof door is provided in the dividing wall. This door is hung so as to swing into the closed position when not forcibly held open. The wall between the vault and the basement of the adjacent building is solid without any opening. This design resulted from property damage on customers premises on occasion of vault fires. Openings in the wall between compartments are located 14 in. or more above the floor, and where a door is necessary a sill 14 in. high is built across it, or of sufficient height to hold all of the oil of the transformers in the enclosed space in case of bursted or leaky tanks. The average floor space required for a single unit vault is approximately 64 sq. ft. for a three-phase, and 88

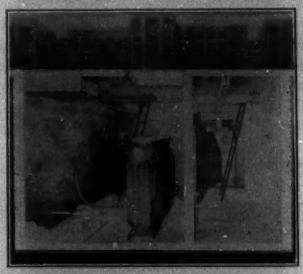

Fig. 8—Low-Voltage A-C. Network Vault

sq. ft. for single-phase primary compartment, and 40 sq. ft. for the secondary compartment. The minimum headroom is 10 ft., providing sufficient headroom for future 500 kv-a. transformers. Transformer banks are placed in individual primary compartments of reinforced concrete where more than one bank is used, thus isolating each bank. One installation recently placed in service contained seven banks. There are numerous others in service with 2, 3, and 4 units. Network switches for such installations are placed to-

gether in a single secondary compartment. Designs are available for isolation of secondary units should future operating experience indicate that this is desirable.

Ventilation for the primary compartment is normally by natural draft. Forced draft is provided in a few instances. The secondary compartment is not ventilated unless a booster is installed. With natural ventilation the inlet and outlet are placed in the side-walk near the building line and covered with sidewalk type gratings. Usually an opening of 4 sq. ft. is obtained. An all metal trap door is provided below each grating, normally held open by a fusible link. In case of fire producing sufficient heat to melt the fuse the door will be closed by a counterweight and prevent flames rising through the grating to the street.

Cable work was reduced to a minimum, especially the secondary work. Primary cable runs from the duct entrance in the wall directly to the pothead which is an integral part of the transformer. It has been common standard practise in the past in secondary runs to use lead covered cables for subway type construction between the transformer and network switch with a wiped joint at the transformer. Recognizing that it might be difficult to burn off a fault occurring between phases where 1,000,000-cir. mil or larger cable is used, it was decided to reduce this hazard materially by using a varnished cambric flame-proof cable with the shortest possible run.

Stud type porcelain bushings are used on the transformer secondary. These bushings are water-tight and provide a ready means of terminating the transformer

Fig. 8a—Detail of Standard Vault—Louisville

Primary cable terminating in pot head at base of oil immersed disconnecting switch on transformer. Operating handle for disconnecting switch is shown on right side of switch box

Fig. 8c—Detail of Standard Vault—Pittsburgh

Subway type network protector with bus and fuse box. Flame proof cable used throughout. Note fire proofed secondary lead covered cable from fuse box into ducts

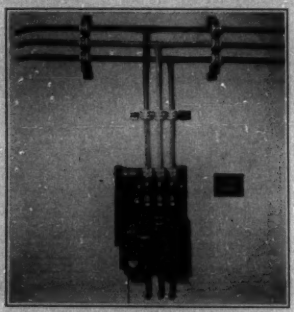

Fig. 8b—Detail of Standard Vault Design—Louisville

Secondary bus construction with line type network protector. Flame proof cable used for bus work. Note cables from lower side of network switch running through barrier wall into primary compartment

Fig. 8d—Rig Used in Lowering Transformer into Vault—Louisville

secondary and at the same time preventing leakage of water into the transformer when submerged. The same type bushing is used on the network protector. The transformer and network protector are thus submersible, and are protected against water seepage through the strands of the flame-proof cable.

The flame-proof cable is continued from the outgoing side of the network protector and terminates in a water-tight fused junction box. Lead cables from the street connect at this point to the wiping bushings. The junction box provides a convenient means of connecting the flame-proof cable to the lead covered cables, providing a water-tight terminal. Vault lighting is supplied through a similar but smaller junction box.

*Transformers.* The 100-kv-a. single-phase subway type transformers previously used in the 4-kv. radial system have been transferred to the 4-kv. network. These transformers have approximately 3.8 per cent impedance and external reactors (cable type, built up of iron punchings) are used to bring the total reactance up to about 10 per cent.

New transformers selected for the 11-kv. network are three-phase, 300-kv-a. units and single-phase, 100-kv-a. units provided with four 2½ per cent taps below normal on the primary side. The inherent reactance of these transformers is 10 per cent. The value of 10 per cent reactance was adopted as a compromise value which would afford the best voltage regulation possible, together with an economical spacing of transformers required to provide sufficient short circuit current to burn off secondary faults, while at the same time providing against overheating or damaging of any one or more transformer banks during a burning off process following secondary network cable breakdowns.

Potheads for the primary cables and a primary grounding switch are mounted in a sheet steel box attached to the case of the transformers. The lead sheath of the cable is wiped to a sleeve on the bottom of this box. No cable joints are therefore required between the manholes and the transformer. A completely water-tight job that can be safely installed in flooded areas is thus obtained. The primary switch is used only for convenience in taking a unit out of service for maintenance or repairs, and cannot be operated while alive. It is mounted in such a manner as to be readily accessible upon removal of a bolted cover. It is electrically interlocked in such a manner that it cannot be opened while the transformer is energized. The operating mechanism is so arranged that it is necessary to close the switch in the transformer position before moving it from the open to the ground position. If the line is energized it will then energize the transformer and cause the electrical interlock to engage, thus making it necessary to de-energize the line before the switch can be operated.

*Network Protectors.* The earliest type of network protector is a solenoid operated carbon circuit breaker controlled by three single-phase relays. The second is of the motor operated contactor type controlled by one master polyphase relay and with a phasing relay which is designed to prevent pumping under exceptional conditions such as when the transformer voltage lags the network voltage.

The latest type is similar to the last but has a trip free mechanism. All future switches installed on the system will be of this type. Switches generally used are rated at 1200 amperes.

*Secondary System.* Cables used in the secondary system are 250,000-cir. mil lead covered single-conductor with 4/0 bare neutral. The three cables and neutral are installed in one duct. When required, more capacity is obtained by an additional set of mains in a separate duct. In such cases they are paralleled at street intersections. The secondary system and transformer vaults are shown in Fig. 6.

The secondary cables are not fireproofed. Sheath currents are allowed to flow, and due to the low mutual reactance and the comparatively high resistance of the sheath circuit, the currents are not of sufficient magnitude to cause appreciable heating.

*Fuses.* All customer's services fed directly from a transformer vault and connections between the transformer banks and the street secondary mains are fused. Customers' services fed from the secondary grid are not fused in the street, but a fused entrance switch adjacent to the cable terminal is supplied by each customer. In the sectionalizing scheme each of the six areas is covered with a solid grid isolated from the others. No fuses or junction boxes are used to sectionalize the secondary grid.

*Boosters.* Boosters are required on services feeding two-wire, 220-volt heating elements as 199 volts is too low for satisfactory operation. It is found that nearly all motors will operate satisfactorily at 199 volts. Boosters are, however, installed for motor services where a higher voltage is desirable. The cost of boosters amounts to only a small percentage of the total cost of a standard installation, and their use does not appreciably affect the cost of service from the network.

*Procedure during Cutover of Load.* Previous to the adoption of the network the smaller loads in the downtown area were fed from distribution vaults each supplied with two 4-kv. feeders. In the case of the first 4-kv. network, it was possible to install network equipment in nine of these vaults by shifting load from one to the other and rebuilding one at a time. Upon the completion of this work the secondaries from these vaults were tied together. Three feeders supplied the nine transformer banks, three banks from each feeder. The network protectors were locked closed forming a non-automatic network. As it required only a few hours to make the secondary ties, the hazard from primary cable trouble was not great. The network

switches were then made automatic putting the network into operation.

New vaults were added one at a time until all vaults in the area were tied into the network.

The conditions were somewhat different in cutting in the second area. There were several 4-kv. radial vaults which were to be eliminated and 11-kv. supply substituted. A small network was formed by connecting the secondaries of the four 4-kv. vaults. Nine 11-kv. vaults had been constructed in the area and the transformers energized, the network switches being locked open. The secondaries from the 11-kv. transformers were next connected to the small 4-kv. network. Upon the completion of these ties, the network switches in the 11-kv. vaults were closed paralleling the 11-kv. and 4-kv. systems. The 4-kv. transformer banks were then disconnected transferring the load to the 11-kv. supply without interruption to service. The remaining 4-kv. vaults were transferred by paralleling their secondaries and disconnecting the vaults one at a time.

The entire process of cutover presented no difficult problem as the 11-kv. and 4-kv. systems were designed for parallel operation when required. Such changes were usually made on Sunday during the light load period.

*Secondary Faults.* A most important consideration in the operating of an a-c. network is to be certain that secondary faults will clear before any serious injury has been caused to the system as a whole. With a solid grid such as that installed in Pittsburgh, secondary faults must burn clear as no other means has been provided for isolating them. The great majority of faults will clear themselves with very little effect on the remainder of the system. In some extreme cases, however, the fault may hold on for some time and produce a considerable amount of smoke and fire which if it does not cause any damage probably will be objectionable from a public-relations standpoint. To guard against these possibilities it is necessary to make certain that the short circuit current that will flow into a fault at any point in the system is sufficient to clear it under the most exacting conditions in a very short time. The short circuit current is determined by the impedance of the primary cables, the number of transformer banks feeding into the grid, their proximity to the point at which the fault occurs, and the impedance of the grid. Generally the proximity of the banks to the fault is the determining factor. To insure the safety of the system at the time of a secondary fault, it is therefore necessary to properly proportion the size of copper used to the number of transformer banks available. In a few cases, it is necessary to install banks which are not required for load conditions, but are required to increase the short circuit current available at the time of a fault. The magnitude of the short circuit current required varies with the size of conductor used for the secondary grid. The Duquesne Light Company has adopted a 250,000-cir. mil conductor for this purpose. Certain 500,000-cir. mil cable is used in a few localities where sufficient short circuit current is available to clear it in a minimum of time.

*Types of Faults.* There are two general classes of faults that may occur on the secondary grid, grounds between conductor and sheath, and phase to phase short circuits involving two or three conductors. They may also be classified as point or surface contact faults, a point contact fault being produced when a sharp point like a pick breaks through the sheath and touches one or more conductors, and a surface contact fault resulting when a live conductor comes into contact with a metal pipe or when two conductors from which the insulation may have been burned come into contact with some metal support.

Point contacts are by far the most common of all cable faults, and generally clear almost instantaneously by either fusing the lead around the entering point when only one conductor is involved or by fusing the point when two conductors are involved. Faults of the second type, although comparatively rare, are frequently very serious. These are the faults that must be considered when a system is designed.

*Short Circuit Tests.* Before adopting the 250,000-cir. mil cable for the secondary mains the Duquesne Light Company ran a series of tests to determine the size copper best suited to the conditions obtaining on the Pittsburgh network, and also to determine the magnitude of the short circuit current required to clear the most serious faults. The test equipment was arranged to simulate conditions that might be actually met, and provide currents as high as 25,000 amperes for long periods. The conclusions reached as a result of these tests confirmed various assumptions which were generally accepted, but for which supporting data were lacking. These may be enumerated as follows:—(1) any size copper will clear if sufficient current is available; (2) the amount of disturbance produced is directly proportional to the size of conductor and the amount of insulation involved; (3) the current required to fuse a given size conductor is considerably less than that determined by Preece's formula,[3] due to the thermal resistance of the cable insulation and duct.

As a result of these tests the 250,000-cir. mil cable was adopted, since 3500 amperes was found sufficient to clear immediately and with little disturbance any fault occurring on this size of cable. The Duquesne Light Company system is accordingly being designed to supply as near as possible 3500 amperes short circuit capacity at all points in the grid. In those localities where 500,000-cir. mil cable is used 6000 amperes short circuit current is provided.

A summary of the test results will be found in the Appendix to this paper.

*Paralleling Feeders from Different Sources of Power.*

3. $$I = . a \sqrt{d^3}$$

wherein $I$ = current required to fuse conductor, $a$ = a constant depending upon the material, and $d$ = diameter of the wire.

No operating difficulty has resulted from paralleling feeders from a substation with those from the generating station, although there is some unbalance in loading. At the present time the loading of the network feeders is normally less than the loading of those feeding into the downtown substations. The same size cable is used for each purpose. The voltage drop from the generating station to the substation is consequently greater than from the generating station to the network. This amounts to low voltage on the substation network feeders and results in their not carrying their full share of the load. This condition will tend to correct itself as more load is cut over to the network, as this will tend to bring the loading on the substation and network feeders more nearly together and equalize the voltage drops.

*Voltage Fluctuations.* In order to minimize voltage fluctuations, all large induction motor installations are required to be equipped with a starter preferably of the resistance type that will limit the starting current to increments of 200 amperes at half-second intervals. Other types of starters are permitted if the increments by which the current increases during the starting period do not exceed 200 amperes. The 200-ampere increment will normally keep the voltage dip below two volts even with the poor power factor in starting. In certain cases this limit has been materially extended.

*Pumping of Network Switches.* Trouble may result from serving one section of a network from two different sources if they should get out of synchronism. At such times the network might be the only tie between them. A heavy cross-current would then flow which might injure secondary equipment and also would reverse the direction of power in one feeder. The network switches on this feeder would then open. This would re-establish normal conditions on the network. The phasing relay would prevent the switches on the out-of-phase feeder from closing if there is sufficient phase displacement. If there is a small difference in frequency, of the order of one or two cycles, opening and closing of the switch might continue for some time and the switch contacts be seriously damaged by the heavy current interrupted. Such trouble is most likely to occur at low load periods, as the network load has a stabilizing effect and tends to counteract the effect of the synchronizing current. A switch not trip-free might in these circumstances be severely burned, therefore trip-free switches are used.

*Voltage Regulation.* The 4-kv. radial system superseded by the network was served by feeders from a regulated substation bus. The network feeders are not regulated, and voltage tests made from time to time since the installation of the network indicate that regulators are not needed. The generating station bus voltage is, however, lowered at night according to a definite schedule, and this prevents any appreciable increase in the customer's secondary voltage. The permissible voltage regulation on the Pittsburgh network is plus or minus 5 per cent for lighting, and plus or minus 10 per cent for power. The normal network regulation, however, is less than 2 per cent.

*Network Switch Operation.* The operating of the network switches has been very satisfactory. There has been a total of 34,100 switch operations since the first section of the network was energized. During this time, there have been fifteen primary faults and so far as is known eight secondary faults. Only once did a switch fail to operate on a primary fault. In this instance, the switch blocked and the fuses blew. A total of 18 failures of switches to operate has been recorded. The switches are inspected and tested once a month or oftener in case of any unusual operating condition. Complete inspection and adjustment is made every six months. Periodic load and voltage checks are also made on each bank.

## Conclusions

A-c. networks are desirable for the following reasons:

(a) Lower cost of serving the district. Network installations have been found to cost from 80 per cent to as low as 50 per cent of the cost of other systems, effecting a saving in yearly fixed charges.

(b) Economies of operation. These economies result from the use of a higher transmission voltage and a reduction of distribution losses. An important item in reducing these losses lies in the possibility of disconnecting feeders with their transformers during light load periods.

(c) Elimination of operation costs in substations.

(d) Elimination of maintenance costs in substations.

(e) The network is capable of almost indefinite expansion within a given area, or extension beyond to include greater area. Other radial a-c. systems such as throw-over or pick-up schemes soon reach a state of development where it is not possible to foresee clearly how the ultimate load can be satisfactorily served. This has been found to be due in part to street congestion, whereas the study of the network system for such a situation showed ample space for ducts, manholes, and vaults for the ultimate load possible to predict (based upon present experience and method of estimating load).

(f) Reliability of service. Operating experience of several years by other companies has demonstrated that reliability of service and close voltage regulation can be obtained at lower cost with a-c. networks. These experiences have been duplicated on the properties described above, and as further experiences are obtained it may be confidently expected that standardization of method of design will result in further economies of construction and operation and permit giving better service at still lower costs.

## Appendix

*Secondary Fault Tests.* From previous tests it had been found that faults between the lead sheath and a conductor will clear in a few cycles and without seri-

ously injuring adjacent cables. Also, that copper to copper faults formed by loosely wrapping with binding wire or by large (⅜ in. square) spikes being driven into the conductors, will clear in a short interval and will not transmit trouble to the adjacent cables. As a conclusion to the previous tests, it was expected that wherever a fault occurred such as driving a drill into a live cable or where the insulation had become charred and the conductors were allowed to come in contact, that the arc established at such a contact would be sufficient to cause the immediate fusing of the copper and that the fault would be cleared in a very short interval providing sufficient current was available.

It has been questionable, in the rare cases where the conductors come solidly in contact and there is no chance for an arc to be established, whether or not the conductors will burn themselves clear, and if so, what value of current will be necessary. In previous tests such faults could not be cleared due to the thermal

Fig. 9—Test Set-Up Showing Location of Transformers and Duct Line. The Reactors were Wound on the Three Cable Reels at the Transformers

capacity of the test equipment not being sufficient to sustain the current for a long enough period. It was decided to make a set-up of test equipment so that currents from 5000 to 25,000 amperes could be maintained for at least an hour.

*Test Set.* Ten 300 kv-a., three-phase, 11,000/200-volt network transformers were connected in parallel fed by a 500,000- cir. mil cable directly to Brunot Island generating station. The maximum short circuit of each transformer is approximately 14,000 amperes on the 115/200-volt side so that neglecting the impedance of the bus tie between banks, a possible current of over 100,000 could be delivered. In order to control this value of current a set of reactors was constructed which limited the current in steps from 5000 to 40,000 amperes and these values of currents could be maintained for some time without endangering the transformers or primary cables. The test set-up is shown in Fig. 9.

The cable to be tested was run through a duct line built especially for the tests and consisted of two 4½-in. iron pipes, one 3-in. iron pipe, four 4½-in. fiber ducts, and two 3½-in. fiber ducts all incased in concrete, with a brick manhole at each end in which the joints were made. One end of the test cable was connected with three sets of 500,000-cir. mil cable and the other end with two sets of 500,000-cir. mil cable and all connected to the transformers through a 2,000,000-cir. mil bus.

Fig. 10—Type of Short Circuit Employed in the Tests

Note the three conductors and neutral bound solidly together with heavy binding wire

*Test Procedure.* In each case a short was applied as illustrated in Fig. 10, and the set of cables pulled into the duct and connected up with standard joints and sleeves as shown in Fig. 11. The transformers were then energized by closing the 11,000-volt test breaker and held on for ten minutes after the fault had cleared. After a few seconds smoke and gases began pouring out of the manhole, followed by ignition of the liberated gases as the cables were clearing, the gases and compound from the cables caught fire, and dense clouds of smoke poured out of the manholes. In order to pre-

Fig. 11—Standard Joints used in Test

serve the damaged cables the flames were extinguished immediately after the fault cleared.

The metering equipment consisted of large ratio current transformers registering on indicating and high-speed graphic ammeters. An oscillograph was used for a few of the tests but due to the duration of the test, it was not possible to record the clearing of the fault. The value of current shown is the total current and is divided as follows: For 500,000 cir. mil supplied by 3-way feed 67 per cent, by 2-way 33 per cent. For 250,000

cir. mil supplied by 3-way feed 62 per cent, by 2-way 38 per cent. This resulted in one end clearing first and is shown on the charts by the sudden decrease in value. However, the times considered in the test results represents the average total time to clear all phases from both ends, and are therefore based on the total fault current.

The conditions under which each test was conducted and the average time to clear all phases are shown in Table II.

mil cable 67 per cent and 33 per cent). The two-way feed with a three-way junction point at one end and a two-way junction point at the other, was used to simulate actual network conditions. This is diagrammatically shown in Fig. 16.

Ignition of the generated gases was noticed on each test, particularly when the sealed joints blew open.

Joints were made up using copper connectors and by wrapping the leads with binding wire and then soldering.

TABLE II
SUMMARY OF TEST RESULTS

| Size cable | Type cable | Duct | Total current | Type fault | Special condition | Time to clear |
|---|---|---|---|---|---|---|
| 500 MCM | 1 cond. | Fiber | 8,000 | Sheath to conductor | | Few cycles |
| 500 MCM | 1 cond. | Fiber | 15,000 | Solid | | 172 sec. |
| 500 MCM | 1 cond. | Fiber | 15,000 | Solid | | 143 sec. |
| 500 MCM | 3 cond. | Iron | 15,000 | Solid | | 129 sec. |
| 500 MCM | 1 cond. | Fiber | 19,000 | Solid | | 90 sec. |
| 500 MCM | 1 cond. | Iron | 25,000 | Solid | Mhs. filled with $CO_2$ gas | 45 sec. |
| 350 MCM | 1 cond. | Iron | 15,000 | Solid | | 78 sec. |
| 250 MCM | 1 cond. | Fiber | 15,000 | Solid | | 42 sec. |
| 250 MCM | 1 cond. | Fiber | 15,000 | Solid | | 41 sec. |
| 250 MCM | 1 cond. | Fiber | 25,000 | Solid | Mhs. submerged with water | 16 sec. |
| 4/0 | 3 cond. | Iron | 15,000 | Solid | | 29 sec. |
| 1/0 | 1 cond. | Fiber | 15,000 | Solid | | 11 sec. |
| 1/0 | 1 cond. | Iron | 19,000 | Solid | | 8 sec. |
| 1/0 | 1 cond. | Fiber | 25,000 | Solid | | 4½ sec. |
| No. 6 | 1 cond. | Fiber | 15,000 | Solid | | 3½ sec. |
| 1000 MCM | 1 cond. | Iron | 6,000 | Sheath to conductor | | Few cycles |

Note: More than 70 tests were made, the above being typical results showing the range.

*Tests Results.* After each test cable length was examined, as well as all the joints, and their condition recorded. In all cases the fault was cleared by burning off the cable in the manholes between the duct edge and the joint. Fig. 12 shows the same three single-conductor 250,000-cir. mil cables as in Fig. 11, after approximately 15,000 amperes had been passed into the fault.

Fig. 12—Joints of Fig. 11 after Test

Note the clearing of the fault at the joint

The time required to burn the various sizes of cable tested at different values of current is plotted in Fig. 13.

In interpreting the curves it should be noted that the current given is the total current from two directions, the proportionate current values are as previously given (for 250,000-cir. mil cable 62 per cent from one direction and 38 per cent from the other; for 500,000-cir.

One of the joints shown in Fig. 12 is shown opened up in Fig. 14.

One interesting result of the tests shows that when single conductor cables are used the lead will, in most cases, be melted off from the cables in the duct run, but

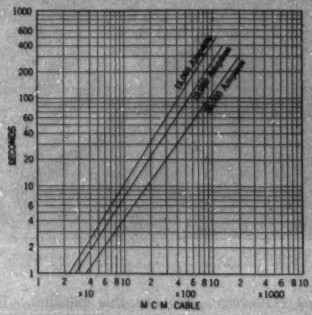


Fig. 13—These Curves show the Total Current Flowing into the Vault from Both Directions and the Time in which Different Size Cables Cleared

Note that the current is the total of a two-way feed approximately 60 per cent supplied from one end and 40 per cent from the other

that when three conductor cables are used the lead sheath will remain substantially intact, although the insulation is entirely burnt away and the conductors are in contact with the lead. This would tend to show that the actual burning of the lead on single conductor

cables is due in part, at least, to the sheath currents which are produced.

When the fault was cleared under water the volume of smoke was less and there was no evidence of fire. Fig. 15 shows the joints after this test.

In the last two tests a tank of $CO_2$ gas was liberated in each manhole through a nozzle prior to energizing the fault. The clearing of the fault was identical to the other tests with 500,000-cir. mil cable as far as time and method of clearing was concerned. The smoke which poured out of the manholes during these tests

Fig. 14—Joints of Figs. 11 and 12 Opened After Test

was as much in volume as in other tests, although the force of the explosions was not as severe and no flames were present. Further tests along these lines might produce interesting results.

*Analysis of Test Results.* Generally speaking it was found that, where arcs are eliminated by making solid copper to copper faults, the cable has characteristics similar to a fuse. The current-time characteristics

Fig. 15—Joints After Submersion Test

discussed elsewhere, indicate this parallel. There is reason to believe, therefore, that any size cable in common use can be burned off and cleared if sufficient current is available. There is a practical limitation, however, in so far as the volume of smoke or flame liberated is concerned. It is generally agreed that the larger the cable the greater the current and time required to burn clear, and the more smoke and flame will be liberated. There is also a greater possibility of manhole explosion.

Another important consideration lies in the possible damage to the electrical system itself. A study of the effect of secondary shorts as far back as the primary cable indicates that the primary cables themselves and the transformers must be designed to withstand short circuit for a considerably longer period. Tests on the network switch indicate that it is adequate and superior thermally and mechanically to the transformer and secondary cables in a normal system. However, both transformer and switch are protected by a fuse which should be so chosen as to fail first.

The secondary system as a whole should suffer no damage as a result of a fault. Damage to all cable which carries the maximum current is to be expected; but when a two-or three-way feed point is passed (and this should be at the first street intersection) the cable will be found undamaged. This condition is illustrated in Fig. 16.

With a two-way feed to the fault the current in the conductors supplying the faulty section is ½ and the thermal effect is ¼ of that in the faulty conductor. With a three-way feed the current is ⅓ and the thermal effect is 1/9 of that in the faulty section. The test

Fig. 16—A Network with Uniform Cable Sections and Transformer Capacities is Assumed

setup simulated the above condition and many tests on a set of cables forming the two-way and the three-way feed did not materially injure them after completely destroying a number of cables under test carrying the full fault current. We may, therefore, expect the faulty cable to clear at the fault or between the fault and the first multiple feed joint on each side of the fault.

This fact was borne out by the tests since the five sets of cables feeding the faulty cable were used throughout all the tests and the insulation was still in good condition and well impregnated.

*Conclusion from Tests.* 1. A 500,000-cir. mil cable in either iron or fiber pipe can be burned clear with currents of 5000 amperes and above, and 250,000-cir. mil cable with 3500 amperes and above.

2. The resultant explosion, flame, and violence of burning clear a fault on cables larger than 250,000-cir. mils is so severe as to be extremely objectionable from an operating point of view in a congested business district with narrow streets.

3. With a single conductor cable installed alone in a fiber duct there is no apparent limitation to the size of the copper that can be safely used. The clearing of the fault in this case is not accompanied by explosion or violence but is practically instantaneous due to the rapid fusing of the lead sheath.

4. In general, faults such as conductor to sheath, conductor to conductor, established by means of a pick, drill, etc., are very easily cleared at the point of fault due to contact fusing. In faults, where the conductors become solidly connected, the conductor may not be burned clear at this point but will fuse back often as far as the first manhole, destroying the insulation and lead until physical separation permits it to clear.

5. It was also noted that in a severe type fault there is no difference in the time of clearing a fault with a given amount of current, whether single- or three-conductor cable, and whether it is in an iron or fiber pipe. Faults also were cleared when the manholes were entirely submerged.

6. The resulting flame and explosion can be minimized by the introduction of $CO_2$ gas in manholes adjacent to the fault.

7. A certain relation between current, time, and conductor size has been established so that it is possible to predetermine with reasonable accuracy what will happen under existing conditions of solid faults.

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## Discussion

**D. K. Blake:** This paper practically completes the descriptive literature on a-c. network systems now in existence and having been in operation for one year or longer. There are a few points that I believe it is worth while to emphasize.

Some engineers hesitate to adopt the network system because they question the reliability of the network protector. Now this paper describes systems having two or three different types made by two different manufacturers, and their testimony is that it is reliable and their testimony is in line with others. So regardless of who makes them there are available reliable network protectors, so it is not a factor in hindering anyone in adopting this system. The real reason why you want an a-c. network system is that the load is growing fast. There is a number of networks on Manhattan Island, and according to the United Electric Light and Power Company, the load density for one of their networks was as low as 1000 kw. per sq. mi. The highest density at that time was about 12,000 kw. per sq. mi. That refers to the a-c. network density, not the d-c. They have found that the low voltage a-c. network system is the most economical way known to take care of the load growth. Because of the rapidity of that growth they are able to start a network with densities as low as 1000 kw. per sq. in. Across the river where there are different conditions, namely spotty concentrations of load, the a-c. network is also chosen.

What makes the network system more economical? It is the use of the high voltage, and that is more economical, because it eliminates the substation.

The question of burning off the secondary cables needs to be seriously considered. I believe this is the first set of tests that really show anything of the ability to burn off cables. I agree with the authors' conclusions. It behooves anyone who is designing a network system to consider the use of the 250,000-circular mil cable instead of the 500,000 circular mil cable. There is not much difference in cost and the difference in reliability involved justifies that little difference.

I believe the authors intended their recommendations of the trip-free mechanism to be confined to the motor centrifugal mechanism which is due to the slowing down of this mechanism after it is de-energized. On solenoid type devices that does not apply. On station breakers we require trip-free mechanism because of the fact that the closing circuit can be energized at the same time as the tripping circuit but in the network protector, the solenoid type or the motor type, the relay has a double-throw contact and it is impossible for both circuits to be energized at the same time. The only reason for requiring a trip-free feature on the motor is because of the time required for the centrifugal weights to stop.

**Henry Richter:** There are now 47 different properties operating or installing the network system with automatic network protectors, four being in foreign countries. The application is also being studied for at least 26 additional cities, four of which are foreign. The network cities are now located in all sections of the country and range in size from New York down to populations of 40,000. Although in many of them the network was chosen because best adapted to rapidly growing loads, continuity of service, economy, simplicity, etc., have been deciding factors in others. This system is well on its way towards becoming the standard for underground distribution.

The table of total annual charges in the Louisville study shows the network with 4 kv. feeders to be from 2 to 12 per cent more expensive than the radial system, depending on the type of substation. In similar studies for other cities at about the same average load density, but using 500,000-cir. mil secondary mains, the network system with 4000-volt feeders has shown a definite though small saving. One cannot help but wonder whether the difference is due to the extra cost of two 250,000-cir. mil mains in two ducts over one 500,000-cir. mil main in one duct. Not a little of the spread of the automatic a-c. network system has been because of its being more economical.

It is unquestionably true that when the generation voltage is used for the network feeders the greater part of the economy lies in eliminating the substation and its operating force, but savings of 8 to 10 per cent have also been shown for well designed network systems even with the substation in the picture. Furthermore, both of these statements apply only against preceding a-c. systems, as huge economies are shown for any type of a-c. network over direct current.

The omission of regulating equipment when the network supply voltage can be varied throughout the day is in line with the policy to derive from the network scheme as much simplification as feasible, but there are many cities in which it cannot be practised. Data on 29 systems including the five cited in the paper show that in 10 per cent of them synchronous condensers are employed, in 7 per cent bus regulators, in 52 per cent feeder regulators, and in 31 per cent nothing. A comparison in terms of transformer capacity connected to the feeders gives percentages of 4, 2, 67, and 27. If the question arises as to how much past practise on existing feeders of the 4-kv. class may have influenced these figures, a check of the transformer capacity fed at 11-kv. and higher shows the division to run 2, 2, 56, and 40.

The high ratios of installed transformer capacity to peak load listed in Table I are temporary, it will be observed, and will hardly be approached when all of the present load in the network area has been cut over to the network.

Several years ago the United Electric Light and Power Company in New York introduced the idea of incorporating a feeder grounding switch with the network transformer, the switch being a safety measure. Shortly afterwards a further advance was made in the Pittsburgh system by the addition of means for disconnecting the transformer, the three-position switch then being put in the high-voltage terminal chamber rather than inside the tank. Not only has it the advantage mentioned in the paper but it is of value when starting network operation with only two or three feeders, for by disconnecting a transformer on which work is to be done the need of taking out of service all the capacity connected to the feeder can be avoided. It can also be used for

breaking the connection between transformers and feeder if a kenotron test on the cable is desired without building the transformers to stand the test.

For three single-phase transformers the Pittsburgh manholes are stated to be about 25 per cent larger in total volume than for one three-phase transformer. This illustrates the outstanding advantage of three-phase network transformers. Other appreciable benefits are:

Lower cost of transformers at about 300 kv-a. and up.

Lower total losses in most instances.

Fewer bushings and cable connections.

A single three-pole three-position switch is cheaper and simpler than three two-pole three-position switches.

Less maintenance.

Only one unit to handle in stocking and installation.

Manhole arrangement simpler than where there is need to pass one transformer by the others to install or remove.

This noteworthy innovation, first used for underground networks in the United States on the Pittsburgh system two years ago, has been adopted by 17 other companies besides the Standard Gas and Electric properties. This makes a total of about half of all network systems operating or being installed. There are now at least 350 of these transformers in use.

Transformers with 10 per cent inherent impedance at full load have practically the same value under short circuit current. When network load densities reach the neighborhood of 100,000 kv-a. per sq. mi., calculations show the possibility of secondary fault currents as high as 50,000 amperes. One probability is that such a current would burn the most severe fault clear so quickly that the disruptive and heating effects due to the magnitude would not be harmful. Another is that a dangerous condition might result. To take reasonable steps to avoid this possibility appears to be sound engineering, and to this end the transformer with 10 per cent impedance by inherent design is justified.

As for limiting the current through the transformer to prevent damage during the burning off of a secondary cable fault, experience with normal impedance transformers shows that no such trouble results if the protector back-up fuse current rating is not over three times that of the transformers.

At the relatively lower load densities encountered in the average network system, the more the current at a secondary fault the more quickly will the latter be cleared and the less the likelihood of the trouble spreading. As external reactors to increase the bank impedance to a total of 10 per cent saturate under short circuit current, the use of normal impedance transformers assists in furnishing the desired high fault current on these average systems. The smaller the network the more is this true.

It has been a decided advantage in some networks not to have the extra reactance in fixed form as in the inherent design arrangement. For example, when operation is started with 4000-volt feeders and 13,000-volt feeders are introduced into the same network later, the extra reactance at the 4-kv. banks is removed if the total impedance at the 13-kv. banks is to be 10 per cent; this is to offset the impedance of the 4-kv. substation transformers.

Again, in building vaults it was customary to connect the building services and street grid to the transformers as in Fig. 1 herewith. When the help normally obtainable from the street mesh is relatively low and the power factor of a service not high, the voltage regulation can be improved by rearranging as shown in Fig. 2, without sacrificing the advantages of the extra reactance.

Furthermore, changing conditions as the network grew have made changes in the total impedance at all banks advisable in some cities.

The obvious advantages of obtaining the additional impedance by inherent design must therefore be balanced against the flexibility of the external reactors. Of a total of 29 network systems on which the facts are available, three-fourths have normal impedance transformers, mostly with external reactors, and the other quarter use 10 per cent inherent impedance. Classifying these groups by approximate transformer capacity now installed, the division stands 82 per cent against 18 per cent.

The excellent record of the network protectors reported in the paper, added to similar expressions from many other sources, comes as a boon to those interests who at the start invested heavily in money and effort on the possibility that this system

Fig. 1

would spread, and ever since have been striving to help make such statements come true. This should answer the question in the minds of those engineers who have held off, waiting for the protectors to be perfected.

There is a reference to troublesome tripping of protectors in Minneapolis on the 4-kv. feeders at light load. These feeders having individual regulators, it is very probable that their voltage can easily be lowered enough during this period to prevent any tripping whatever.

Non-lead-sheath cable for the large-size connections usually run between network transformer and subway type protector, and between the latter and the secondary mesh, was started in Pittsburgh and is somewhat startling in wet manholes. Considerable experience in service indicates the application to be entirely successful. The idea is rapidly spreading to other cities besides the Standard Gas and Electric group.

Some claim that these lengths of cable constitute so small a part of the total low-voltage cable in a network system that the possibility of a serious fault on them may be discounted. On the other hand, as this extra precaution against trouble costs no more and requires but little change in the transformers and protectors, it appears to be a distinct step forward. Its success depends, of course, on the seal at the porcelain bushings really keeping the water out. One type of seal is a gasket. A superior method is the soldered seal on porcelain, originally developed for mercury arc rectifiers and since extended to potheads, insulating rings in cable splicing sleeves for suppressing sheath currents, etc. This joint is now tested at the factory with hot oil under 80 lb. per sq. in. pressure.

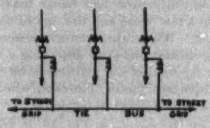


Fig. 2

The secondary junction box in the protector compartment is one way of making connection between the flame proof cable from the protector and the lead-covered cable from the mesh, but is just another piece of apparatus to maintain. Experience on both d-c. and a-c. networks also shows that such boxes are unnecessary for sectionalizing purposes, so it would be advantageous to find some way of dispensing with them. It is possible to connect the lead-covered cables directly to the non-lead sheath cable and to ensure a watertight joint by care in taping. If better assurance is desired some form of soldered-seal-on-porce-

lain connection can be applied. By arranging the joints as close to the ceiling as possible the likelihood of water getting at them is reduced to a minimum. This method facilitates the measuring of current in the mesh cables by a split core transformer without error due to sheath currents, and permits of easily adding more cable connections.

It is difficult to see the value of the fuses between the transformers bank and street secondary mains, for the zinc back-up fuses in the network protectors are provided for the very same purpose.

While the simplified vault arrangement derived by using a three-phase transformer is an asset both in lower cost and easier operation, in some cities the firewall, with its extra manhole opening or fire door, is considered an added complication. In one of the first automatic network systems provision was made for firewalls if found necessary but none have been put in thus far. A severe explosion once occurred in a manhole transformer but the protector, located on the opposite wall, cut the bank off from the network instantly and the trouble did not spread.

The principle of ample manhole ventilation adopted for these properties is an excellent example to follow. So is the use of porcelain saddles under lead-covered cables on racking arms. There is a number of systems where their omission, in combination with other adverse circumstances, may be an invitation to trouble.

From Fig. 7 it appears that most of the six sections into which the secondary grid has been divided in Pittsburgh are so small that considerable advantage in diversity between transformer banks and secondary mains is sacrificed. Much more spare transformer and feeder capacity is also required for a three-feeder network than a six-feeder network in providing against one's being out of service. Considerable experience in other cities shows no need for this precaution if the network is properly operated. There is even some question whether dividing the network into a number of small grids may not sacrifice some reliability as regards outage of feeders, there being a total of six feeders to rely on if the grids are merged into one, against only three feeders for each small network.

In a few cities where 250,000-cir. mil mains as inherited from the radial system are on both sides of almost all streets, it was natural for this size to be continued for new loads. In many cities, however, the mains were 500,000 cir. mils, particularly where confined to one side of the street and there is a desire to continue with this size in the network.

Two 250,000-cir. mil mains in two ducts are more expensive than one 500,000-cir. mil main in one duct. It is true that the cost of duct space for the second duct need not be included if enough ducts are available for the period of comparison, usually 10 years; but frequently new duct banks must be constructed immediately or in a few years and the cost of the duct therefore cannot be omitted. Where the network results in big savings, as by eliminating substations or in displacing a d-c. system, this extra expense for the smaller size mains may be readily absorbed. It may be an important factor, however, when the margin in favor of the automatic network is not large.

Exterpolating on the curves in Fig. 13, it appears that 6000 amperes on a 500,000-cir. mil fault of the most severe type requires about 8 minutes to clear. If this is found to be within the borders of permissible (though not desirable) time for Pittsburgh conditions, and it is admitted that such faults are quite rare, many engineers will be unwilling to go to extra expense to do better than this.

Should it be thought advisable to limit the amount of flame and smoke further, but to retain the simplicity rendered by the 500,000-cir. mil size, cutting the time in half would probably give satisfactory results. This is largely a question of furnishing enough current. According to the curves it could be accomplished with about 10,000 amperes. In areas of such high load density as in Pittsburgh the fault currents will far exceed this value except possibly around the edges and while the network is in the initial stages of construction. In the average network system that can economically employ 500,000 cir. mil mains 10,000 amperes will be obtained over the greater part of the system if the transformers are of normal impedance.

Wherever this current is not available in the normal design of the system the transformer capacity can be increased to make it certain. The authors describe an instance in which this was done, even though the capacity added was not required by the immediate load. The extra capacity is usually not long idle. Where the lack of current might give rise to too much disturbance but it is desired to limit the expense to prevent this, the method of confining the remedy to only those portions of the network in which the deficiency of current would exist is offered as an alternative to the use of 250,000 cir. mil secondary mains throughout.

**S. M. Hamill:** The Cincinnati company which I represent has had an a-c. network in operation for about two and one-half years. This network is supplied with three 13,000-volt feeders from the generating station. The secondary mains are three-phase four-wire, only one set of mains being used, 120 volts for lighting and 208 for power work. Mr. Blake mentioned the reliability of the network protectors. This has been shown to us by the fact that we have had three feeder faults and in each of these cases the feeders cleared practically instantaneously with no resulting disturbance to the system. Inasmuch as the authors have touched on the maintenance of their network system, I should like to mention its inspection.

In addition to the regular inspections in the vaults themselves the Union Gas & Electric Company daily checks the operation of the network protectors from the generating station supplying the 13.2-kv. feeders. This is done in the early morning light load period by opening one at a time the feeder oil circuit breakers. If the protectors of the opened feeder are all in good operating condition they will open immediately on reverse excitation current. The generating station operator determines this by noting the pilot light of the potential transformer connected to the feeder. In case one or more protectors fail to open, the pilot light does not go out. The feeder is then left de-energized from the generating station until a check is made to determine what protector remains closed. This check can be made very rapidly as there are red and green position-indicating lamps mounted in the vaults where they may be seen from the sidewalk through the grating, so that the patrolman does not have to get out of his automobile to check what feeder failed to open. This has been of some use because in each of the three primary feeder faults which I mentioned, on the day before, one of the network protectors failed to open when the test was made.

**H. W. Eales:** I should like to mention that the low-voltage d-c. system on Manhattan Island has now reached the staggering proportions of 400,000 kw. In the face of that load, and in the face of a rapid continuing growth in the load and especially a growth in the very heavy density reaching the order of 100,000 kw. to the sq. mi. as contrasted with some figures mentioned by one of the discussors earlier today of 1000 kw. to 12,000 kw. per sq. mi., you will see that New York City is confronted with a considerable problem in taking care of the physical side of its policy adopted during the current year, of taking on no more d-c. business on Manhattan Island.

The new Chrysler Building in upper Manhattan is 70 stories in height, nearly 1000 ft. We have in this building the problem of a network going vertically. The total transformer connections in the Chrysler Building will be of the order of 3000 kv-a.

Very briefly, the scheme of supply from the power company system to the network in the building is this: They have found it desirable to establish what I shall term a high-voltage network, that is to say, a network of 13,200-volt cables in the street which in turn are tapped into transformer vaults located in various

floors in the building. There will probably be four separate transformer vaults located strategically through the building from the basement to the roof with particular respect to the location of the load. Naturally the elevator loads, with the motor-generator sets in the top of the building, represent a point on concentrated load. To supply such a building there will probably be brought into it a minimum of four of these 13,200-volt cables. There are no switches provided in the 13,200-volt system within the building, the high-tension switching being conducted at the power company substations. Full dependence is placed upon the network protectors, as emphasized by Mr. Blake, in clearing the building in all its network from any faults which occur on the high-tension system beginning with the transformer.

The power company will own the high-tension cables and the transformers. The building will supply the transformer vault space and all the low-tension network. I shall leave to your imagination, the comparison of the tremendous decrease in building low-tension copper which results in these enormous structures when the supply is through the low-tension a-c. network as compared to the tremendous lot of copper which would be required to bring all of this capacity from the basement of the building to the roof.

**W. H. Johnson:** In the last two months we have placed a low-tension a-c. network system in service in Evanston, Illinois, a very small one in comparison to the one outlined by Mr. Sinclair, but the load is rapidly increasing and the primary reason for installing this system was the necessity for a high standard of service, and the system we are discussing today supplies that need and justifies its application.

I was particularly interested in the actual results of cable tests run by the Duquesne Light Company. I believe we should have more discussion on a very common problem, that is, voltage fluctuations on account of the combined light and power on one set of mains, the principal causes of voltage variation being due to the starting current characteristics of motors.

I should like to know of Mr. Sinclair's experience with motor-starting devices which restrict the motor starting currents to definite increments in order to prevent excessive fluctuations in voltage. Some resistance type starters will normally keep the voltage within proper limits so as not to be objectionable, but we understand that after working them for a short time a customer can jam the starter and the result is, increased voltage fluctuations which are naturally objectionable to the service rendered.

**M. T. Crawford:** (by letter) In this paper is described a number of excellent and original features which are of profound interest to operators of networks systems, and I should like to ask a few questions.

What were the underlying reasons for the decision to divide the Pittsburgh networks systems into separate sections, other than the fact that different primary voltages were to be used in two portions of the area?

We have been trying to decide if the Seattle networks system should be split or extended as a unit. It covers an area about the same as in Pittsburgh, one-half square mile, but is oblong, and the load is about 15,000 kw. In nearly nine years operation it has cleared itself of all troubles and no experience indicates the need of splitting on the secondary side. In one case of trouble where all networks switches were located out in a radius of several blocks, the service was maintained with a minimum of 90 volts near the trouble for an hour while service men replaced switches. The secondary mains fed in heavily from outlying sections with no damage except a few bulged splices.

The separation of transformer and network switch compartments is a distinct advance for high-voltage heavy-duty service. It would be of great interset to know the factors influencing the selection of varnished cambric cable for the vulnerable secondary transformer leads, in preference to rubber-covered braided cable, or perhaps lead-covered cable with insulating joints to permit ground isolation of the sheath. Will the cable selected stand up in the flood area?

At points where the load density required up to seven 300-kw. transformers at one location, what were the economies as compared with several larger sized transforming units.

**C. T. Sinclair:** As far as Mr. Blake's remark relative to the trip-free mechanism is concerned, he is correct in his assumption. Our statement should be interpreted to apply only to the motor-driven mechanism because only in the case of the motor-driven mechanism is that problem as we have described it here.

Mr. Richter brings out a number of points, one of which I wish to mention, and that is the question of feeder regulator. He is quite right when he says that the feeder regulator cannot be omitted in all cases. I would not even go so far as to say it can be omitted in the majority of cases. Our particular position is that there is a number of systems where it can be omitted, and where it can be omitted it is just one less piece of equipment, as far as service maintenance cost is concerned. We eliminate it where we can.

The next point I think was Mr. Hamill's. He mentioned the fact that they had three feeder faults thus far, and they had all cleared. Normally, we do not boast about feeder faults, but we have had eleven or twelve of them and they have all cleared. We hope we do not have to clear any more. We recently had a transformer failure which broke the casting in four parts without any network trouble. I was very much interested in the statement that Mr. Hamill's company checks the breaker operation every day. We do not go quite so far. We rotate our feeders, one a night in each of the network sections. I rather think this proposal is somewhat safer, although I believe rotating them one a night is adequate. I like his idea of using the red and green lights so that the inspector does not have to get out of his car to see whether the switch is open or closed. We have considered that but there are some local conditions which make it undesirable.

Mr. Eales mentioned the Chrysler Building in New York. We have a similar problem in Pittsburgh. The structure to which I refer is 600 ft. high which we think is going to prove economical on the basis of vertical distribution.

Mr. Johnson brings up an important subject I am sorry we did not have time to discuss at length, and that is the question of voltage fluctuation. Considering the details of the several types of starters that are available, we have used the carbon-pile starter with considerable success. We have had them in operation for a number of years, and with normal operation and maintenance they have been very satisfactory. There is a number of types of step-by-step resistance starters available which are very sturdy and which thus far have given no trouble, although quite frequently they are a little more costly, dependent on motor size. I might say this, that everyone in starting in a network is usually quite worried about this problem not only of lamp voltage but of voltage fluctuation, and I think it is customary to come to the conclusion that the problem of voltage fluctuation is not serious. As the network becomes larger your secondary bus becomes stiffer, and the problem of lamp flicker is not a serious one. There are individual cases where we find a motor or a starter that gives trouble, but usually there is some solution. Thus far we have not found any problem of that sort that we haven't been able to take care of.

Mr. M. T. Crawford in his letter has raised the question as to the underlying reasons for the decision to subdivide the Pittsburgh Network System into separate sections. The fact that different primary voltages were used in the two portions was not in itself a determining factor for this subdivision. Both the 4-kv. and 11-kv. systems are designed to operate in parallel and have been so operated. The principle purpose in the sectionalizing scheme is to permit any section to be shut down completely without affecting the others.

The design of the system is such as to permit the combination of these sections or the further subdivision if operating experience indicates that either is desirable.

In answer to Mr. Crawford's second question as to the factors influencing the selection of varnished-cambric cable for the vulnerable secondary transformer leads, I may say that both rubber-covered braided cable and lead-covered cable with insulating joints were considered. There is no serious objection to the use of rubber-covered braided cable other than the fact that it has a somewhat lower current-carrying capacity than the varnished cambric. The lead-covered cable with insulating joints should be satisfactory but is somewhat more costly and requires additional lead work in the vault. The flameproof cable mounted on insulators is a cheap and satisfactory method of accomplishing the purpose. This cable has been operated under water for long periods of time.

The third point raised by Mr. Crawford relates to the use of the seven 500-kv-a. transformers at one location. Undoubtedly several larger size transformers would have been satisfactory. There is a limit, however, to the network switch sizes available. Considering this, with the fact that 300- and 500-kv-a. transformers and equipment is standard for our system, led us to choose the 500-kv-a. size. For example, the seven 500-kv-a. transformers in this particular installation could possibly have been replaced by three 1200- or four 1000-kv-a. units. However, the standard network switch available today is not large enough for this size unit. It was felt undesirable to attempt to operate two of these switches in parallel which might have been the solution.

Referring to Mr. Richter's discussion I note that he makes the statement that external reactors used to increase the bank impedance to a total of 10 per cent saturate under short-circuit current, and therefore the normal impedance furnishes more short-circuit current to a secondary fault and thus the fault will clear quicker. It should not be interpreted from this statement that a 5 per cent impedance transformer furnishes a short-circuit current to a given fault twice that furnished with a 10 per cent transformer with inherent impedance. As a matter of fact short-circuit calculations indicate that the total amount of current furnished an average vault using 5 per cent transformers is not greatly in excess of the short-circuit current furnished from a system utilizing 10 per cent transformers with inherent impedance. This is due to the fact that the short-circuit current furnished from the 10 per cent system reaches out further into the network as far as the surrounding transformers are concerned.

To illustrate this I have taken a point on our system at random which shows that with 5 per cent transformers the total current to a given point approximately midway between two transformer banks is 8000 amperes in one direction and 11,000 in the other, or a total of 19,000 amperes. The same point calculated with 10 per cent transformers shows 7200 amperes in one direction and 9800 amperes in the other, or 17,000 amperes total.

# An Economic Study of an Electrical Distributing Station

BY W. G. KELLEY[1]
Fellow, A. I. E. E.

***Synopsis.***—*This paper outlines some of the physical reasons and economic advantages influencing the establishment of Washington Park Distributing Station of the Commonwealth Edison Company of Chicago.*

*This station is located at the electrical center of the load which it supplies. It receives energy at 66 kv. from an outlying generating station, State Line Station. The voltage is reduced at the distributing station and fed to a number of substations at 12 kv.*

*The past practise of this company has been to feed the substations at 12 kv. directly from generating stations. However, a study indicated several reasons for discarding the practise in this case.*

*The main physical reasons were the congested condition in the underground cable system surrounding Calumet Generating Station and the distance from Calumet Station to its dependent substations.*

*The economic advantages consisted primarily of the decrease in transmission line costs due to the location of the distributing station at the center of the zone load and the savings resulting from the use of 66-kv. instead of 12-kv. for the primary transmission system.*

THE subject matter contained in this paper is confined to a study of the transmission costs incident to the establishment of the Washington Park Distributing Station of the Commonwealth Edison Company of Chicago.

A distributing station differs from a generating station in that it receives electrical energy over transmission lines instead of producing the energy by means of generators. The energy is usually transmitted to the station at a higher voltage and distributed from the station at a lesser voltage to a number of adjacent substations.

The three-phase electrical system supplying energy to the distributing station may be termed the primary transmission system and consists in this case of three single-conductor 750,000-cm., 66-kv. cables. The three-phase system conveying energy from the distributing station to the substations may be termed the secondary transmission system, and the feeders are in this case three-conductor, 500,000-cm., 12-kv. cables.

A map of the City of Chicago, showing the various generating stations, Washington Park Distributing Station, and the substations receiving energy from the distributing and generating stations is given in Fig. 1. The various zones or districts fed by the generating and distributing stations are also outlined on the map. As the generating stations must be located on property accessible to water for condensing purposes, they can seldom be located at the electrical center of load for their respective zones.

Table I and Fig. 2 show the load in kilowatts for the various station zones from the years 1920 to 1928, inclusive.

In the case of Calumet and Fisk-Quarry Stations, the zone loads now exceed the generating capacity and part of the energy is supplied to these two zones from State Line Generating Station by means of 66-kv. underground transmission lines.

The distribution of energy in the Calumet Station zone has introduced certain physical and economic difficulties; first, due to the high cable temperatures in

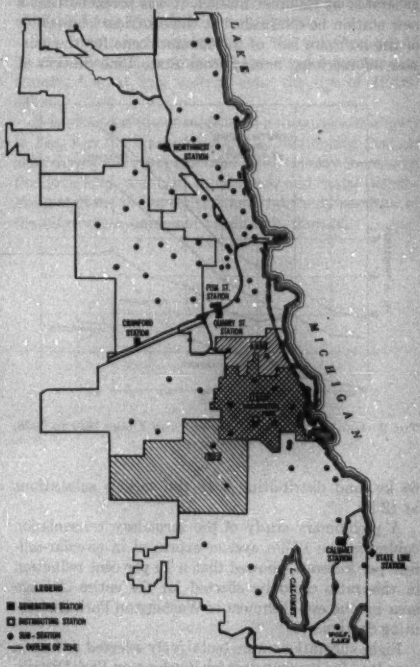


FIG. 1—MAP OF CHICAGO SHOWING THE LOCATION OF STATIONS AND SUBSTATIONS

the underground conduit system resulting from the large number of heavily loaded cables radiating to the west and north of the station; and second, due to the

1. Assistant Engineer of Distribution, Commonwealth Edison Co., Chicago, Ill.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.*



29-146

TABLE I

GROWTH OF 60-CYCLE ZONE LOAD AT TIME OF SYSTEM MAXIMUM

| | 1920 Kw. | 1921 Kw. | 1922 Kw. | 1923 Kw. | 1924 Kw. | 1925 Kw. | 1926 Kw. | 1927 Kw. | 1928 Kw. |
|---|---|---|---|---|---|---|---|---|---|
| Northwest | 50,000 | 65,000 | 81,430 | 91,000 | 84,780 | 101,850 | 118,210 | 128,922 | 143,260 |
| Fisk-Quarry | 140,000 | 122,000 | 155,200 | 91,980 | 112,985 | 136,278 | 140,220 | 190,840 | 177,723 |
| Crawford | | | | 53,920 | 80,350 | 103,019 | 158,020 | 177,982 | 218,777 |
| Washington Park | | | | | | | | | 55,388 |
| Calumet | | 26,000 | 38,770 | 91,290 | 101,187 | 141,885 | 159,000 | 172,952 | 123,880 |
| Total | 190,000 | 213,000 | 275,400 | 328,190 | 379,302 | 483,030 | 575,450 | 870,646 | 719,028 |

length of the 12-kv. secondary transmission lines from Calumet Station to the various substations in the zone.

The number of 12-kv. underground cables at Calumet Station is designated by the figures shown on the conduit line in Fig. 3.

Due to the fact that a considerable portion of the zone load is brought into the district at 66 kv. and not generated at Calumet Station, it was proposed that a new station be established at the electrical load center of the northern half of the Calumet zone for the purpose of receiving energy from State Line Station at

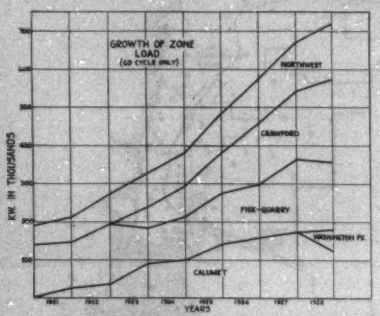


FIG. 2—GROWTH OF ZONE LOAD FOR THE YEARS 1920 TO 1928, INCLUSIVE

66 kv. and distributing it to the various substations at 12 kv.

A preliminary study of the secondary transmission cables on the 12-kv. system expressed in circular-mil-feet per kilowatt, showed that a 10 per cent reduction in this ratio could be effected for the entire Chicago area by the establishment of Washington Park Distributing Station.

Eight substations were tentatively selected to form a zone load for the first year for Washington Park Distributing Station and for the year 1928, the load in this zone was 55,388 kw.

Table III shows the load on the eight substations selected for the years 1923 to 1928, inclusive, segregated under the three headings, four-kv., railway, and industrial load.

The average distance from these substations to Calumet Generating Station, weighted for load, was found to be 41,600 ft., while the average distance to

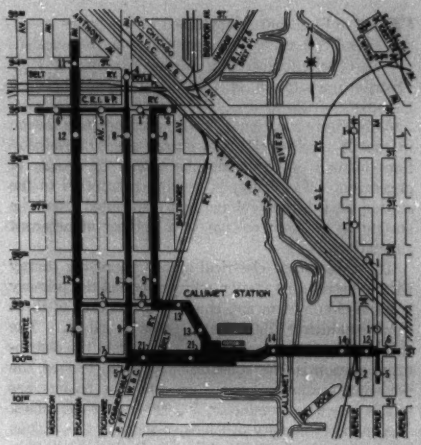


FIG. 3—DIAGRAM OF UNDERGROUND TRANSMISSION CABLES AT CALUMET STATION

The numerals denote the number of three-phase 12-kv. cables in each conduit line

TABLE II

TRANSMISSION COPPER IN 12-KV. DIRECT TRANSMISSION LINES

| | Length circuit feet | Copper Volume 1,000,000 cir. mil. ft. (one phase) | Peak load | 1,000,000 cir. mil. ft. per kilowatt |
|---|---|---|---|---|
| 1923 | 1,961,882 | 728,885 | 328,100 | 2.22 |
| 1924 | 2,202,563 | 980,044 | 379,302 | 2.58 |
| 1925 | 2,376,517 | 1,079,283 | 483,030 | 2.23 |
| 1926 | 2,887,780 | 1,352,029 | 575,450 | 2.35 |
| 1927 | 3,133,648 | 1,505,647 | 670,646 | 2.24 |
| 1928 | 3,118,895 | 1,483,448 | 719,028 | 2.06 |

Washington Park Distributing Station, weighted for load, was found to be only 8690 ft. This represented a marked decrease in the amount of cable necessary,

TABLE III
GROWTH OF PROPOSED WASHINGTON PARK ZONE LOAD

| | 1923 | 1924 | 1925 | 1926 | 1927 | 1928 |
|---|---|---|---|---|---|---|
| Hyde Pk. | 11,600 | 10,400 | 9,880 | 8,900 | 7,430 | 8,100 |
| Prairie | 5,180 | 4,920 | 5,890 | 5,630 | 4,900 | 5,740 |
| 63rd St. | 9,100 | 7,820 | 8,825 | 9,270 | 9,400 | 10,200 |
| Harper | | 3,660 | 4,450 | 4,300 | 5,300 | 5,210 |
| 56th St. | 10,720 | 9,320 | 9,600 | 9,650 | 7,560 | 7,350 |
| Lowe | 760 | 3,100 | 4,530 | 3,950 | 6,360 | 7,400 |
| Total 4-kv. | 37,360 | 39,220 | 43,175 | 41,700 | 40,950 | 44,000 |
| 62nd Railway | 5,760 | 5,530 | 4,140 | 4,130 | 4,070 | 4,058 |
| E. 63rd Railway | | | 1,970 | 2,670 | 4,000 | 3,370 |
| Total Railway | 5,760 | 5,530 | 6,110 | 6,800 | 8,070 | 7,428 |
| Hyde Pk. Indus. | | | 22 | 655 | 416 | 104 |
| 62nd Indus. | | | 149 | 663 | 445 | 1,573 |
| 56th Indus. | | | 307 | 436 | 1,148 | 1,460 |
| Wash. Pk. Indus. | | | | 457 | 725 | 323 |
| Total Indus. | | | 478 | 2,211 | 2,734 | 3,460 |
| Grand Total | 43,120 | 44,740 | 49,763 | 50,711 | 51,754 | 54,888 |

and formed one of the main economic factors leading to the construction of Washington Park Distributing Station.

The following cost data were used in making the study:

12-kv. three-conductor cable.....$1.95 per ft.
66-kv. single-conductor cable.. 2.64 to 3.07 per ft.
Conduit per duct..... 1.00 per ft.

Due to the fact that the energy for this zone is brought to it at 66 kv., it would have been necessary to install switching equipment, transformers, and the necessary buildings either at Calumet or Washington Park Stations, and the cost of these was assumed to be the same whether installed at one point or the other.

The cost per kilowatt of the 66-kv. primary transmission lines, with the necessary conduit from Calumet Station to Washington Park Distributing Station, was $11.40, and the total cost allocated to the Washington Park Distributing Station plan, based on the load of 55,388 kw., was therefore $630,000. The cost of 12-kv. secondary transmission lines and conduit from Washington Park Distributing Station to the eight substations, was $220,000, making a total cost for this plan, of $850,000.

The cost of 12-kv. secondary transmission lines and conduit from Calumet Station to the various substations, assuming Washington Park is not to be built, was found to be $994,000, making a difference of $144,000 capital investment in favor of the construction of Washington Park Distributing Station.

This saving is due primarily to the development of 66-kv. underground cable and the greater economy of transmission at this voltage over the use of 12-kv. cable.

It is proposed to put additional substations as shown in Fig. 1 in the Washington Park Distributing Station zone during the years 1929 and 1930, thereby increasing the zone load, and also to establish additional distributing stations in the central and northern sections of the city, when economic conditions warrant.

# Experience with Carrier-Current Communication

## On a High-Tension Interconnected Transmission System

BY PHILIP SPORN* and RAY H. WOLFORD*

Member, A. I. E. E. Non-member

*Synopsis.—The paper gives a historical outline of the development of carrier-current communication on power systems. It discusses the principles of the various systems of carrier current developed to date and outlines the fundamentals of a carrier communication system over a transmission network.*

*A description of the installations on a 132-kv. network having an extent of 2500 linear miles is given and the general experience with carrier, which is the sole means of communication operated and provided by the power companies on that system, is outlined.*

*A carrier-current communication system is analyzed into its component parts and the experience with these various parts given. Extensive experience with various forms of couplings, various forms and makes of coupling capacitors is described. Experience with the protective system, the lead-in system, and the tuning used in connection with the coupling is given in detail.*

*Detailed experience is given with the transmitting system and the receiving system of various makes of carrier employed. An outline of the experience with the various makes of power supply is given.*

*A discussion of the operation of carrier on a large system such as the one described and the necessity for zoning and interzoning is given and experience in establishing and maintaining these zones is outlined. Definite data are cited as to cost, maintenance, reliability, traffic, and safety. A description of various types of portable sets developed and their use is given. Some of the lines of future development found desirable in the light of the author's experience is indicated.*

### Introduction

A NUMBER of papers on carrier current has been given before the Institute on various phases of carrier-current communication. Most of these papers have been presented by manufacturers' engineers. In the two cases where operating engineers have presented papers they covered operation of a carrier-current installation on either a single or on two lines, the maximum number of terminals considered being three. No paper to date has been presented either by a manufacturing or an operating group that made an attempt to give operating experience with carrier current on a transmission system or to describe a complete system of carrier-current communication.

It is quite patent that two or three sets do not make up a system and that the practicability of carrier or of any system of carrier-current communication cannot be determined from the operating results obtained with two or three sets. Besides, the isolated line utilized for transmitting a block of power from a generating point to a point of use is decidedly the minority case today, and is more likely to be so in the future. We are rapidly approaching the point where the country will be covered by a network of interconnected transmission lines. In the Chicago territory, for example, there is a solidly connected 132-kv. system operating in parallel twenty-four hours a day that runs from Twin Falls, Wisconsin, south to Kingsport, Tennessee, and to Roxboro, North Carolina, and east as far as Wheeling, West Virginia, a total lineal mileage of approximately 2500 miles and circuit mileage of approximately 3450 miles. There seems to be no reason to doubt that interconnection and the development of systems of the same type will go much further in the future.

The American Gas and Electric Company's subsidiaries have been associated with carrier current and carrier-current operation from its very inception and have been operating a larger single transmission high-voltage network than operated by any other group. The experience obtained on this network primarily and on other portions of the system in the operation and application of carrier may, therefore, be expected to be of interest to other members of the Institute.

### History

The principle of multiplex telephony with which carrier current is so intimately tied up has been known for at least 38 years, the first patent disclosures having been made on it by Leblanc in 1891. The use of a pair of wires for guiding a high-frequency wave signal is due to Squier, who did his first development work on it in 1910. This was disclosed in an historic paper before the Institute in June 1911. The idea of using high-frequency current on a high-tension transmission line was previously proposed by Neu in 1905. This, however, was not carried very far for many years. Equally slow was the development of the idea proposed by Squier, the prevailing opinion of the best communication engineers at that time being that the scheme proposed by him had only limited rather than general application.

The real beginning of development of carrier communication on power lines can be stated to have begun with 1920. In July 1920 an experimental installation of carrier telephony, the result of the conception and work of Tidd, Sindeband, and Milnor, was made on the system of the American Gas and Electric Company between Atlantic City and Ocean City, New Jersey, over an 11,000-volt transmission line. An account of these tests appears in the July 17, 1920 issue of the *Electrical World*, from which the following is quoted:

"At last successful telephone communication has been conducted over live high-tension lines by the American

*Both of the American Gas and Electric Company, New York, N. Y.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.*



29-162

Gas and Electric Company, which has been convinced thereby that the method employed will solve one of its most important problems, namely, a reliable and less expensive mode of communication between its load dispatchers and interconnected stations.

"The tests which proved the practicability of the method were conducted . . . between the company's Atlantic City and Ocean City stations over a live 11,000-volt, 60-cycle transmission line, 12 miles (19.2 km.) long. Between the transmitting and receiving sets were the windings of the power transformers at both ends of the line and an underground cable, making the equivalent length of transmission about 21 miles (33.6 km.). The carrier current for the communications was at a frequency in excess of 5000 cycles. The transmitting and receiving sets were connected with the 2300-volt buses at each station."

In this test coupling to the power line was accomplished in three ways:

(a) Through a chain consisting of a current transformer secondary and primary, plus a power transformer stepping up from the voltage of the current transformer primary to the voltage of the transmission line.

(b) Through a double transformation consisting of a potential transformer secondary and primary in series with a power transformer stepping up to the voltage of the transmission line.

(c) Through the secondaries of the bushing transformers in the bushing of an oil switch operating at the voltage of the transmission line.

In the same year coupling wires were first used to couple the carrier to a high-tension line on the 135-km., 110-kv. line between Golpa and Runnelsberg in Germany. In the same year again, condenser coupling on a 22,000-volt line was first used in connection with carrier on a transmission line in Japan.

The impetus given by all of these installations resulted in the work being taken up by American manufacturers, and in December, 1921, the first American commercial carrier set was demonstrated; the first commercial installation was made about a year later, in November 1922.

In the meantime the development work was continued on the A. G. & E. system, and in July 1921, tests were conducted on the Windsor-Canton 132-kv. line with the same type of transmission as had previously proved successful over the Atlantic City Electric Company's line. The carrier in these tests was placed on the high-tension transmission line through the secondary of an 11,000-volt current transformer; from the 11,000-volt end connection was made to the high-tension 132,000-volt line through standard power transformers. Voice communication was not quite successful in these tests, although code communication was established very successfully. The higher impedance of the high-voltage transformers undoubtedly was the major cause for the failure to go through successfully.

Shortly after that, owing to the fact that the carrier-current problem was undertaken so vigorously by the regular electrical manufacturers, development work on the A. G. & E. System was entirely suspended and none has been carried out since except for full cooperation with all manufacturers who have evinced an interest in advancing this particular art. Today there are on the system of the A. G. & E. Co.'s subsidiaries, either in operation or in process of installation, a total of 50 carrier-current sets exclusive of portable equipments.

## Principles of Operation of Various Systems Developed

The carrier telephone equipments developed by the various manufacturers in this country may be classified as follows:

(a) Simplex, single-frequency, ground return.
(b) Simplex, single-frequency, inter-phase.
(c) Duplex, two-frequency, inter-phase.
(d) Duplex, single-frequency, inter-phase.
(e) Duplex, single-frequency, single-sideband, suppressed carrier.

Some of these are of course no longer being produced today.

A brief description of the above types of equipments and the communication facilities provided by each type will be given.

The first power line carrier telephone equipments developed in the United States were of the simplex ground return type. The same frequency was used for both transmission and reception, particularly where a system comprised more than two stations.

To prevent the transmitter from reacting upon the receiver, a manual switching control was used to render the transmitter inoperative during reception, and to render the receiver inoperative during transmission. Coupling to the transmission line was usually secured by stringing an antenna approximately 2000 ft. long parallel to the power conductors, the same antenna generally being used for both transmission and reception.

It was soon observed that the noise level secured by the ground return system could be greatly reduced by employing a full metallic carrier-current circuit, resulting in the development of sets using two antenna conductors coupled to different phases of the transmission line.

Although experience showed that the simplex manually controlled type of sets was capable of giving a high quality of communication, still these sets required a certain amount of skill in using them on account of the necessity of manual control of transmission and reception. The demand arose for equipment with which communication could be carried on without the use of manual control, leaving the control to automatic devices, thereby resulting in the development of duplex type equipment, that is equipment providing for simultaneous transmission in both directions.

In order to secure the duplex feature, the various

manufacturers resorted to different means. The Westinghouse Electric & Manufacturing Company developed duplex equipments, using a system employing two carrier frequencies, one frequency for transmission and the other for reception.

In their system the carrier frequency is transmitted continuously during the operation of the equipment, that is, during receiving periods the carrier frequency is transmitted but not modulated. Coupling to the transmission line is usually made by two antennas for

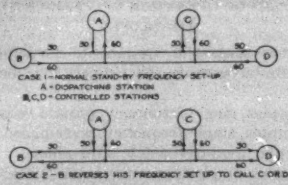


Fig. 1—Schematic Diagram Illustrating Communication Provided by the Westinghouse Electric and Mfg. Co. Two-Frequency Duplex System

transmission coupled inter-phase to the transmission line.

Fig. 1 shows schematically a system of four stations arranged to communicate with each other. Station $A$ is the main control or dispatching station, and stations $B$, $C$, and $D$ are controlled stations. The system operates as follows: Under normal standby conditions, station $A$ is adjusted to transmit at a frequency of, say, 50 kilocycles and to receive at 60 kilocycles. Stations $B$, $C$, and $D$, are adjusted to

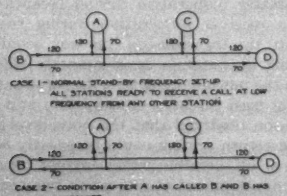


Fig. 2—Schematic Diagram Illustrating Communication Provided by the Western Electric Co. Two-Frequency Duplex System

transmit at 60 kilocycles and receive at 50 kilocycles. Under the normal condition $A$ may call and talk to either $B$, $C$, or $D$, but $A$ having established communication with $B$, then $C$ and $D$ are not able to establish communication with each other nor with $A$ or $B$. Either $B$, $C$, or $D$ may also call and talk to $A$. $B$ desiring to call and talk to $C$ or $D$ may do so by reversing his frequency set-up, but having done so cannot talk to $A$. This system therefore provides a means for any two stations on a channel calling and talking to each other, at which time all other stations on the system cannot be in communication with the two stations which are talking, nor with each other.

The Western Electric Company also developed duplex equipments using a two-frequency system similar to the one just described. This system likewise employs continuous transmitted carrier frequency.

Fig. 2 shows schematically a system of four stations arranged to communicate with each other. In this system the receivers of all stations are normally set to receive a call at the lower freqeuncy. Calling stations transmit at the lower frequency and receive at the higher frequency from the called station. With this arrangement, all the stations on a channel are equally able to call and talk to any other station on the channel. However, if any two stations, for example $A$ and $B$, are talking to each other it is not possible for any other two stations to carry on a separate communication or to carry on a communication with either $A$ or $B$. While $A$ and $B$ are talking, stations $C$ and $D$ are able to hear one side of the $A$ and $B$ conversation, the side available depending upon whether $A$ or $B$ originated the call.

Fig. 3—Schematic Diagram Illustrating Communication Provided by the General Electric Co. Single-Frequency Duplex System

Any station is in position to call and talk to any other station; full party line service is provided for either giving general orders or for conference

The original two-frequency, duplex equipments produced by the Western Electric Company were designed for use with two antenna wires for coupling inter-phase to the transmission line. However, when the use of high-voltage coupling capacitors came into use, the equipments were modified for capacitor coupling.

The duplex type equipments developed by the General Electric Company employ one frequency used for both transmission and reception in contrast to the two different frequencies used by the other manufacturers mentioned. The single-frequency duplex equipment functions similarly to the simplex single frequency sets which were first developed by the General Electric Company, except that the control of the transmitter and receiver is made automatic instead of manual by the use of vacuum tube relays. This results in a system in which the carrier frequency at a station is only transmitted at the time of speaking, no carrier being transmitted during receiving periods. The system works as follows. Fig. 3 shows a group of five stations on a channel, the transmitters and receivers of all stations being tuned to the same frequency. Any station—$A$ for example—may call and talk to any other station, such as $B$. While $A$ and $B$ are talking all other stations on the channel—that is $C$, $D$, and

*E*—can hear the entire conversation of both *A* and *B* and may join in and participate in the conversation. That is, this system provides a means so that simultaneously all stations on a carrier channel may be in communication with each other, provided, of course, that the conversation is orderly and two parties do not attempt to speak at once.

The two-frequency duplex type of equipments, as mentioned above, are both capable of giving a true duplex communication channel. That is, when two parties on a channel are talking, no interference to the operation of the equipment will result if both parties should speak at the same time. With the single-frequency duplex equipment as produced by the General Electric Company, it is possible for communication to be disturbed when two parties speak at the same time. However, experience with the use of these equipments has shown that for all practical purposes, duplex operation is secured for the reason that during orderly conversation between two parties, only one party speaks at a time.

The duplex two-frequency inter-phase equipments of the Western Electric Company now have been superseded by a duplex single-frequency, single-sideband suppressed-carrier system. None of this latter equipment is in operation at the present time on the A. G. & E. Co. system. In this system, after the carrier frequency has been modulated by the voice signal, one sideband and the carrier frequency are eliminated and only the other sideband transmitted. At the receiving end a locally generated carrier frequency is combined with the received single sideband and the resulting modulated carrier frequency demodulated to produce the audible frequency. This system provides a duplex carrier channel similar to the single-frequency duplex equipment produced by the General Electric Company and enables all the stations on a channel to be in simultaneous communication with each other, providing, of course, that two parties do not speak at the same instant.

## Fundamentals of a Carrier Communication System over a Network

It would seem well to outline the fundamentals of a carrier-current communication system for communication over power lines in order to be able to interpret properly the experience that will be described here. Attention should be called to the fact that the experience described covers experience obtained on a system or a network and not on isolated lines. The tendency, as previously pointed out, is toward the development of fewer and larger systems, in other words toward high-tension networks.

The author's experience has been that most literature emanating from manufacturers or manufacturers' representatives has not been sufficiently free from the commercial point of view. Scientific accuracy seems to have been sacrificed in too many cases to talking points. As an example, in one paper presented before the Institute, the author placed the fundamentals at three. In another technical paper, however, in an article from a different manufacturing group, the total number of fundamentals is listed alphabetically, and the alphabet is almost completely exhausted before the entire series is enumerated. In each case of necessity each manufacturer's equipment completely met the fundamental requirements set up by him. This, of course, has made the problem of deciding for or against and proper application of carrier on the part of the power system engineer all the more difficult, and undoubtedly it has not helped the advancement of the carrier-current art.

What really are the fundamentals? Based on our experience with an interconnected system, by which is meant a system consisting of an extended high-tension transmission network sufficiently extended, as to have more than one dispatching point, the following fundamental requirements are of primary importance:

1. Ability to carry on more than two conversations on any channel; in fact, ability to carry on as many conversations on a channel as there are stations in a channel, simultaneously. This automatically means the ability of any one station on a channel to cut in on a conversation if it has anything of an emergency nature to report or if it has any information to contribute to the business that is being discussed.

It is to be noted that this is a definite reversal of what is considered a prerequisite in ordinary telephone conversations where it is considered as an absolute essential that nobody, unless particular arrangements for it have been made, be able to cut in on a two-party conversation. Those who have had experience in the operation of transmission and power systems will realize the absolute necessity for this requirement.

2. Reliability. This is so fundamental that it is almost axiomatic. Under this can be included therefore such items as simplicity, safety, ease of maintenance, and all other items that contribute to reliability.

Here again, it may be of interest to point out that in the early days carrier was looked upon by many people as a very good standby service for other means of communication, which would be used normally. The experience which we shall cite later will show that it has been possible to bring about a reversal of the situation in that carrier can be made to continue to function when other forms of communication fail.

3. Ability to furnish a maximum number of channels on any one system. This of course assumes that the system is big enough to require more than one channel; in fact, it assumes that the system is so big, and this has been brought out previously, that more than one dispatching point is utilized, and it therefore becomes imperative, in order to be able to carry on the business of the system effectively and expeditiously, to confine a particular channel to a definitely limited geographical area. As a direct corollary to that is the statement

that the system must use only one frequency for transmitting and receiving, and the selectivity between various channels must be of a very high order. It is obvious of course that the use of two frequencies per channel automatically cuts in half the number of possible channels available in any particular band of frequencies.

comprises 2500 linear miles of 132-kv. transmission line and 3450 miles of circuit, of which the portion in solid represents 1340 linear miles of transmission and 2050 circuit miles operated by American Gas and Electric Company subsidiaries, and the dotted portion indicates the foreign lines. No attempt will be made to give any experience with sets on foreign lines. They are shown

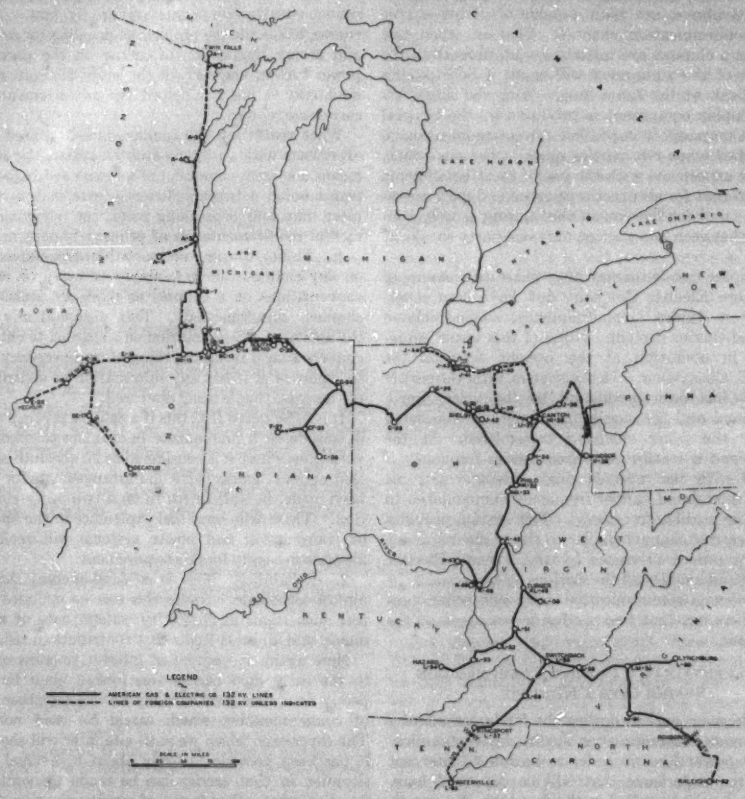


FIG. 4—132-KV. INTERCONNECTED TRANSMISSION SYSTEM AND LOCATION OF CARRIER SETS

The above we have found, as a matter of experience covering a period of ten years, to be the fundamentals. Our experience and our opinions with regard to the performance obtained will be understood more clearly when considered in the light of these fundamentals.

## DESCRIPTION OF INSTALLATIONS ON AMERICAN GAS AND ELECTRIC SYSTEM AND GENERAL EXPERIENCE

Fig. 4 shows the 132-kv. system in question. It

here for the reason that they have a bearing on the problem since they are all located, as already pointed out, on a single 132-kv. transmission network that extends from Twin Falls, Wisconsin, south to Kingsport, Tennessee, and Roxboro, North Carolina, and east as far as Windsor, West Virginia. The system of the American Gas and Electric Company is operated from five central dispatching points as follows: South Bend, Indiana, Shelby, Ohio, Canton, Ohio, Turner

(Charleston), West Virginia, and Switchback, West Virginia. District dispatchers are located at practically every 132-kv. station of importance.

The dots on the map indicate the location of sets; that is, each dot represents a single set. Table I gives the details with regard to these sets. This table will be referred to again later.

All these sets are single-frequency, duplex operation, selective ringing sets of General Electric manufacture. They operate in this network over 14 channels and of these 14 channels 9 are utilized by the subsidiaries of the American Gas and Electric Company.

The general experience with this system of carrier on the 132-kv. system has been highly satisfactory from the very beginning. There were troubles in the early days with the simplex sets, particularly with the simplex ground return sets in signaling, in getting through, and in the quality of speech; troubles were experienced in getting the proper signal strength in the early days when antenna coupling was employed; difficulty was experienced with the growth of the system and the number of sets in maintaining proper separation between the various channels; there was experienced some trouble with some of the types of coupling capacitors employed as will be brought out later; but on the whole carrier has for the past five years provided on this system the means of load dispatching and the means of maintaining contact on all similar and related business without any outside supplement. Again and again when all other sources of communication in a particular district failed, carrier continued to provide service of the same high type and of the same high quality as it provided under normal conditions.

In brief, the experience on the whole with carrier has been highly satisfactory. Its development on our system has demonstrated the fact that carrier on our system has reached a stage where it will, if properly applied, provide a quality of communication with a reliability that is generally obtainable at present through no other source at the same cost. Further, our experience has been that those of the equipments that were built and developed in the earlier

TABLE I

CARRIER-CURRENT COMMUNICATION STATIONS AND CHANNELS A. G. E. 132-KV. TRANSMISSION SYSTEM AND INTERCONNECTING 132-KV. SYSTEMS

| Reference | Channel reference letter | | Frequency in kilocycles | | Location of set | Operating company |
|---|---|---|---|---|---|---|
| A- 1 | A | | 50 | | Twin Falls, Mich. | Wisconsin Public Service Co. |
| A- 2 | A | | 50 | | White Rapids, Mich. | Northern Electric Co. |
| A- 3 | A | | 50 | | Green Bay, Wis. | " " " |
| A- 4 | A | | 50 | | Appleton, Wis. | Wisconsin Public Serv. Co. |
| A- 5 | A | | 50 | | Milwaukee, Wis. | Milwaukee Elec. Ry. & Lt. Co. |
| A- 6 | A | | 50 | | White Water, Wis. | " " " " " |
| AB- 7 | A | B | 50 | 110 | Waukegan, Ill. | Public Service Co. of Northern Illinois |
| AB- 7 | B | A | 110 | 50 | Waukegan, Ill. | " " " " " |
| B- 8 | B | | 110 | | Electric Jct., Ill. | " " " " " |
| BD-15 | B | D | 110 | 60 | Joliet, Ill. | " " " " " |
| B-10 | B | | 110 | | Chicago Hgts., Chicago, Ill. | " " " " " |
| B-11 | B | | 110 | | 108th St. Substa., Chicago, Ill. | Commonwealth Edison Co. |
| C-12 | C | | | 85 | Hammond, Ind. | Northern Indiana Public Service Co. |
| BC-13 | B | C | 110 | 85 | Aetna Sub., Ind. | " " " " " |
| C-14 | C | | | 85 | Michigan City, Ind. | " " " " " |
| BD-15 | D | B | 60 | 110 | Joliet, Ill. | Public Service Co. of Northern Illinois |
| DE-16 | D | E | 60 | 72 | Kewanee, Ill. | Illinois Pr. & Lt. Co. |
| DE-17 | D | E | 60 | 72 | Powerton, Ill. | Super Power Co. of Ill. |
| E-18 | E | | 72 | | La Salle, Ill. | Illinois Pr. & Lt. Co. |
| DE-16 | E | D | 72 | 60 | Kewanee, Ill. | " " " " |
| E-19 | E | | 72 | | Galesburg, Ill. | " " " " |
| E-20 | E | | 72 | | Keokuk, Ill. | " " " " |
| DE-17 | E | D | 72 | 60 | Powerton, Ill. | Super Power Co. of Ill. |
| E-21 | E | | 72 | | Decatur, Ill. | Illinois Pr. & Lt. Co. |
| BC-13 | C | B | 85 | 110 | Aetna, Ind. | Northern Indiana Public Service Co. |
| C-22 | C | | 85 | | South Bend, Ind. | Indiana & Michigan El. Co. |
| C-23 | C | | 85 | | Twin Branch, Ind. | " " " " |
| CG-24 | C | G | 85 | 125 | Ft. Wayne, Ind. | " " " " |
| CF-25 | C | F | 85 | 115 | Marion, Ind. | Indiana General Service Co. |
| C-26 | C | | 85 | | Muncie, Ind. | " " " " |
| CF-25 | F | C | 115 | 85 | Marion, Ind. | " " " " |
| F-27 | F | | 115 | | Kokomo, Ind. | Indiana Electric Corp. |
| CG-24 | G | C | 125 | 85 | Ft. Wayne, Ind. | Indiana & Michigan Elec. Co. |
| G-28 | G | | 125 | | Lima, Ohio | The Ohio Power Co. |
| G-29 | G | | 125 | | Fostoria, Ohio | " " " " |
| G-30 | G | | 125 | | Shelby, Ohio | " " " " |
| HI-31 | H | I | 46 | 90 | Shelby, Ohio | " " " " |
| HK-32 | H | K | 46 | 60 | Philo, Ohio | " " " " |
| HK-33 | H | K | 46 | 60 | Crooksville, Ohio | " " " " |
| H-34 | H | | 46 | | Newcomerstown, Ohio | " " " " |
| HI-35 | H | I | 46 | 71 | Canton, Ohio | " " " " |
| H-36 | H | | 46 | | Windsor, W. Va. | " " " " |
| HI-31 | I | H | 90 | 46 | Shelby, Ohio | The Ohio Power Co. |
| IJ-37 | I | I | 90 | 71 | Massillon, Ohio | Ohio Public Service Co. |
| HI-35 | I | H | 71 | 46 | Canton, Ohio | The Ohio Power Co. |
| IJ-37 | J | I | 71 | 90 | Massillon, Ohio | Ohio Public Service Co. |
| J-38 | J | | 71 | | Alliance, Ohio | " " " " |

TABLE I—(*Continued*)
CARRIER-CURRENT COMMUNICATION STATIONS AND CHANNELS A. G. E. 132-KV. TRANSMISSION SYSTEM AND INTERCONNECTING 132-KV. SYSTEMS—*Continued*

| Reference | Channel reference letter | | Frequency in kilocycles | | Location of set | Operating company |
|---|---|---|---|---|---|---|
| J-39 | J | | 71 | | Ashland, Ohio | Ohio Public Service Co. |
| J-40 | J | | 71 | | Lorain, Ohio | " " " " |
| J-41 | J | | 71 | | Sandusky, Ohio | " " " " |
| J-42 | J | | 71 | | Mansfield, Ohio | " " " " |
| J-43 | J | | 71 | | Port Clinton, Ohio | " " " " |
| J-44 | J | | 71 | | Toledo, Ohio | Toledo Edison Co. |
| HK-32 | K | H | 60 | 46 | Philo, Ohio | The Ohio Power Co. |
| HK-33 | K | H | 60 | 46 | Crooksville, Ohio | " " " " |
| K-45 | K | | 60 | | Rutland, Ohio | " " " " |
| K-46 | K | | 60 | | South Point, Ohio | " " " " |
| K-47 | K | | 60 | | Portsmouth, Ohio | " " " " |
| K-48 | K | | 60 | | Ashland, Ky. | Kentucky & W. Va. Pr. Co. |
| KL-49 | K | L | 60 | 79 | Turner, W. Va. | Appalachian Elec. Pr. Co. |
| KL-49 | L | K | 79 | 60 | Turner, W. Va. | " " " " |
| L-50 | L | | 79 | | Cabin Creek, W. Va. | " " " " |
| L-51 | L | | 79 | | Logan, W. Va. | " " " " |
| L-52 | L | | 79 | | Sprigg, W. Va. | " " " " |
| L-53 | L | | 79 | | Clear Creek, Ky. | Kentucky & W. Va. Pr. Co. |
| L-54 | L | | 79 | | Hazard, Ky. | " " " " " |
| L-55 | L | | 79 | | Switchback, W. Va. | Appalachian Elec. Pr. Co. |
| L-56 | L | | 79 | | Saltville, W. Va. | " " " " |
| L-57 | L | | 79 | | Kingsport, Tenn. | Kingsport Utilities, Inc. |
| L-58 | L | | 79 | | Glenlyn, Va. | Appalachian Elec. Pr. Co. |
| LM-59 | L | M | 79 | 52 | Roanoke, Va. | " " " " |
| L-60 | L | | 79 | | Reusens, Va. | " " " " |
| LM-59 | M | L | 52 | 79 | Roanoke, Va. | " " " " |
| M-61 | M | | 52 | | Fieldale, Va. | " " " " |
| M-62 | M | | 52 | | Raleigh, N. Car. | Carolina Pr. & Lt. Co. |
| L-63 | L | | 79 | | Waterville, N. Car. | Tennessee Public Service Co. |
| L-64 | L | | 79 | | Canton, N. Car. | " " " " |

days and that were therefore not able to render the service that is rendered by the newly built sets can with a reasonable amount of expenditure and effort be revamped and brought up to give substantially the same service as those that are being put out today and where

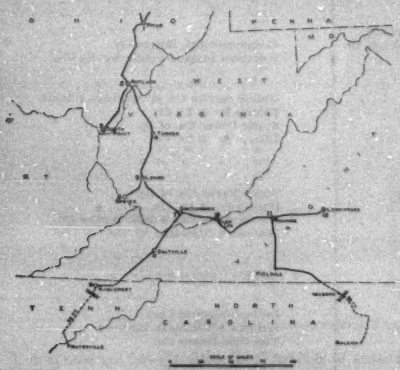


Fig. 5—Points on A. G. & E. Co. 132-Kv. System Where Western Electric Co. Sets were Located

we have had sets of that type, they have been or are being brought up to that level.

The marked physical change in the development of these sets is shown by Figs. 6 and 7, respectively. Fig. 6 shows one of the early 50-watt simplex sets rebuilt for duplex operation on the 27-kv. system of the Indiana & Michigan Electric Company. Fig. 7 shows one of the latest CC-8B, 50-watt sets (Reference No. G-29, Table I) also installed within the last two years. The latest development of the set shown in Fig. 7, the KCA-1, has practically the same appearance and is

Fig. 6—Early Type of General Electric Co. 50-Watt Single-Frequency Duplex Set

electrically practically the same, the only difference being in the physical detail of wiring.

Fig. 5 shows the southern portion of the A. G. & E. Co. system. It will be noted that the portion of the system considered starts at Philo and extends south to Kingsport and to Lynchburg. On this system there were installed at one time 12 Western Electric sets, the locations of these sets being indicated by a dot. Here

the operation of the sets was continued for a period of approximately three years, at the end of which time the sets were all removed and put in service on more isolated networks operating at a lower voltage. Fig. 8 is typical of one of these sets.

Fig. 7—General Electric Co. 50-Watt Primary Set, Type CC-8B, Ohio Power Co., Fostoria, Ohio

The main difficulty experienced with these sets was the fundamental difficulty brought about by the two-frequency system, which did not permit more than two conversations to be carried on at the same time. It

Fig. 8—Western Electric Co. 50-Watt Set

was found that such a restriction almost crippled the system and in a number of cases resulted in very bad interruptions as a result of the fact that a station in trouble could not get in touch with the central dispatcher taking care of that particular district since the dispatching point was in communication at that time with some other station on the system. Attempts were made to revamp these sets for single-frequency operation but economic considerations determined their removal to points where they could be used without any change and without the great expenditures which would have been otherwise called for. There were other difficulties experienced with the sets but by

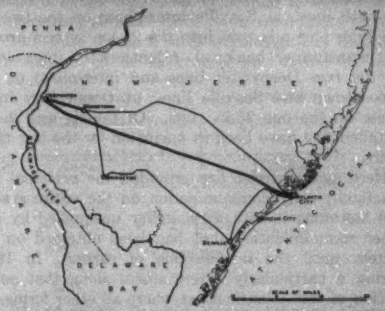


Fig. 9—66-Kv. Transmission System of the Atlantic City Electric Co. Showing Location of Sets

comparison with the main difficulty, they were of a minor nature. For example, the two-frequency system operation was also found to result in great difference in signal level received at various stations due to the unequal attenuations of the two frequencies along the system. These resulted in low voice levels and also considerably affected the reliability of the signal system employed.

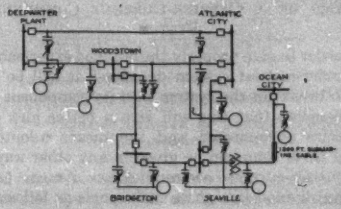


Fig. 10—Schematic Diagram Showing Coupling and By-Passing on Atlantic City Electric Co. System

Fig. 9 shows the 66-kv. transmission system of the Atlantic City Electric Company, which consists of a double circuit line from the Deepwater Plant to Woodstown, New Jersey, and another double circuit line from the same point to Atlantic City with other lines running from Woodstown by way of Bridgeton and Seaville to Atlantic City. At Seaville a step-down is made into the 25,000-volt system which runs partly

overhead and partly through many sections of submarine 25,000-volt cable to Ocean City.

Fig. 10 shows the coupling arrangement employed at each of the six points where sets are installed, the coupling being as follows: At Deepwater on the two lines to Atlantic City, inter-circuit; on the two lines to Woodstown, inter-circuit; at Woodstown on the Deepwater lines, inter-circuit and on the lines to Bridgeton and Atlantic City inter-phase; at Bridgeton inter-phase on both lines; at Seaville inter-phase on the two 66-kv. lines plus a bypass into the 25-kv. system around the transformer bank; at Atlantic City inter-circuit on the two Deepwater lines and inter-phase on the Woodstown and Seaville lines; at Ocean City inter-phase on the one 25-kv. line. Of the six sets shown installed five have been in operation for the last three years.

Here again carrier has provided the principal and practically only communication on the entire system and has done it with a reliability unequalled by any other communication that had been obtained on the system until the introduction of carrier. In 1927, during a particularly severe storm along that entire section of the Atlantic coast where all other forms, including all commercial forms of communication in the territory, were very seriously crippled, communication between Atlantic City and the then extreme point, Woodstown, was maintained without the slightest interruption through carrier. It may be of interest that in the section between Seaville and Ocean City there are 2 pieces of 25-kv., 3-conductor submarine cable, aggregating a total of 1200 ft. The communication between Seaville and Ocean City and between Atlantic City and Ocean City is nevertheless of a very high grade, no difficulty having been experienced in getting through all the cable.

## Analysis of a Carrier-Current Communication System

In order to give properly the detailed experience with the carrier-current system described, it will be necessary to break up the system into its component parts. It is believed that this will give a better idea of the difficulties encountered and the means adopted for solving them than can be given in any other way.

A carrier-current communication system can be logically divided into three main parts as follows:

(A) Equipment
(B) General channel arrangement
(C) General phases of system.

The equipment (A) can be divided into the following:

1. Coupling system. This embraces—
   (a) The connection to the line
   (b) The coupling proper. The coupling itself can be either in the form of an antenna or in the form of a capacitor, and there are of course many types of capacitors.
   (c) The protective equipment. This includes the disconnecting switches, fuses, drainage coils, spark-gaps, ground switches, and other protective devices on the apparatus side of the coupling equipment used for the purpose of protecting the equipment itself and the operators from the power voltage.
   (d) Tuning equipment. This includes the equipment used for resonating the circuits from the transmitter to the line.
   (e) Carrier traps. These are used for preventing the dissipation of carrier energy into circuits through which it is not desired to communicate, for the purpose of preventing the carrier energy being short-circuited by open branch lines and also for breaking up loop circuits so as to prevent neutralization of signal at the receiving end caused by unequal propagation over the two sides of the transmission loop.
   (f) By-passing equipment. This includes equipment utilized for by-passing a high impedance to carrier such as power transformer, power reactor, etc.
   (g) Lead-in conductors.
2. Transmitting system. This embraces—
   (a) Frequency control. By this is meant the master oscillator circuit.
   (b) Speech amplifier. This consists of the amplifying equipment used to raise the voice signal for input to the modulation system.
   (c) Modulation system.
   (d) Power amplifier system. By this is meant the circuits used to amplify the modulated signal for input and transmission to the line.
   (e) Transmitter blocking system. This is, of course, non-existent in the case of a two-frequency system. In the case of the single frequency system it is utilized for blocking the transmitter output except when the particular station actually does the speaking.
   (f) Signaling system. This consists particularly of the relay equipment and modulating equipment used for calling other stations.
3. Receiving system. This embraces the following:
   (a) Calling system. This includes the equipment used for receiving calling signals from distant stations and translating them into audible signals.
   (b) Tuning and selective system. This includes tuning and amplifying circuits used to select the proper carrier frequency and deliver it to the de-modulation system.
   (c) De-modulation system.
   (d) Audio amplifying system.
   (e) Extension system. This includes the equipment necessary to provide wire line extensions to the equipment. In some cases

these extensions may have to be several miles in length. An actual experience will be cited in connection with some very long extensions.

4. Power supply system for transmitter and receiver. This includes:
   (a) The supply for all the filaments.
   (b) The grid biasing supply.
   (c) Plate supply.
   (d) Control relay supply.

B. General channel arrangement. This can in turn be subdivided into the following:

1. Zoning. As either the system of transmission or the system of communication on a definite transmission system grows, and the carrier installations grow, it is of necessity found desirable to limit the geographical spread of the number of stations on any one channel, which means that a series of channels has to be established. In cases such as the system cited, where the principal dispatching functions are carried on from a number of points, this would logically result in certain zones that are more or less independent of each other.
2. Inter-zoning. As long as the system is a unit system, inter-zone communication will be found necessary under certain conditions. The feasibility of maintaining these zones will be dependent upon clearness, sharpness of tuning, attenuation, and similar questions, and these will be discussed.

C. General phases. Under this can be included the following items:

1. Cost of installations.
2. Maintenance; that is, maintenance considered both from the standpoint of extent and cost.
3. Extent of traffic and ability to handle.
4. Safety.

## Coupling System Experience

Before the development of coupling capacitors a number of installations of two-wire antenna coupling, such as is shown schematically in Fig. 11, was installed on the system of the American Gas and Electric Company. These antenna couplings functioned with fair success. However, they were subject to several difficulties and had several objections.

It was found that the tuning of the coupling system varied considerably with changes in weather conditions. In wet weather the volume of received speech was considerably reduced. This was attributed to the change in capacity values of the coupling and to the leakage from the insulator supporting the antenna. On account of the nature of the coupling capacity secured by antenna coupling, the antenna coupling systems gave a much sharper tuning of the output circuit and therefore changes in the value of the antenna capacity caused a very great change in the output circuit tuning.

At the time the transmission towers were installed, no thought was given to providing additional strength so as to support antenna coupling wires without reducing the safety factor. The towers were designed for two circuits and one ground wire. Later developments required the installation of another ground wire so that if antenna coupling had been continued it would have been necessary to place three more conductors on the structure than the structures were originally designed for or sacrifice either the ground wire or the factor of

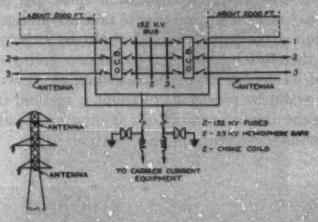


Fig. 11—Schematic Diagram of an Antenna Coupling Installation

safety. Again difficulties were encountered due to the rigid requirements of the railroad companies covering the method of supporting conductors across their rights-of-way.

On the antenna coupling systems which were installed, the same size and kind of conductors were used as for the power conductors in order to secure the same sag and the same deflection under wind. Even with these precautions, as will be noted from the diagram, the installation of the antenna conductors in line with the

Fig. 12—Schematic Diagram of Antenna Coupling Arrangements

vertical center line of the towers so reduced the clearance between the power conductors as to run the danger of their falling upon the antennas if the power conductors should break. One case of this trouble was experienced at the Canton substation in the year 1924, when the power conductors came down across the antenna coupling wires. The antenna coupling wires were protected by 132-kv. fuses, which were installed very close to the transmitting equipment immediately outside the building. While the fuses blew nevertheless a considerable amount of damage was done to the carrier telephone set.

Another difficulty experienced in the use of antenna coupling is brought about by the asymmetrical stringing of double circuit lines. Referring to Fig. 12, a two-wire antenna system is shown at *A* coupled to a double circuit line strung symmetrically. This method produces a satisfactory coupling to the transmission line. A double circuit line strung asymmetrically is shown at *B* with the antenna conductors located at the same place as at *A*. It will be noted that both the upper and lower antenna conductors are equally coupled to phases 1 and 3, thereby causing the coupling to be neutralized and to be of no effect.

Our double circuit transmission lines are now all strung asymmetrically in order to take advantage of the reduction in reactance brought about by this method. It will therefore be seen that antenna coupling cannot be used on double circuit lines strung as shown at *B* and it would be necessary to adopt a method of supporting the antenna conductors, as shown at *C*, in order to secure an effective coupling to the line.

Fig. 13—Mica Dielectric Capacitor Installation, Ohio Power Co., Canton, Ohio

All of the above considerations contributed to the adoption of high-voltage capacitors for coupling as soon as they were developed. The first installation of coupling capacitors on the American Gas and Electric Company lines was made on the 132-kv. double circuit line from Canton to Philo, Ohio, in the year 1925. This installation consisted of two 132-kv. assemblies at Canton and two at Philo connected inter-circuit to the double circuit line. See Fig. 13, showing the installation at Canton. The capacitors were of the mica dielectric type. Mica was chosen because at that time it was the only thing available. Twelve units were used for each 132-kv. assembly, each unit having a normal operating voltage rating of 22 kv. and a capacity of 0.003 $\mu$ f. Six units were connected in series and two series of six units in multiple to produce a 132-kv. assembly having an over-all capacity of 0.001 $\mu$ f.

These four original 132-kv. assemblies have continued to operate without any trouble whatsoever.

In making the first few installations of capacitors on the 132-kv. system, high-voltage disconnecting switches and choke coils were installed between the line and the capacitors. The choke coils were installed with the idea of protecting the capacitors from voltage surges and the disconnecting switches were installed so as to facilitate the taking of the capacitors out of service for maintenance and repairs, or to provide a quick means of clearing the capacitors from the line if they should break down, very little at that time being known concerning the reliability of such devices.

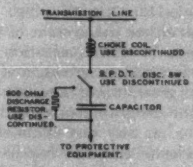


Fig. 14—Protective and Safety Features Used on Early Capacitor Installations

In the first installations a safety device was installed as shown by Fig. 14. This consisted of an 800-ohm resistance so connected that when the high-voltage disconnecting switch was open its blade would come in contact with one terminal of the resistance, the other terminal of the resistance being connected to the low side terminal of the capacitor, thereby discharging the capacitor through the resistance and rendering the capacitor safe to work on.

The disconnecting switches, choke coils, and protective resistance considerably increased the cost of the capacitor installations. As more experience was secured with the capacitors and confidence in their reliability obtained, the use of switches for disconnecting the capacitors from the line was discontinued and the capacitors connected solidly to the line.

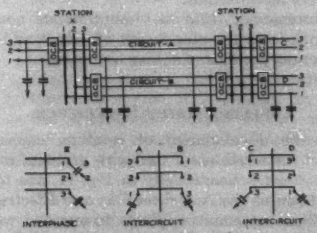


Fig. 15—Inter-phase and Inter-Circuit Coupling Arrangements

Fig. 15 shows schematically systems of inter-phase and inter-circuit couplings by means of capacitors. The coupling to line *E* is an inter-phase coupling. The coupling to lines *A* and *B* at each of their ends is made

by inter-circuit coupling, the two lines being strung asymmetrically on the transmission towers. The same holds true for circuits *C* and *D*. Although the relative location of the right and left hand circuits on the two towers supporting the last two groups of lines is interchanged, no interference results in the method of coupling employed, the circuit being a perfectly complete carrier-current circuit. The method of inter-circuit coupling offers particular advantages in economy where a double circuit line is employed, and while it is not fully as effective under all emergency conditions as full inter-phase coupling on every circuit, nevertheless it results in so much reduction of cost that the slight inconvenience that results sometimes is more than compensated for by this lesser cost. In spite of its extensive use on the system, there has practically never arisen a situation where communication was interfered with to any appreciable extent as a result of one of the two circuits going out, the general experience being that if one of two coupling points provided at each of the two terminals of a particular line remained coupled, communication could be carried on over the line.

As pointed out, the first capacitors were of mica. The principal reason for this was that they were the only ones obtainable. Even here it was necessary to carry on considerable cooperative work with the manufacturers before a successful unit was developed. However, the experience that had been obtained over many years in the operation of a power system with solid dielectrics suggested the necessity for great caution in proceeding with the extensive use of mica for very high voltages. The development of carrier communication had resulted in a number of other manufacturers taking up the capacitor problem, so that within a short time from the first installation on the A. G. & E. system, there were available on the market at least three other types of capacitors and one other make of mica capacitor. A series of very extensive tests made of all these units, including elaborate impulse tests, fully substantiated the fears entertained with regard to mica as a result of general experience. Accordingly very few mica installations after that date were made on the 132-kv. system, the principal installation being confined to the following types:

(a) A cable type capacitor. This has been described before the Institute.[21]

(b) A modification of the original cable type capacitor, combining a current transformer feature with the capacitor. A typical installation of the first of these is shown in Fig. 16. It will be seen that the unit is connected directly to the line, the fuses indicated in the photograph being on the equipment side of the capacitor. A typical installation showing a cable capacitor with current transformer feature is shown in Fig. 17. The current transformer secondary can be seen very clearly in the bottom portion of the cable loop of the left-hand side capacitor. The equipment shown between the two capacitors contains the protective equipment. Details of this protective equipment showing its connection to the capacitors, as well as the details of the line tuning equipment, are shown in Figs. 18 and 19, respectively.

Fig. 16—General Electric Co. Cable Type Capacitor Installation, Ohio Power Co., Canton, Ohio

In Fig. 20 is shown a diagrammatic sketch of an arrangement in which a combination of current transformers and coupling capacitors is installed on two lines connected to a high-tension bus. It will be seen that the existence of the current transformers has practically no effect on the method in which the capacitor itself is

Fig. 17—General Electric Co. Combined 132-Kv. Cable Capacitors and Current Transformers, Indiana General Service Co., Marion, Ind.

used and that the same connection to the carrier-current sets and to the lines is employed as in the straight capacitor.

In connection with these current transformer com-

bination capacitors, it may be of interest to give some experience with the accuracy obtained from the two-stage current transformers. Table II gives the accuracy

TABLE II

RATIO AND PHASE ANGLE CHARACTERISTICS OF A 150-AMPERE, 132,000-VOLT, 2-STAGE CURRENT TRANSFORMER WITH 2 TURN PRIMARY COMBINED WITH A CABLE CAPACITOR

| | | |
|---|---|---|
| Secondary burden = 33.3 volt amperes at 0.94 power factor<br>Tertiary burden = 15.0 volt amperes at 0.98 power factor | | |
| Secondary amperes | Ratio correction factor | Phase angle in minutes |
| 0.5 | 0.9983 | +4 |
| 1.0 | 0.9986 | +3 |
| 2.0 | 0.9987 | +3 |
| 3.0 | 0.9987 | +2 |
| 4.0 | 0.9987 | +2 |
| 5.0 | 0.9987 | +2 |
| Secondary burden = 10.9 volt amperes at 0.90 power factor<br>Tertiary burden = 10.7 volt amperes at 0.91 power factor | | |
| 0.5 | 0.9985 | −1 |
| 1.0 | 0.9986 | −1 |
| 2.0 | 0.9987 | −1 |
| 3.0 | 0.9987 | −1 |
| 4.0 | 0.9987 | −1 |
| 5.0 | 0.9987 | −1 |

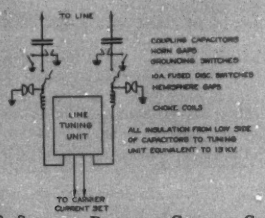


Fig. 18—Schematic Diagram of Capacitor Coupling Protective System

characteristics of these transformers and it will be noted that the accuracy is comparable to the accuracy obtained with standard definite wound high-voltage transformers. In fact, the accuracy secured is of a higher order and is not subject to change on account of variable instrument burdens to the extent met with in definite wound transformers.

The experience obtained with these cable type capacitors, whether of the straight type or combination type, has been uniformly successful and covers now a period of three years. In that time there has not been a single break-down, although there are installed at the present time approximately 80 of the units on the 132-kv. system. There has been some trouble experienced with the sylphon bellows used at first on the bushing, the principal difficulty being the leakage of oil, but these were replaced with expansion drums similar to the construction employed in high-voltage cable work and the difficulty has been entirely eliminated.

In Fig. 21 is shown an installation of the so-called tank type capacitors on a 132-kv. bus at Philo. These consist essentially of two metallic cylinders forming the capacitors plates with oil as a dielectric, the oil being, of course, broken up by a series of insulating cylinders. It was believed, and the tests carried out fully proved this, that while the cable type capacitor offered a

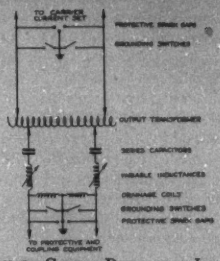


Fig. 19—Schematic Circuit Diagram of Line Tuning Unit

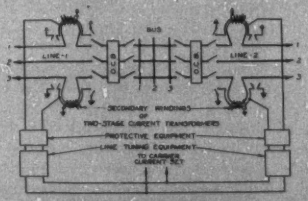


Fig. 20—Inter-phase Coupling with Combined Capacitors and Current Transformers

Fig. 21—General Electric Co. 132-Kv. Tank Type Capacitors, Ohio Power Co., Philo, Ohio

piece of equipment sufficiently adequate for all purposes, particularly from an impulse strength standpoint, experience with even more reliable equipment would be desirable in case some unlooked for operating experience

developed with the cable type capacitors. A number of installations of this tank type capacitor was therefore made. No trouble of any kind was experienced with them and the maintenance work on them has been confined strictly to such routine work as inspection for leaks, painting, etc.

In Fig. 22 is shown an installation of a combination oil and porcelain capacitor, some of which were made on the 132-kv. system in connection with Western Electric sets. These capacitors consisted of a series of porcelain shells with metallic sheathing on the inside and outside which formed the capacitor unit. A complete unit consisted of two such shells, one within the other connected in series, and a group of these was built up between two metallic cradles, one near the bottom and the other near the top of the tank which acted as a paralleling medium for the various units. A number of these individual units with an individual capacity of approximately 0.0003 $\mu$ f. was built up to give a total capacity of 0.007 $\mu$ f. This large capacity was

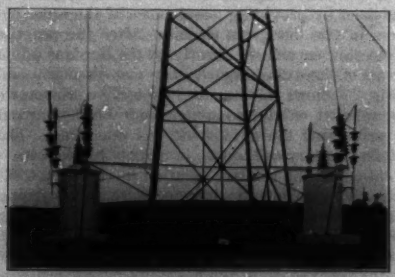

Fig. 22—Ohio Brass Co., 132-Kv. Tank Type Capacitors, Ohio Power Co., Canton, Ohio

felt by the carrier-current manufacturers' engineers to be highly desirable, apparently in view of the low power input employed on these sets. The capacity of all other capacitors employed on the 132 system has never been in excess of the maximum 0.001 $\mu$ f. and the experience obtained with that capacity has shown that under all conditions it has been more than adequate to provide adequate couplings.

The capacitors shown in Fig. 22 were originally equipped with series resistors on the high side. It was found impossible, however, to maintain these resistors in service owing to the large number of failures that occurred when trouble was experienced with the capacitor itself. A total of four separate failures on two capacitors was experienced and, as a result of that, the use of this particular type of capacitor was abandoned.

It was replaced with the capacitor shown in Fig. 23 which shows an installation at Cabin Creek. This consists of a series of porcelain shells electroplated on the inside and on the outside, the porcelain shell being approximately one inch thick. Regular insulator type of petticoats are employed at the bottoms to give the necessary leakage distance for outdoor use. Each of these units has a capacity of 0.001 $\mu$ f. and a combination such as shown in Fig. 23 of four of these units in

Fig. 23—Ohio Brass Co. 132-Kv. Dry Type Porcelain Capacitor Assemblies, Appalachian Electric Power Co., Cabin Creek, W. Va.

parallel and four in series, gives a capacity of 0.001 $\mu$ f. at 132 kv. Like the cable capacitors, they are connected solidly to the bus. The maximum length of service on any one of these units has been approxi-

Fig. 24—Ohio Brass Co. 66-Kv. Dry Type Porcelain Capacitor Assemblies, Ohio Power Co., Steubenville, Ohio

mately a year. To date the operating experience has been entirely satisfactory.

An installation of the same type of unit consisting of a two by two combination, is shown in Fig. 24. This is on a 66,000-volt installation which has been in service

approximately six months with entirely satisfactory results to date.

A 132-kv. installation of the mica capacitors is shown in Fig. 13. As pointed out before, subsequent to the insulation tests, particularly the impulse tests carried out on various makes of capacitors, the use of this equipment on the 132-kv. system was entirely abandoned. Quite a number of points that had previously had installations of mica made on them, were changed to some of the other types enumerated, where it was found possible to utilize the mica units at lower voltages. Nevertheless, in spite of the reduction of coupling points, in the past three years there have been five cases of distinct failures or break-down of mica capacitors on the 132-kv. system and with the exception of the failures of the combination porcelain and oil capacitor previously referred to, these have been the only failures.

The use of mica on low-voltage systems such as

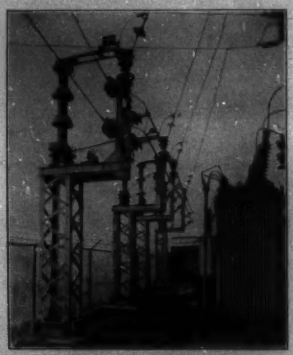

Fig. 25—Dubilier 66-Kv. Mica Capacitor Assemblies, Ohio Power Co., Crooksville, Ohio

66,000 volts and below, has been continued and is being employed on the system today. A typical installation at 66,000 volts is shown in Fig. 25. Extensive experience has been obtained in the past five years with mica on circuits of 66,000, 44,000, 33,000, 27,500, and 25,000 volts and not a single case of failure was experienced. It should be noted, however, that in the low voltages, such as 25,000 volts and 33,000 volts, no fewer than two single 22-kv. rated units were ever employed in series.

In view of all the above it is believed that the coupling problem has very definitely been solved and that equipment is available today with as high a factor of safety, if not higher, (since the capacitor with a capacity of 0.001 $\mu$ f. has an appreciable amount of self-protection) than is obtained in all the other links of the transmission chain. Some progress can still be made in the direction of reducing costs, but even this, it is felt, is very promising for the future.

## Protective System

As mentioned previously, on the first installations of coupling capacitors, disconnecting switches and choke coils were installed between the transmission line and the high side terminals of the capacitors. On all installations made within the past three years, no disconnecting switches or choke coils have been used, the capacitors being tapped directly to the transmission circuit and treated from an insulation standpoint similar to that of an insulator dependent solely upon the automatic breaker protection of the line to clear the line if a faulty capacitor should develop.

On the first installation of capacitors where high side disconnecting switches were employed, it was thought desirable from a safety standpoint to provide a means of discharging the capacitor after it had been disconnected from the line. Fig. 14 shows schematically how this was done by providing a resistance of the order of 800 ohms in the discharge circuit. After the practise of connecting capacitors directly to the line was adopted, the use of these discharge resistors was discontinued.

Fig. 18 shows the standard protective scheme which is employed on the equipment side of the capacitors for protecting the equipment and operators. This is self-explanatory, although it might be well to call attention to the relative location in the circuit of the fuses, choke coils, and sphere gaps, the object being, of course, to make sure that under the discharge of the gap, fuse action is obtained at all times. Supplementary protection is provided by the 60-cycle drainage coils located in the line tuning units. The practise of placing a two-pole telephone type fused disconnecting switch in series with the lead-in conductors close to the carrier equipment, has also been followed consistently.

It will be noted that the drainage coils used to drain the 60-cycle exciting current of the capacitors to ground are located in the line tuning unit. Fig. 19. The capacitors obtain their ground point through the drainage coils. If, therefore, the sphere-gaps act to blow the fuse, the capacitors will discharge over the horn gaps in Fig. 18, and the passage of the discharge current across the horn-gaps will result of course in a high-frequency disturbance over the entire system. This can be remedied by the throwing in of the ground switch, shown in the diagram, or by re-fusing of the fuse. It is planned, however, to change the position of the drainage coils to the line side of the fuses so as to eliminate this trouble.

The protective system outlined has in no case failed to function as contemplated or failed to take care of any situation that has arisen on the power end. In other words, it has acted entirely satisfactorily during the whole period covered.

### Lead-In Conductors

In making the first installation of carrier sets, the conductors connecting the antenna coupling wires or coupling capacitors with the carrier sets were run overhead, a nominal insulation of 33-kv. being used. In placing these lead-in conductors overhead, it was necessary to support them on the steel framework of the station structures by means of pillar type insulators, using copper tubing. It was also necessary to provide towers to support these conductors from station structure to the station building. These overhead lead-in conductors were very costly to install and introduced additional hazards, due to possibility of contact with power conductors. They were more or less unsightly and were many times found to be in the way of future construction.

Within the last two years, practically all of the lead-in conductors for new installations have been placed under ground, and also a number of the overhead lead-in conductors of earlier installations are now being placed under ground.

The lead-in conductors now being used for underground services consists of a two conductor No. 8 A. W. C. cable insulated for 2500-volt service with Kerite or 30 per cent para rubber, lead covered and steel armored. This cable is buried in the ground without any additional protection. The cost of an underground lead-in installation using this cable is approximately one-half the cost of an overhead installation.

At the time we first started to use underground cable lead-ins, the manufacturers would not guarantee satisfactory operation with cables greater than 600-ft. in length. Recently underground cable lead-in installations made at several of the larger stations required the use of cable to the extent of over 1000 ft. in length. After these installations were put into operation trouble was experienced in the form of distortion of received signals, which was attributed to the long underground lead-ins. The manufacturer immediately undertook a study to determine the means to secure satisfactory operation with long cable lead-ins, the result of which study has been the development of an impedance matching transformer. This transformer will be used as follows: A length of lead-in cable will be installed from the carrier set to a distribution point located in the outdoor switching yard, approximately equi-distant from the various sets of coupling capacitors installed on the transmission line. At this distribution point one winding of the impedance matching transformer will be connected to the high-frequency conductors from the set, and underground branch lines will be run from taps in the second winding of the transformer to the various line-tuning units. One of these impedance matching transformers will be used in each line-tuning unit to replace the air-core auto transformers generally used in these units where overhead lead-in conductors are employed. Laboratory tests indicate that the use of these impedance matching transformers will enable the use of underground lead-in conductors of any length which may be required in any commercial installation.

### Tuning of Couplings and By-Passing

Fig. 19 shows the schematic circuit of a line tuning unit which is connected between the carrier set and the coupling equipment for the purpose of resonating the coupling circuit to the frequency used.

In earlier equipments where overhead lead-in conductors were used, the tuning equipment for resonating the coupling was included in the transmitting equipment. In the later sets the lead-in conductors are treated as a high-frequency transmission line and the tuning done directly at the coupling. The line tuning unit consists essentially of two variable inductances in the form of variometers. Two capacitors are provided for the introduction of either series of shunt capacity in the tuning circuit. An air-core auto transformer is also included for the purpose of stepping up or stepping down the carrier voltage.

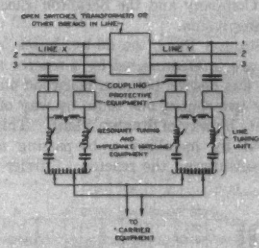


Fig. 26—Schematic Diagram of By-Passing with Line Tuning Units

Fig. 26 shows two line tuning units connected to the transmission lines $X$ and $Y$, which lines are isolated from a carrier-frequency standpoint due to open switches or intervening transformers. When both of these line tuning units are tuned to the same carrier frequency, it will be noted that a tuned path for that carrier frequency is provided around the break in the line. At the same time, when both line tuning units are tuned to the same frequency this frequency may be transmitted into both lines, or when the two line tuning units are tuned to different frequencies they serve the purpose of directing each frequency into its proper line.

In some of the earlier installations the couplings to each line of a number of lines were not separately tuned, but the low side terminals of all the couplings were connected in parallel and the combined coupling to all the lines tuned by means of one line tuning unit. This scheme of tuning was found to work satisfactorily, and in most cases fairly successful by-passing was secured. However, by tuning each coupling separately,

much more efficient by-passing is secured and it is felt that the additional cost of tuning each coupling separately is justified by the greater reliability of by-passing secured.

Fig. 27 shows schematically the carrier telephone installations on the systems of the Pennsylvania Power and Light Company and the Scranton Electric Company in Pennsylvania.

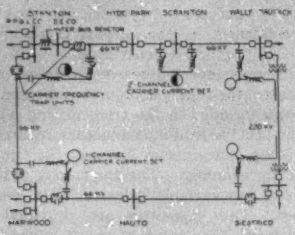


Fig. 27—Schematic Diagram of Coupling, Tuning, and By-Passing on Interconnected Systems of Scranton Electric Co. and Pennsylvania Power and Light Co.

At the Stanton Plant the 66-kv. buses of the two companies are interconnected by a reactor tie. Communication was desired between Harwood and Wallenpaupack by two routes, one route by way of Siegfried and one route by way of Stanton Plant. This has been accomplished by installing a by-passing system at Stanton Plant around the reactor. Carrier-frequency trap units, as shown in Fig. 28, are installed in the feeders used for the carrier channel to confine the carrier energy to the desired circuits and exclude the carrier energy from other circuits through which communication is not desired and in which the energy would otherwise be wasted. These trap units are also installed at Harwood and Siegfried for preventing loss of carrier energy in other circuits.

Fig. 28—Tuned Carrier-Current Trap Unit

These trap units consist of a 400-ampere choke coil, having an inductance of approximately 70 microhenries with an adjustable capacitance in shunt, the capacitance being arranged so that the unit may be tuned to resonance at any frequency from 50 to 150 kilocycles.

These carrier trap units are also suitable for blocking carrier energy out of stub feeders where the length of

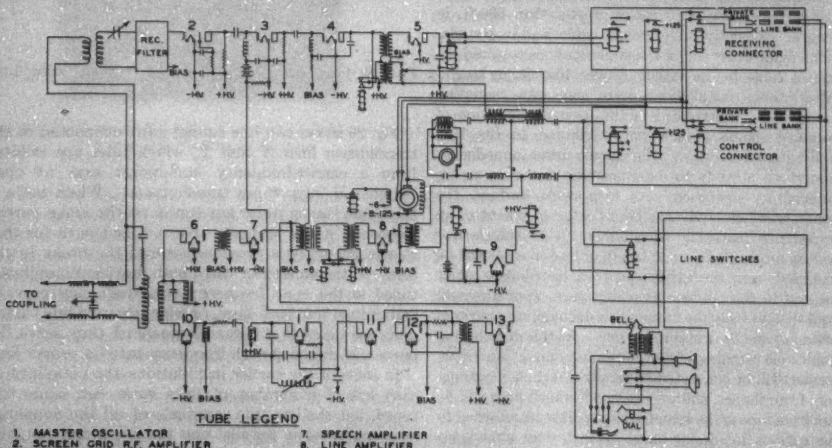


Fig. 29—Schematic Circuit Diagram of a 50-Watt Primary Set, Type KCA-1, General Electric Co.

the feeders is such as to absorb an undue amount of the carrier energy. They are also suitable for breaking up loop transmission circuits and directing the flow of carrier energy around the desired portion of the loop so as to prevent reflection or neutralization of the signal energy. In connection with the 132-kv. system, we have not yet found it necessary to employ trap units for the two last-mentioned purposes, although there is little doubt but what these applications will be required in the future.

### Transmitting System Experience

Fig. 29 shows a simplified schematic diagram of the circuits of one of the latest type of primary 50-watt sets, known as a type KCA-1 set. This set uses a 7.5-watt master oscillator (1) in a Colpitts circuit driving 50-watt power amplifier. (10) A 7.5-watt line amplifier (8) and a a 7.5-watt speech amplifier (7) are used to build up the voice energy for input to a 50-watt modulating tube (6) which modulates the carrier energy in a Heising modulating circuit. The modulated carrier energy is delivered to the coupling system through a two winding radio frequency output transformer.

The operation of the oscillator blocking circuit used to secure duplex, single-frequency operation is as follows: A 7.5-watt audio amplifier (13) designated control amplifier receives the audio signal from the line amplifier (8) and amplifies the audio signal which is then impressed upon the control rectifier, (12) which is a 7.5-watt tube functioning as a half wave rectifier, rejecting one-half of the amplified audio voltage received from the control amplifier. The rectified pulsating d-c. voltage output of the control rectifier, (12) after being smoothed out, is impressed upon the grid of the control tube. (11) The grid of the control tube during reception periods is normally biased negative to cut-off. The filament return circuits of the master oscillator is obtained through the plate-filament circuit of the control tube. When the plate-filament circuit of the control is open or cut off by the high negative grid bias on the control tube grid, the plate circuit of the master oscillator is open circuited, preventing the master oscillator from oscillating. When a voice signal is impressed on the microphone, the control amplifier and control rectifier act to place a high positive bias on the grid of the control tube overcoming the normal high negative bias of its grid. This positive bias on the control tube grid reduces the plate-filament impedance of the control tube, providing a low impedance return path for the plate-filament circuit of the master oscillator, allowing plate current to flow to the oscillator and permitting the oscillator to function.

This blocking system is quite simple and on the later models of sets works highly satisfactorily. In the earlier sets the action of the blocking system could usually be heard in the receiver as a click, but in the later models of sets this does not exist, and when properly adjusted no evidence is given to the speaker of the action of the blocking system.

The various bias voltages for the transmitting tubes are secured from taps taken from a resistor shunted across the output of a 125-volt d-c. generator which is one of the units of the 4-unit motor generator set to be referred to later.

Signaling is accomplished by introducing into the grid circuit of the speech amplifier a 300-cycle a-c. voltage produced by a small rotary converter supplied from the 125 voltage station storage battery.

The transmitting system as a whole is quite simple, and the performance has shown this up; practically no trouble has been experienced with it.

### Receiving System Experience

In the earlier models the tuning system for selecting the desired frequency consisted of two simple coupled tuned circuits, feeding a non-regenerative detector. This simple tuning scheme was sufficient at first but as the number of stations on the system and the number of

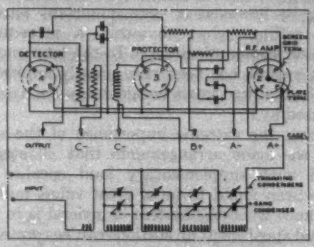


Fig. 30—Schematic Circuit Diagram of Selectivity Filter

channels increased, it was found that the simple tuning system was not sufficiently selective, with the result that stations operating on other frequencies were able to interfere with the reception of desired signals. This brought about the development of receiving systems having higher selectivity characteristics. Fig. 30 is a schematic diagram of the circuits of this filter. A high degree of selectivity is secured by the four coupled tuned circuits, the last one of which feeds into a 4-element screen grid tube (2) used as a radio frequency amplifier. This radio frequency amplifier feeds into a non-regenerative detector. (4)

The middle tube is a protector tube (3) which is used to block the receiving circuits automatically during transmission periods. During receiving periods the grid of the protector tube has a negative bias giving the tube a high filament-plate impedance. During transmission periods a positive bias is used to overcome the normal negative bias, reducing the filament-plate impedance of the tube, thereby short-circuiting the input to the detector, resulting in blocking of the receiving circuit.

Reception is secured directly out of the detector circuit without the use of audio amplification. This results in an exceptionally clear signal. One stage of audio amplification (5) fed by the detector is used for operating the calling relays. Automatic selective telephone switching equipment is provided for connecting the extension lines to the transmitting and receiving circuits, provision being incorporated for a maximum of 10 two-wire telephone extensions.

The carrier telephone system is being used primarily for dispatching and very little other communication is allowed to go over it. For this reason, very few cases have come up where extensions to the carrier equipment have been required. One such extension, however, is in operation at Canton, Ohio, between the substation and the main office, about two miles distant. This extension is made over a pair of telephone wires in a cable circuit leased from the telephone company. The extension has operated entirely satisfactorily.

Of all of the component parts of the carrier communication system, the signaling system has probably given more trouble than any of the others. The signaling is, however, a very important part of the system, calling being obviously a prerequisite to carrying on communications. In the later models the signaling system has been very greatly improved, and within the last two years considerably less trouble has been caused by it.

Realizing the extreme importance of the signaling system, we made arrangements that all stations be provided with supplementary loud speaker calling. This has been found to be of great value, particularly during times when the system in general is in distress, as the loud speakers at all stations can be connected and instantaneous voice calling used. It takes an appreciable length of time to operate the dialing system to call a station, and during times of system trouble the time of the operators is at a premium and the loud speaker calling saves considerable time and also enables the dispatching operator to be in communication at all times during the trouble with all the other stations on the channel, and enables all other stations on the channel to keep informed regarding the status of the system trouble.

## Power Supply

Fig. 31 shows schematically the four-unit motor generator set used to supply the several forms of current and voltage for the 50-watt primary sets. The d-c. motor of the unit receives its supply from the station storage battery. This four-unit set operates only during periods of transmission. In the same diagram is shown schematically the full wave tungar charger used to trickle charge the 6-volt storage battery which supplies the filaments of the receiving tubes. The filaments of the transmitting tubes are supplied from the alternator of the four-unit set. The plate supply for the receiver tubes is taken directly from the station storage battery. This entire power supply system has been found practical and reliable.

In the earlier sets the 6-volt filament battery was trickle charged by means of a motor generator set. This required that the motor generator set operate continuously. Considerable trouble was experienced in maintaining these motor generator sets in operating condition due to their continuous service. All of the trickle charging motor generator sets have now been replaced with tungar chargers and the experience so far has been that these chargers require practically no maintenance.

In addition to the 6-volt filament battery a small 24-cell, 48-volt battery, which is not shown on the diagram, is used to supply current for operating the various control relays in the set. This battery is trickle charged from the 125-volt station storage battery through a variable resistor. In the earlier sets the control relay supply was taken from the 6-volt battery used for the filaments. This low voltage is not satisfactory for relay work and considerable trouble has been experienced due to dirty or oxidized contacts offering a relatively high resistance to the 6-volt supply. Since the adoption of the 48-volt control battery this trouble has practically ceased and very little maintenance work is now required to keep the various relay contacts in good operating condition.

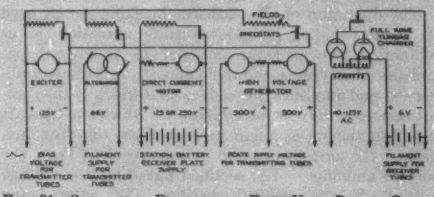


Fig. 31—Schematic Diagram of Four-Unit Power Supply Set or Type KCA-1 Primary Set

The following general troubles have been experienced with the 4-unit motor generator sets, particularly the sets furnished with the earlier models of equipments: Oil from the bearings found its way on to the commutators, which combined with the carbon dust from the brushes and formed a high-resistance short circuit between the commutator bars. These short circuits between the bars were of such high resistance that they would probably not have any effect upon the satisfactory operation of a generator used for supplying power for commercial purposes. However, these short circuits produced very noticeable fluctuations or ripples in the output of the generators, which seriously interfered with the quality of speech transmitted by the sets. This trouble has been practically overcome in the later sets by completely redesigning the generators for communication service.

Fig. 32 shows schematically the various rectifiers used to supply the filaments, plates, grids, and control relays of the secondary type of set. The receiver filaments are supplied from a 6-volt storage battery trickle charged by a half-wave tungar rectifier. The relay control circuits receive their supply from a 48-volt storage battery, which is trickle charged from the rectifier used to supply the receiver plates. In order to make this set independent of failure of the a-c. supply a 2-unit motor-alternator is provided. This machine ordinarily stands idle and only comes into use automatically upon the failure of the a-c. supply. Its motor is supplied from the station storage battery and the alternator supplies the a-c. input to the set. One of these secondary sets has been in service for about one year at Rutland, Ohio, (reference Number K-45) with very satisfactory results.

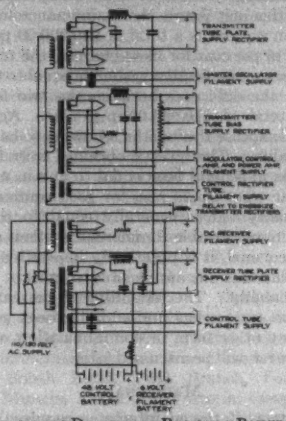


Fig. 32—Schematic Diagram of Rectifier Power Supply for Type KCA-100 Secondary Set

## Zoning and Interzoning

Fig. 33 shows a diagram of the A. G. & E. portion of the 132-kv. system shown in Fig. 4. The diagram not only shows the 132-kv. transmission lines and the various locations of carrier-current sets but also indicates how the various channels have been distributed. As will be seen from the diagram, nine channels are at present utilized (if Toledo is taken into account) on the A. G. & E. system.

These channels are outlined in detail in Table I; the table is, however, more complete and covers the entire 132-kv. system. Thirteen channels are indicated in the table (Toledo not being shown), of which nine are used on the A. G. & E. 132-kv. system.

An examination of Fig. 33 will show very distinctly that Lynchburg, for example, by the very nature of the geographical distance, can have little business with South Bend that could not be cleared up and better taken care of by some other point or somebody else in the system very much closer to Lynchburg. As a matter of fact, Switchback, which is one of the five principal dispatching points previously mentioned, is as far as Lynchburg ever needs to go. In fact, the system set-up is such that if Lynchburg goes farther than Switchback, it becomes a positive nuisance and results in the cluttering up of the system with carrier to the detriment of the carrying on of other business. This is true of a system such as the one shown in Fig. 33, where there is some measure of co-ordination between a group of companies subsidiary to one parent company. Obviously this is more apt to be so where the companies are merely inter-connecting companies, with no other relationship except certain contract relationships between them.

All this was clearly indicated from the very beginning of application of carrier and as the system was extended, the necessity for it became absolutely imperative. As a result the grouping indicated was worked out, taking into account such things as operating relationships of the various points, location of dispatchers, location of interconnection points, amount of business transacted in a certain area, etc. It will be noted that three of the five principal dispatching points have two frequencies, and one of the points (Shelby) has actually

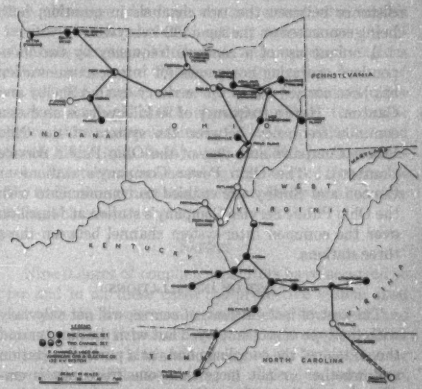


Fig. 33—Diagram Showing Carrier Channels on American Gas and Electric Co. 132-Kv. System

two sets, since three channels are utilized at that station. Where two channels only were found necessary in a station, this was done by a so-called inter-system attachment which consists of nothing more than a separate receiver with an arrangement for automatically changing the frequency of the transmitting system.

No repeater stations have been found necessary or

have been employed in this entire system, it having been so arranged that practically every channel is a more or less self-contained area. What business has to be carried out between one channel and the next is carried out by relaying, but experience has indicated that this is used to a very small extent.

Some of the zones, as is indicated, are quite close together. Since, in order to obtain all the channels, it was necessary to work on rather close frequency spacing (approximately 10 kilocycles) it is obvious that sharpness of tuning is one of the prerequisites for the successful operation of a system such as outlined. The development of selectivity filters previously referred to, solved this problem and has resulted in a situation where no interference is experienced between one channel and the next. In other words, the system as set up from that standpoint has shown itself to be entirely successful. A point that ought to be noted in this connection where such a wide flung system is involved is that natural attenuation makes it possible to operate two frequencies very close together in different portions of the system and yet have each one of them cover a channel of its own without any interference between them. For example, channel *A* covering the six stations in Michigan and Wisconsin operates at approximately 50 kilocycles without interfering in any way with channel *H* which operates around Philo at approximately 46 kilocycles; there is no other barrier except distance between the two channels in question, both being connected on the same 132-kv. system.

A unique use of a common frequency by two independent operating companies for inter-communication has been carried out in the territory around Shelby and Canton. Here a frequency of 90 kilocycles is used as a common frequency between the system of the Ohio Power Company and that of the Ohio Public Service Company. The Ohio Power Company's stations at Canton and Shelby are enabled to communicate with the Ohio Public Service Company's station at Massillon over the common inter-system channel between these three stations.

## Cost of Installations

The cost of installations, of course, will not only vary with the type of sets employed but with the number and the voltage of the coupling points at a particular station and whether or not more than one frequency is employed at that station. Up to the present time line coupling exclusively has been employed on our 132-kv. system. It is possible, of course, to reduce this cost considerably by going to bus coupling. However, on the basis of the coupling practise followed, which has been fully described, the average cost per terminal has been running in the neighborhood of $15,000.00. This includes all the overheads. The cost of the 30 terminals therefore represents an investment of approximately $450,000.00.

These 30 points provide communication for a total of 1340 linear miles of 132-kv. line. It is estimated that the cost of a single leased line to provide approximately equivalent communication would amount in rentals to approximately $72,500.00 per annum.

Complete data on maintenance are not available over the system as a whole but on one portion of the system, where cost records were kept, the maintenance cost, including all the necessary personnel, of 18 sets in 1928, was approximately $9000.00 or $500.00 per year per set. Utilizing this unit figure, the maintenance for the 132-kv. system represents a total of $15,000.00 per annum. Allowing 15 per cent for fixed charges, the total cost of the carrier communication system is equal to $82,500.00 per year, the difference between the two forms thus being a total of $10,000.00 per year. Against this additional expense there is the following to be balanced:

1. Quality. The quality obtained over the carrier system has in general been equal to and in many cases better than what would pass for good commercial telephone quality. It is generally equal to the quality obtained in an all-cable commercial system, and in the territory covered, it is practically impossible to obtain an all-cable line of any appreciable length.

2. Reliability. The reliability of the carrier communication system has undoubtedly been superior to that of any other form of communication obtainable. This, however, will be discussed later.

## Maintenance

The extent of the maintenance required has been discussed and some data with regard to maintenance have been given in the detailed analysis of the various phases of the equipment. In general, maintenance has been confined to routine inspection. Many matters that have given trouble considerably during a portion of the time covered have, through attention to that particular phase, been brought up to the point where they have been completely eliminated as a main source of trouble. Today, therefore, with the elimination of coupling, calling system, and similar troubles, only routine maintenance is necessary.

The cost, as already indicated, is not available for the entire system but the experience gathered on a portion of the system indicates that it runs $500.00 per terminal per year. It is believed, however, that no small portion of this is attributable to expenditure involved in training new personnel, etc., and that as time goes on, this figure can be cut from 20 to 30 per cent.

## Reliability

The experience on our system has been that in many cases when contingencies develop that cause a breakdown of supporting structures or of lines that provide commercial communication, the carrier system of communication, depending upon the transmission line for the guidance of high-frequency current, was still operative.

Typical of the many cases experienced along this line are the following:

In June of 1929 important circuits of the private telephone system used for dispatching between the Stanton plant and the Pennsylvania Power & Light system went out during a storm and were out for a total of 19 hours and 48 minutes. The communication between Scranton (see Fig. 27) and other points of the Scranton electric system provided with private commercial telephone service was interrupted for periods ranging from three hours upwards. The carrier telephone system, however, functioned perfectly at Scranton during all this period.

On June 30, 1929, a severe thunderstorm in Indiana resulted in loss of all private telephone communication used for local dispatching between Marion and Muncie, (see Fig. 4). During that period, however, as well as during other periods under similar conditions, continual communication by means of carrier was maintained between these two points and was the only form of communication.

Again, on May 2, 1929, a very severe sleet storm was experienced in the South Bend territory. A leased commercial circuit, the majority of which is in cable, was used in this territory for local dispatching between seven points on the local system. The phones on this leased circuit went out of service and remained out for periods from 44 to 73 hours. During this entire time carrier communication was maintained continuously between South Bend, Twin Branch, Fort Wayne, Marion, Muncie, Lima, and Fostoria, excepting for a period of approximately 11 hours when carrier communication was not available between South Bend and Twin Branch while the lines between these two points were taken out of service and grounded for making repairs. During this storm, conductors of both circuits between South Bend and Twin Branch were broken and on the ground but regardless of this condition carrier communication was actually maintained between South Bend and all other stations on the channel until the circuits were actually grounded at both ends for making repairs.

From a reliability standpoint we believe, therefore, that carrier, properly applied, installed, and maintained, provides over our system a continuity of service economically possible by no other means of communication.

## Traffic

Table III gives the results of a traffic check made on a channel with 11 sets. Turner and Switchback were the main dispatching points on this channel. From the data shown the following are obtained:

(a) Total number of two-way conversations, 1016.

(b) Average number of times channel was used per hour, 14.1.

(c) Average duration of a conversation, 1 min., 39 sec.

(d) Percentage of time channel was in use, 38.5 per cent.

TABLE III

SHOWING RESULTS OF TRAFFIC COUNT OVER A SINGLE CHANNEL OF 11 STATIONS. COUNT TAKEN OVER 9 WEEK DAYS DURING HOURS 8 TO 12 A. M. AND 1 TO 5 P. M.

| Stations | Total calls placed or received | Average times used per day | Total time in use during 72 hours | | Average percentage of time in use |
|---|---|---|---|---|---|
| | | | Hours | Min. | |
| Philo | 58 | 6.5 | 1 | 30 | 2.3 |
| South Point | 123 | 13.6 | 2 | 53 | 4.0 |
| Turner | 558 | 61.8 | 15 | 14 | 21.0 |
| Logan | 201 | 22.3 | 5 | 20 | 7.4 |
| Sprigg | 91 | 10.1 | 2 | 46 | 3.8 |
| Switchback | 459 | 51.0 | 12 | 38 | 17.5 |
| Saltville | 24 | 2.7 | 0 | 36 | .8 |
| Kingsport | 81 | 9.0 | 2 | 4 | 2.7 |
| Glen Lyn | 79 | 8.8 | 2 | 4 | 2.7 |
| Roanoke | 216 | 24.0 | 6 | 49 | 9.5 |
| Lynchburg | 144 | 16.0 | 3 | 46 | 5.2 |
| Totals | 2032 | 226.0 | 55 | 49 | 76.9 |

The transmission of meter readings and similar routine dispatching data from the controlled stations to the dispatching points can usually be done at off-peak periods. Scheduling of the use of the channel by the stations on it and the transmitting of record data at off-peak periods have been of great help in making one channel serve a large number of stations. The party line feature permits routine communication to proceed and enables any operator to break in whenever it is necessary to use the channel for more urgent matters. One advantage of a large channel as indicated in this territory is that the chief system operator may communicate directly with all plants and important stations under his control. Regular communication is carried on between Turner station (ref. KL-49) and all other stations on the *K* and *L* channels. When the traffic figures shown were obtained, Philo (ref. HK-32) and South Point (ref. K-46) were included in this channel. By systematic scheduling it is believed that double the traffic shown here can be conveniently handled over a single channel.

## Safety

Nine failures of coupling capacitors have occurred so far and in all these cases the protective system used between the power conductors and the equipment and operators has functioned correctly and no damage or injury of any kind has occurred to equipment or operators. With the placing of all lead-in conductors underground the present extremely small hazard will be further reduced. The hazard is surely less than that existing in connection with the use of telephone circuits strung on transmission lines or even of some commercial overhead circuits. The experience at Canton when the power conductors came in contact with the antenna coupling wires resulted in damage to equipment only. In all our carrier experience no case has ever occurred where injury to any person has resulted from failure of the equipment.

### Portable Sets

It is believed that the data cited indicate that the development and application of carrier to the higher voltage lines has now reached a high level.

Fig. 34—General Electric Co. Type KCA-200 Booth Type Set

Very little has so far been done, however, toward applying carrier to the communication requirements of transmission networks operating with voltages of the order of 44, 33, and 22 kv. Here an entirely different problem is met. The lines are not built as strongly; more tap lines, transformers, loop circuits, sectionalizing points, etc., are encountered than on the higher voltage lines, all of which tend to increase attenuation and make the system unstable. Also the points at which communication is required are much more numerous and many of the points are located in out of the way places difficult to get to for inspection and maintenance. Dependable power supplies such as station storage batteries are not available.

Fig. 34 is an illustration of a booth type set designated type KCA-200 recently developed by the General Electric Company for this work. It is built for either indoor or outdoor mounting and may be used with either dry cell batteries for intermittent service or with storage batteries for continuous use. It operates on the simplex, single-frequency, interphase principle, and is provided with selective signaling. A loud speaker may be connected for voice calling.

Fig. 35 is a group of diagrams showing schematically the circuits for transmitting and receiving. Two tubes are used, operating as oscillator and modulator respectively for transmitting and detector and audio amplifier for receiving. The set has an output of 0.25 watt.

Fig. 36 is a photograph of a portable type set, designated type CC-5B, made by the General Electric Company. It uses one dry cell tube for both oscillator or detector, operating on the simplex, single-frequency principle, either interphase or phase-ground return.

Fig. 37 is a group of diagrams showing schematically the circuits for transmitting and receiving.

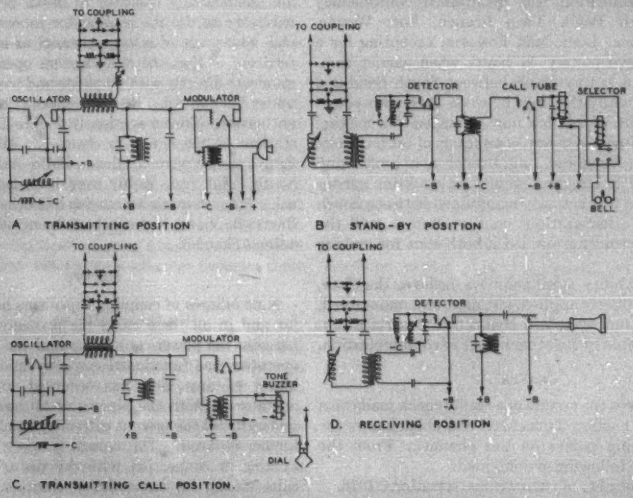


Fig. 35—Schematic Circuit Diagrams of Booth Type Set

Fig. 38 shows schematically the installation of one of these sets at a sectionalizing point for patrol communication. Here the set is used with phase-ground return circuit.

At present a trial installation is being made on a 50-mile, 33-kv. line from Ashland to Haldeman, Ky. of three type KCA-200 sets and two type CC-5B sets

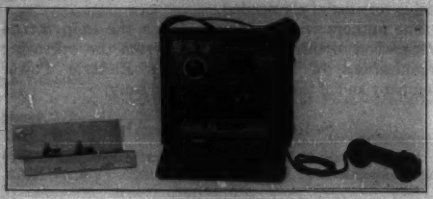

Fig. 36—General Electric Co. Type CC-5-B Portable Type Set

located at sectionalizing points and communicating with a type KCA-100 terminal set at Ashland.

Fig. 39 shows a typical pole type installation adopted for either type of set.

Another experimental installation is being made on a portion of a 44-kv. transmission network of approximately 300 line miles located around Cabin Creek,

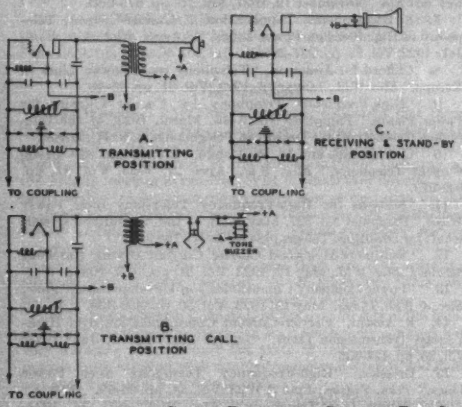


Fig. 37—Schematic Circuit Diagrams of Portable Type Set

West Virginia. This system covers very mountainous country. The dispatching and patrol communication has heretofore been done over leased commercial circuits practically all of which are open wire lines. Experience with the commercial circuits in this particular territory has not been fully satisfactory and it is planned, therefore, to introduce carrier as a means of communication. Ten type KCA-200 sets are being installed initially. It is planned that these two experi-

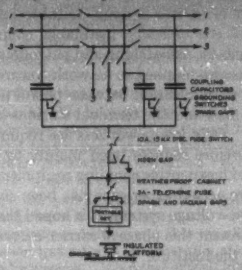


Fig. 38—Schematic Diagram Showing Phase, Ground Return Coupling, and a Portable Set

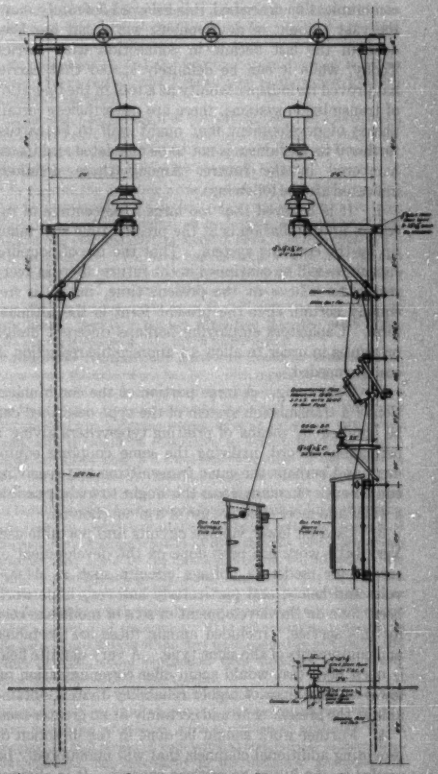

Fig. 39—Outdoor Installation for Booth and Portable Sets

mental installations of small sets on low-voltage transmission networks will provide the experience for the development of carrier systems suitable for providing reliable, and economically justifiable communication over such lines for dispatching and patrolling communication. It is also planned to do work towards applying carrier for communication between patrol points along the 132-kv. lines and the terminal stations at each end of the lines. Only low-power sets are required and the problem therefore reduces itself mainly to developing adequate and inexpensive coupling equipment.

After more actual experience has been secured with carrier on low-voltage systems it is hoped that it will be possible to present this phase of carrier-current development before the Institute.

### Future Line of Development

The experience obtained with the carrier system of communication described, it is believed definitely shows the vast amount of development work that has been done in the last decade in connection with carrier. Today, while it can be definitely stated that carrier has proved its indispensability as a tool in the operation of transmission systems, there are nevertheless certain phases of development that ought still to be carried further if its usefulness is not to be restricted and its use hampered in the future. Among those definitely indicated are the following:

1. It is believed that too large a percentage of the cost of an installation is at the present time still taken up by the coupling system. That the use of coupling capacitors will be continued in the future, there is every reason to believe at the present time, but it is not equally certain that the present form is the ultimate form. Capacitors employing perhaps different design principles in order to allow an appreciable reduction in cost are needed.

2. Teletyping. A large portion of the communication of a transmission system of the type described can be handled by means of printing typewriters giving a permanent record, utilizing the same coupling equipment and perhaps the same transmitting and receiving equipment. In many cases this ought to make possible a wider and more effective use of a given channel.

3. Used on lower voltage circuits and portable use. Very little work has been done on the development of carrier for moderate voltage circuits such as 44,000 volts and below, and particularly has very little work been done on the development of sets of moderate cost for this service. Included among these are portables and equipments of the same type. A very definite field is open here that would again offer communication on lower voltage lines of higher reliability than is obtainable at the present time and certainly at no greater cost.

4. Further work should be done in the direction of providing additional channels that will undoubtedly be needed in the future as systems expand. It is obvious that little more can be done in the direction of reducing the number of frequencies employed in a given channel so that the logical direction of development would be in the path of reducing the width of frequency band required per channel. It is possible that the development of the single-sideband carrier system will answer this purpose but the objection to it in its present form is its greater cost. A development that would obtain substantially the same results at much lower cost is very definitely needed.

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## Discussion

**R. J. Wensley:** Mr. Sporn makes a statement that there is no paper by a large system operator covering the system they have in use. He also omits mention of a paper presented by Woodcock and Robinson[1] of the Alabama Power Company at the Atlanta meeting in October, 1928, in which they described the large double-frequency carrier system now in operation on the Alabama Power Company System. It describes the satisfactory results obtained with high-power double-frequency carrier telephone communication over a system of 2000 mi. of 110-kv. transmission lines. On that system there are four operating channels with a lower frequency of 27 kilocycles. They are having no interference trouble according to latest reports.

The Indiana Electric Corporation has over 20 sets of the high-power two-frequency in operation on a much more compact but very intricate network over the state of Indiana. That company is quite satisfied with double-frequency operation and finds no bar to successful load dispatching.

We hold no particular brief for the double-frequency system. It would be quite as easy for us to build the single-frequency. It only means adding a few more vacuum tubes to the tuned circuits.

We are wondering as to the actual future of carrier equipment. Our own feeling is that wherever fully protected sheathed cable on high-grade pole construction is available, leased wires through those cables probably offer the best means of system communication. But as soon as you get out into the areas where cable is not available, the stronger construction of the transmission system offers a more dependable means of communication than the much lighter built telephone long-distance circuits with the small wire and the light construction.

One point in answer to Mr. Sporn's requirement of a cheap means of coupling, we have developed a form of coupling capacitor which looks like a string of suspension insulators and requires no other construction than to hang the string on the tower.

**J. D. Burbank:** We have a system of about ten or twelve stations on our lines, and most of it is General Electric equipment. We find that it gives us very satisfactory communication, but there are certain points concerning which I should like to ask Mr. Sporn to give his experience.

We find that the control system used on single frequency on the voice circuits tends to impair the quality, while if you go to the double frequency system, you run into complications due to the fact that the transmission characteristics are not the same over different frequencies. It is rather difficult to find two bands which will be sufficiently wide to carry sidebands as well as your carrier waves for those two frequencies. That is the difficulty we are up against.

I was just wondering whether he had any trouble with the quality, in using a single-frequency system, due to the blocking action of his control tube.

Furthermore, we find the selective ringing system is by no means always perfect, and I should like to know just what his experience has been.

In general, I would say it is very satisfactory. We have had a number of heavy sleet storms, and that has been the only communication available as a rule. The private lines are wiped out, and the open-wire Bell lines are not much better.

As regards the coupling arrangement, we use all the systems that he mentioned. We use the mica type and the cable type. We have one of the original oil capacitors, as a matter of fact the first one ever installed, at Niagara Falls. The oil capacitor is very satisfactory. We have had no trouble with it. We also have some of the Ohio Brass Company porcelain type which have been satisfactory to date. Those are newer. We found, however, that in a good many cases the old coupling wire comes in very handy, and it is far less expensive than the other types. You can do by-passing, etc., much easier with it.

**Alexander Nyman:** (by letter) It would be interesting to know what the experience has been with regard to the surge protection introduced on account of the capacity connected between the transmission line and ground. As is well known, the surges and particularly, lightning surges, have an extremely steep wave front, and it would be reasonable to expect, therefore, that a capacitor would absorb a considerable amount of the energy of this steep wave front, thus reducing the shock on the other apparatus and in a way, acting as a lightning arrester. If such an installation has been present for any length of time, the operators near this particular installation, should certainly be aware of the reduction of surge troubles at their stations, and it also seems possible that some of the break-downs on the capacitors are really due to lightning surges, the condenser thus serving as a protector for the remaining apparatus and sustaining the damages which could have otherwise inflicted much more serious losses on other apparatus of the system. It is interesting to note that in the actual installation of the first mica condenser at Canton and Philo in 1925, these condensers have stood up continuously since that time without any trouble.

With regard to carrying out impulse tests, especially on apparatus which would be later put into actual service, this is a very dangerous procedure, since a condenser subjected to the necessarily high strain of such impulse test, is likely to have incipient damages, not necessarily in the dielectric producing the capacity but in impregnating materials or mounting parts such as bakelite rods or porcelain separators. A condenser weakened by

1. *Carrier-Current and Supervisory Control on Alabama Power Company System*, A. I. E. E. Quarterly Trans., Vol. 48, Jan. 1929, p. 214.

such test and later placed into service, would therefore be more likely to break down due to a subsequent surge.

During recent years, considerable development work in new types of condensers has been carried out with the result that a type of coupling condenser has been developed which is considerably cheaper than the present type of mica, cable, or porcelain condensers, which has a higher impulse ratio of the order of 10 to 12, and which permits placing a much larger capacity within the same space than the present type of condensers.

**Philip Sporn:** In answer to Mr. Wensley, I am sorry if we overlooked the paper of Messrs. Robinson and Woodcock. The article mentioned as item No. 35 in the Bibliography is, I think, on the same system; it is indicated as the Southeastern Power & Light Company. There is a reference, therefore, to that system although not to the particular paper.

I believe there is no real difference between Mr. Wensley and us on the question as to whether a two-frequency system will or will not work all right. We set down as one of the fundamentals, ability to furnish a maximum number of channels on any one system. The idea that we started out with is that it is possible to have a large power system and a four-frequency carrier system that will work all right, but the question is: What will happen when the two channels that four frequencies will give aren't enough?

Our stand in the matter—and we believe we have tested the curve a little further to the breakdown point than it has been tested in Alabama, perhaps—is that the two-frequency system will work, but obviously as long as you have to have two frequencies there will come a time when you will be able to have only half the channels that a single-frequency system will give you. If you don't need so many channels, the two-frequency will be all right. If you have to have all the channels you can get, obviously you are wasting possible channels. We have reached the point on our system where we can't waste any channels. We must have all we can get. That is the point I made.

There is also the question as to whether it is a fundamental requirement to have all the people on a given channel come in at any time during the conversation. There is much difference of opinion on that. Our own operating people requested that we develop this. They couldn't operate safely unless everybody who had any business on the channel was able to come in on an emergency regardless of other conversations on his channel. We had two very bad spills as a result of not being able to do that with another carrier system that we described. If the electrical system is set up so that the load dispatcher is czar of the system and nobody else dare say anything, I imagine the other set is all right. Our own people don't work that way.

As regards the field of application for carrier and cable, here, again, I think we are in entire agreement. Where the distances are short, and that is a point Mr. Wensley didn't mention, and where you have available cable service, I think you cannot justify carrier. That does not happen to be the case on most high-tension overhead systems. There are many sections where there is no reliable telephone service available.

Mr. Burbank brought up two or three questions, the first about quality. On the sets we have been able to get in the last two or three years the quality is comparable to very good Bell service, and better than a lot of Bell.

The question of selective ringing that Mr. Burbank mentions was one of the weak things in the system, and we think today probably is still open to improvement. We supplement the selective ringing by loud-speaker calling and find it very satisfactory.

As regards the question raised by Mr. Nyman, there is no doubt that some of the failures of mica capacitors mentioned were due to lightning; that is exactly the point we made, that the mica capacitor is fundamentally unsuited to stand impulses as well as capacitors utilizing other material, as for example, oil-impregnated paper. It happened that the Canton capacitors stood up well but other capacitors of the same type which went into service much later failed after a very short time in service. Of course none of the capacitors which were used in the laboratory were actually put into service later. As Mr. Nyman points out, it would be entirely unfair to the apparatus and besides would be a rather risky operation. The new capacitors which Mr. Nyman mentions as having an impulse ratio of 10 to 12, are unusually interesting, particularly if they actually meet the claim made for them. It will be interesting to find out for what type of impulse wave the impulse ratio of 10 to 12 is predicted.

# Automatic Regulation of Synchronous Condensers

## Equipped with Superspeed Excitation

BY L. W. THOMPSON[1] and P. J. WALTON[2]

Non-member Member, A. I. E. E.

*Synopsis.—This paper describes extensive field tests made on the super-high-speed excitation equipment used with the 30,000-kv-a. synchronous condensers at the Plymouth Meeting Substation of the Philadelphia Electric Company. Oscillograms and calculated curves showing the performance of the synchronous condensers with this equipment are included, together with a discussion of the results obtained.*

* * * * *

THE speed and maximum voltage characteristic of the excitation system used on synchronous condensers is of prime importance in determining the amount of corrective kv-a. which can be furnished by the condenser during a system disturbance.

On the Conowingo Line at the Plymouth Meeting Substation there are installed three 30,000-kv-a. condensers equipped with a supersystem of high-speed excitation and a method of control that is sufficiently novel to warrant a general description.

To obtain the same corrective kv-a. with ordinary types of excitation, a much larger installation of condenser capacity would be required.

These machines are installed for the purpose of voltage regulation of the system and as an aid during transient conditions. Since other articles have described the synchronous condensers, no description is given herein.

Excitation for the main exciter field is furnished from a subexciter. The subexciter itself is of standard design and is a straight shunt-wound machine. The main exciter is of very special design. It has laminated poles and yoke, heavy series winding (which will be referred to later), and an armature ceiling voltage of approximately 1000. Also, it is provided with two shunt-field windings.

The main shunt field is directly connected to the subexciter through a simple motor-operated rheostat which if properly set will give in general the proper main exciter volts to produce the desired kv-a. on the condenser under steady conditions of load and voltage.

At this time there will be little or no current in the second or regulating shunt field on which the regulator contacts operate. This of course is very desirable.

This regulating or auxiliary field itself will not produce an exceedingly high rate of rise of the exciter voltage, but can take care of ordinary conditions of load and voltage that may come during normal operation. This range of the auxiliary field itself is somewhat unusual as it is capable of controlling the condenser from approximately 20,000-kv-a. lag to 60,000-kv-a. lead under all steady-state conditions, and if there were any requirement for it even this range could be extended.

The regulator is of the high-speed type equipped with a three-phase torque motor as the master voltage element, so as to provide proper response of the regulator on any type of disturbance. The relay contacts of this regulator are connected to the auxiliary field through an unbalanced resistance bridge so that a reversal of the auxiliary field can be obtained, depending on the ratio of time opened to time closed of these relay contacts. This regulator controls the line voltage under normal conditions because of its ability to vary the condenser kv-a. through the above mentioned range.

However, for transient conditions, resulting from line-to-ground, double-line-to-ground, or three-phase faults when the average line voltage is depressed five per cent or more, the main shunt field is brought into play by means of a second master voltage relay which operates a high-speed contactor, opening the regulating field and cutting out the resistance in series with the main shunt-field winding. When this resistance is cut out of the main field, a rate of rise of approximately 7000 volts per sec. is obtained on the main exciter. This resistance is not cut-in again until the line voltage is restored or until the kv-a. per condenser has reached approximately 60,000.

At this time a current relay in the main condenser field operates at a value corresponding to this maximum kv-a., which again inserts the resistance in the main exciter field, the auxiliary field being closed simultaneously with the insertion of this resistance. This transition between the two shunt fields is very smooth and does not produce fluctuations to any extent in the main exciter voltage, or any fluctuations in the kv-a. on the main unit, as the transformer action between these fields tends to keep the flux constant. As the main field tends to collapse, it induces substantially a corresponding increase in ampere-turns in the auxiliary field sufficient to maintain the original flux produced by the main field. After this change the regulator again operates upon the auxiliary field either to maintain voltage or a maximum kv-a.

At a time when conditions return to normal, the regulator rapidly backs the exciter voltage down from its original high value to the value required to give the proper voltage on the system bus. This rapidity of die-

1. General Electric Co., Schenectady, N. Y.
2. General Electric Co., Philadelphia, Pa.

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29-148

down is due to the auxiliary shunt field at this time receiving a reversed voltage, which in turn accelerates the decay of the main exciter. This scheme of connections is shown in Fig. 1.

### Discussion of Curves and Calculations

The benefit derived from superexcitation in regard to increased condenser capacity can best be understood by considering a specific example.

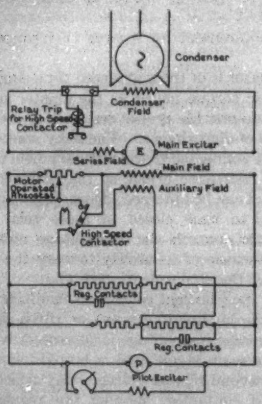


Fig. 1—High-Speed Excitation Scheme for Synchronous Condenser

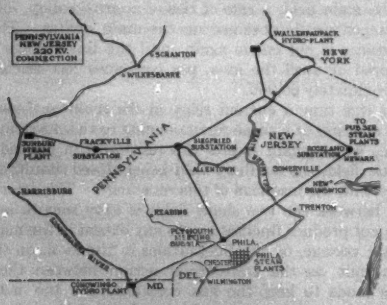


Fig. 2—Map of Interconnection

The diagram of system connections is shown in Fig. 2; schematic diagram of system in Fig. 3.

Consider Siegfried, Conowingo, and Westmoreland interconnected, Siegfried floating on the line, and Conowingo feeding 150,000 kv-a. to Westmoreland. If a two-conductor-to-ground fault occurs at $F$ on the Siegfried bus and two condensers are operating at Plymouth Meeting at 10,000 kv-a. leading, giving a total of 20,000 kv-a., there will be an instantaneous rise to 43,000 leading kv-a. from the Plymouth Meeting condensers at the moment of fault.

After the fault has been applied, the condenser kv-a. will continue to rise as determined by the superexcitation system from the above-mentioned initial value of 43,000 kv-a. to approximately 150,000 kv-a. in 0.5 sec. This is shown graphically in Fig. 4.

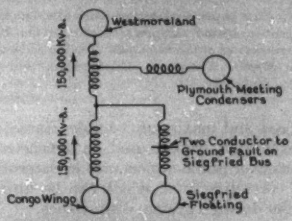


Fig. 3—Schematic Diagram of System upon Which Calculations Were Based

The fault $F$ on Siegfried bus results in a decrease in positive phase sequence voltage at the terminals of the condensers of 30 per cent and an increase in positive phase sequence condenser current of 208 per cent. Conowingo assumed to be furnishing 150,000 kv-a. to Westmoreland

From Fig. 5 it is seen that two condensers with standard excitation are, at the first instant, equal in corrective effect to two condensers with superexcitation, but at the end of one-half second, approximately ten condensers with standard excitation are required to give corrective effect equivalent to two condensers with superexcitation.

Before the fault occurs it is assumed that the condenser bus voltage is being held at its proper value by the 20,000 kv-a. delivered by the two connected condensers. In order to deliver this same initial kv-a. with a larger number of condensers with ordinary excitation, the excitation on each condenser would necessarily be less than that of either one of the two units with superexcitation.

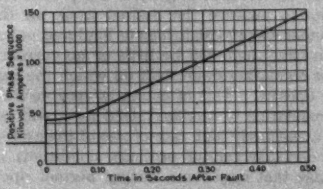


Fig. 4—Graph Showing Rise of Condenser Kv-a. after Two-Conductor-to-Ground Fault

Referring to Fig. 5, the integrated kv-a. or kv-a. seconds shown, could be furnished by approximately five and one-half condensers with standard excitation at the end of 0.5 sec., but the maximum instantaneous

kv-a. at the end of 0.5 sec. with two condensers having superexcitation is approximately equal to ten condensers with ordinary excitation.

## Requirements

It was required of the condenser that it be capable of operating at 10,700 kv-a. lag up to 55,000-kv-a. lead;

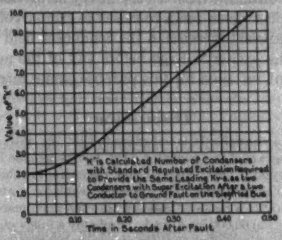


Fig. 5—Curve Showing Number of Condensers Needed with Standard Excitation to Give Same Correction as Two Condensers with Superexcitation

also with the condenser carrying 10,000 kv-a. lead initially, the time from the occurrence of a fault on the system to reaching 55,000-kv-a. lead to be not more than 30½ cycles on the basis of 60-cycle time, the exciter voltage to be not more than 900-volts ceiling.

These requirements meant that the voltage regulator must operate over a range of from about zero volts to 900 volts.

This condition will be appreciated when it is remembered that the usual voltage regulator is required to operate over a range of from 70 to 140 volts or a range of 1 to 2.

In case of a short circuit on a line, it is possible for the voltage of one-phase to be higher than before the short circuit occurred and for this reason, the voltage-regulator element and the element for applying the superexcitation each consists of a three-phase torque motor.

To insure the high-speed feature being applied independently of the regulating equipment used for normal conditions, and to have it come in with the least amount of time delay after the occurrence of a fault and to adjust the voltage at which it would be applied independently of other conditions, a separate torque motor was used for the purpose of applying the high-speed excitation in addition to the torque motor operating as a normal voltage regulator.

Fig. 6—Oscillograph Records of High-Speed Excitation Tests

Fig. 7—Oscillograms of Test on Condenser Having High-Speed Excitation

Fig. 8—Oscillograms of High-Speed Excitation Test

### Tests

The kv-a. taken by a condenser for a given field current depends upon the voltage at the condenser terminals. It was impossible to hold constant voltage when suddenly increasing from 10,000 kv-a. to 55,000 kv-a. owing to the reactance of the transformer bank, to the tertiary winding of which the condenser is connected.

In testing, therefore, to determine the time to increase from 10,000 kv-a. to 55,000 kv-a., the starting point was taken as the field current to produce 10,000 kv-a. at rated voltage 13,800 volts; and at the starting point, the voltage was reduced by having lagging kv-a. on another condenser to try to reach 13,800 volts when the kv-a. reached 55,000 on the condenser under test.

In other words, the time is that required to build up the field current of the condenser, as the a-c. amperes depend on the condenser field flux, and tests showed that there was practically no time delay between field amperes and a-c. amperes and consequently field flux.

Referring to Fig. 6, the torque motor resistance is the voltage across a resistance inserted in the torque motor circuit to reduce the voltage applied to the torque motor to correspond to a short circuit on the system.

When the system voltage dropped as indicated by the voltage across this resistance, it will be noted that within a cycle, the torque motor contact closed, applying voltage to the coil of the high-speed contactor.

The instant when the high-speed contactor closed is indicated by the point when the exciter main field current starts to increase.

Following the short-circuiting of the resistance in the exciter main field by the high-speed contactor, the field current of the main exciter rapidly increases, building up the exciter voltage to the desired value, approximately 900 volts, as shown in Fig. 7. After this the exciter voltage held practically constant because of the combined effect of lowering the pilot exciter voltage by omitting its series field and by the action of the series field of the main exciter. This is also shown in Fig. 8.

With the adjustments used, the kv-a. of the condenser built up to about 73,000, or well beyond the 55,000 kv-a. agreed upon.

Summarizing these tests, the time required to reach the required kv-a. is approximately 25 cycles on a 60-cycle basis, though in actual practise the required kv-a. would be reached much earlier because of an instantaneous increase of kv-a. through a reduction in terminal voltage resulting from a short circuit on the line, to which is added the subsequent increase due to the high-speed excitation. Additional benefit in regard to rate of rise is obtained from a very heavy series field on the main exciter which tends to raise the exciter voltage due to the transient increase in the condenser field current, raising the exciter voltage before any of the automatic equipment installed for this purpose comes into play.

## Discussion

**J. H. Ashbaugh:** It is unfortunate that the author did not show a diagram of the regulator itself, but we assume it is of the vibrating type. This being the case, the current in the auxiliary field which is handled on the vibrating regulator contacts must vary over quite a range in order to take the main machine from 20,000 kv-a. to 60,000 kv-a. lead. Probably a follow-up arrangement has been provided on the motor-operated rheostat in order to keep the current at a small value in the auxiliary field.

We have been using an arrangement somewhat similar to this in paper mills and steel mills, and have found it to be quite satisfactory. In some cases we used a booster in place of the auxiliary field, and then a wheatstone bridge on the field of the booster. These have been worked out for both the vibrating and the carbon-pile type of regulators. We have also used this wheatstone bridge arrangement with the exciter rheostatic regulator, working directly on the main field of the main exciter.

The authors state that this regulator operates over quite a wide range in voltage from 0 to 900, whereas the usual voltage regulator is limited in a range of from 70 to 140 volts or 1 to 2. I don't feel they mean quite this, as we have had broad-range regulators on the market for years in which the range was limited only by the exciter itself and not by the regulator. These unlimited range regulators are available in both vibrating and exciter rheostatic type, in fact, any regulator which does not obtain its power from the exciter is not limited in range over which it must work.

**P. J. Walton:** Replying to the discussion by Mr. Ashbaugh, the regulator is of the vibrating type, as indicated by the regulator contacts in Fig. 1 of the paper. As to the range in the current in the auxiliary field, it so happens that the fixed excitation in the main field plus positive excitation in the auxiliary field is sufficient for 60,000 kv-a. lead, whereas the fixed excitation in the main field less negative excitation in the auxiliary field of the same value is sufficient for 20,000 kv-a. lag. There is no follow-up on the motor-operated rheostat.

As to the wide range in voltage, the main exciter actually operates over a range from a negative voltage instead of zero voltage, and after super-speed excitation has been applied, the control is taken over by the regulator at a time when the exciter voltage is 900 volts, although this voltage is rapidly decreased after the voltage regulator takes control.

# Polyphase Induction Motors

## A Labor Saving Method of Calculating Performance from Previously Determined Constants

BY W. J. BRANSON[1]

Associate, A. I. E. E.

***Synopsis.***—*This paper presents a method of calculating polyphase induction motor performance which eliminates a large amount of detail work without making use of approximations which sacrifice accuracy. In any rigorous system for calculating induction motor performance, the determination of the relation between input and current values makes the greater part of the work.*

*By the procedure here presented, the relation of watts to amperes for all cases likely to be encountered in ordinary design work may be accurately calculated once for all and recorded in a set of curves. When making practical calculations tedious detail work may be eliminated by taking the necessary values from the curves, in much the same way that sines are taken from sine tables.*

*The calculation begins with the torque, from which the corresponding secondary input is obtained by a simple formula. Then, by reference to the appropriate curves and a few simple slide rule operations, the primary and secondary currents are determined. With the secondary input and the current values known, the completion of the calculation requires nothing more than a few operations of simple arithmetic. The entire process for one load point may be completed in from five to seven minutes.*

### I. Introduction

THE methods most frequently used in calculating the performance of polyphase induction motors are:

(1) The Steinmetz analytical equations based on the "exact equivalent circuit."

(2) The various forms of the circle diagram.

With the exception of a slightly unscientific treatment of core losses, the Steinmetz equations are rigorously correct mathematical processes, but they require a large amount of detail work. Using ordinary facilities, the time required to calculate the output, revolutions per minute, efficiency, power factor, etc., for a single load point is usually about 40 or 45 minutes.

If properly constructed, the circle diagram also constitutes a rigorous mathematical process, but the forms commonly used and presented in text books are based on approximations which sacrifice accuracy while still requiring a very objectionable amount of labor.

### II. General Character of the Process

This paper presents a method of procedure by which it is possible to complete an accurate performance calculation in from 5 to 7 minutes,—that is, in about one-sixth of the time required by the Steinmetz equations. The processes which eliminate so much detail work are somewhat analogous to the use of tables of trigonometric functions. If trigonometric tables did not exist, the easiest way to obtain the sine of an angle would be to construct an appropriate triangle and divide the side opposite the angle by the hypotenuse. Anyone who had occasion to do this frequently, however, would naturally discover that by constructing, once for all, a series of triangles, he could draw a curve from which the sine of any angle might be read directly.

In a similar manner, it is possible to make curves showing any desired geometrical relations of the circle diagram, corresponding to all possible combinations of motor constants; and, with properly constructed curves of this character available, a performance calculation for an ordinary polyphase motor requires no detail work beyond reading the necessary values from the curves and carrying out a few simple arithmetical operations.

### III. Mathematical Basis Compared with That of the Steinmetz Equations

Although the mathematical processes used in preparing these curves are based on the circle diagram, they are exactly equivalent to the Steinmetz analytical equations except in one point, the treatment of core losses.

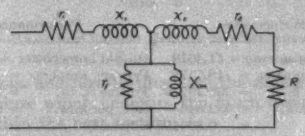


Fig. 1—The "Exact Equivalent Circuit"

In the "exact equivalent" diagram (Fig. 1) the core loss is represented by a copper loss in a fictitious resistance unit, $r_f$. The location of this resistance in parallel with the exciting reactance, $X_m$, makes the core loss vary with the flux which crosses the air gap and consequently fall off as the load increases. For the ordinary transformer, this arrangement is probably as accurate as any that could be suggested. In the case of the induction motor, however, conditions are somewhat different. As the load increases, the core loss falls off slightly in the stator but at the same time increases in the rotor. Alexander Heyland suggested more than thirty years ago that the increase of rotor core loss

1. Designing Engineer, Robbins & Myers Inc., Springfield, Ohio.

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29-153

should be assumed to be equal to and to offset the decrease in stator core loss, making the total constant at all loads; and this assumption, which underlies all forms of the circle diagram, has been approved explicitly or tacitly by nearly all writers on the induction motor.

This rather small difference in the treatment of core loss has been explained at some length because it introduces the only *discrepancy in results* between the system presented in this paper and the Steinmetz system which is given in text books and extensively used in practical work.

## IV. Comparative Calculations

If the core loss be made equal to zero, that is, eliminated, the two systems will give absolutely identical results provided all the arithmetical work is correct. This is illustrated by the parallel columns below in which arithmetical errors have been avoided by the use of a calculating machine.

### Calculations
#### From Equivalent Constants

| By the Process Presented in this Paper | By the Steinmetz System |
|---|---|
| **Data** | **Data** |
| $E = 1000$ | $E = 1000$ |
| $X_{R}' = 10$ | $x_1 = 4.09526$ |
| $X_o' = 100$ | $x_2 = 6.29199$ |
| $K_p = 0.959047$ | $X_m = 95.9047$ |
| $r_1 = 3$ | $r_1 = 3$ |
| $r_2 = 4$ | $r_2 = 4$ |
| Synchronous rev. per min. $= 1000$ | Synchronous rev. per min. $= 1000$ |
| Core loss $= 0$ | Core loss $= 0$ |
| **Performance** | **Performance** |
| Output horsepower = 51.4619 | Output horsepower = 51.4619 |
| Primary amperes = 18.7178 | Primary amperes = 18.7178 |
| Torque ft. lb. = 290.137 | Torque ft. lb. = 290.137 |
| Rev. per min. = 932.846 | Rev. per min. = 932.846 |
| Efficiency = 0.866459 | Efficiency = 0.866459 |
| Power factor = 0.789043 | Power factor = 0.789043 |

A comparison of the constants listed under the word "data" in the right and left hand columns will show that the reactances are different both as to symbols and numerical values. The use of different reactances is a result of the fact that the two systems of calculation are based on different methods of analysis, but all of the various reactance values have definite mathematical relations which will be explained below.

## V. The Transformer

Fig. 2 shows a transformer with magnetizing and leakage characteristics similar to those of an induction motor. The broken lines represent flux paths.

$\mathcal{P}_m$ = Permeance of the path through both coils

$\mathcal{P}_L'$ = Permeance of the primary leakage path

$\mathcal{P}_L''$ = Permeance of the secondary leakage path.

The most important of the fundamental constants which determine the performance of a transformer or an induction motor may be expressed as ratios between the permeance values.

$$\text{The primary flux factor } K_p = \frac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L'},$$

$$\text{The secondary flux factor } K_s = \frac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L''}.$$

## VI. Reactance

The reactance of a transformer represents the ratio

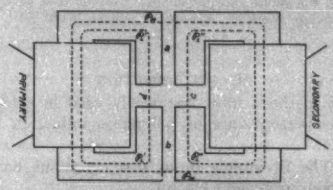



Fig. 2—The Flux Paths of a Transformer with an Air-Gap and Large Magnetic Leakage

of inductive drop to amperes, just as resistance represents the ratio of resistance drop to amperes. In a circuit containing only resistance, the current

$$I = \frac{E}{R}$$

while in a circuit which has reactance without resistance,

$$I = \frac{E}{X}$$

Since the induced e. m. f.

$$E = 2\pi f N^2 10^{-8} \mathcal{P} I$$

we may derive the fundamental equation for reactance as follows:

$$I = \frac{2\pi f N^2 10^{-8} \mathcal{P} I}{X}$$

and

$$X = 2\pi f N^2 10^{-8} \times \mathcal{P}$$

It is convenient and helpful to think of this expression for reactance as made up of the two main factors which are separated by a multiplication sign. The combination of symbols on the left, $2\pi f N^2 10^{-8}$, will be found in exactly the same form in all of the seven equations which appear in the two lists below, while the characters which stand for permeance take a special form in each equation and determine the significance of the various reactances.

A comparison of the permeance values in the first list of equations with those which appear in the second list will show that the reactances are of two fundamentally different types. Each equivalent circuit reactance represents the effect of only a portion of the total flux which passes through the winding and, therefore, is only a *component* of the total reactance. On the other hand, each of the reactance values which make up the second list and are used in the system presented in this paper represents the effect of all the flux and constitutes the total reactance of the winding for the particular condition specified.

*Equivalent Circuit Reactances.*

Reactance of the primary winding due to the primary leakage flux

$$x_1 = 2\,\pi\,f\,N^2\,10^{-8}\,\mathcal{P}_L'$$

Reactance of the secondary winding due to the secondary leakage flux

$$x_2 = 2\,\pi\,f\,N^2\,10^{-8}\,\mathcal{P}_L''$$

Reactance of the primary winding due to the flux which passes through both coils.

$$X_m = 2\,\pi\,f\,N^2\,10^{-8}\,\mathcal{P}_m$$

*Reactance Values Used in This Paper.*

Reactance of primary with secondary open.

$$X_o' = 2\,\pi\,f\,N^2\,10^{-8}\,(\mathcal{P}_m + \mathcal{P}_L')$$

Reactance of secondary with primary open.

$$X_o'' = 2\,\pi\,f\,N^2\,10^{-8}\,(\mathcal{P}_m + \mathcal{P}_L'')$$

Reactance of primary with secondary short circuited.

$$X_{sc}' = 2\,\pi\,f\,N^2\,10^{-8}\,(\mathcal{P}_L' + \mathcal{P}_L''\,K_s)$$

Reactance of secondary with primary short circuited.

$$X_{sc}'' = 2\,\pi\,f\,N^2\,10^{-8}\,(\mathcal{P}_L'' + \mathcal{P}_L'\,K_p)$$

In practical work it is usually assumed that $\mathcal{P}_L' = \mathcal{P}_L''$ and consequently that

$$K_p = K_s$$
$$X_o' = X_o'' = X_o$$
$$X_{sc}' = X_{sc}'' = X$$

A series of diagrams showing the flux paths corresponding to all of the reactance values listed above will be found in Figs. 3 to 9.

From the permeance values, it may easily be demonstrated that

$$X_o' = \frac{X_m}{K_p} \qquad x_1 = X_{sc}'\,\frac{1 - K_p}{1 - K_p\,K_s}$$

$$X_o'' = \frac{X_m}{K_s} \qquad x_2 = X_{sc}''\,\frac{1 - K_s}{1 - K_p\,K_s}$$

$$X_{sc}' = x_1 + x_2\,K_s \qquad = X_{sc}'\,\frac{K_p\,(1 - K_s)}{K_s\,(1 - K_p\,K_s)}$$

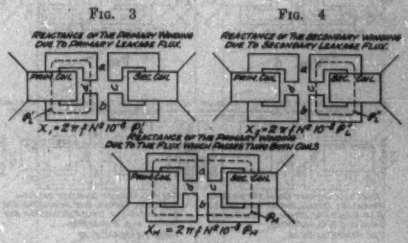
$$X_{sc}'' = x_2 + x_1\,K_p \qquad X_m = X_o'\,K_p = X_o''\,K_s$$

## VII. Circle Diagram

The development of a mathematically exact form of the circle diagram may be traced through Figs. 10, 11, 12, and 13. These figures are so constructed and arranged as to show successively the effects of the various constants. In Figs. 10 and 11 the motor is assumed to have reactance without resistance or iron loss. Fig. 12 shows the modifying effects of secondary resistance while Fig. 13 shows the modifying effects of primary resistance and core losses.

Fig. 14 is a practical working diagram and is similar to the upper right hand portion of Fig. 13 except that the primary resistance drop is represented by an extension of the current vector instead of a separate parallel line. The complete procedure for making calculations by this diagram is given on the work sheet shown in Fig. 15.

This work sheet is introduced to show how the circle diagram may be used in a correct form for practical




Figs. 3-5—Reacance Values Used in the Steinmetz System

calculations and also to illustrate the general method of procedure which underlies the much easier process explained in the next section.

The only measurements taken from the diagram are $O\,T$, $M\,T$, $T\,R$, and $Z\,E$ from which we obtain

$$\text{Secondary input} = T\,R \times S_1 \times E \times \text{phases}\left(\frac{O\,E}{Z\,E}\right)^2$$

and the corresponding values of

$$\text{Primary amperes} = O\,T \times S_1 \times \frac{O\,E}{Z\,E}$$

and

$$\text{Secondary amperes} = M\,T \times S_2 \times \frac{O\,E}{Z\,E}$$

When these quantities are known, the completion of the calculation requires only a few operations of simple arithmetic.

Input = Secondary input + primary copper losses + core loss.

Output = Secondary input—(Secondary copper loss + $F$ & $W$ loss)

R. P. M. = Synchronous rev. per min.

$$\frac{\text{Secondary input—Secondary copper loss}}{\text{Secondary input}}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$\text{Power factor} = \frac{\text{Input}}{\text{Apparent input}}$$

## VIII. The Basis of the Curve Method

The outline given below shows a simple and straight forward procedure for the calculation of polyphase induction motor performance without the circle diagram. This process, or something equivalent, would probably be used by all designers if suitable equations were available for the third and fourth steps.

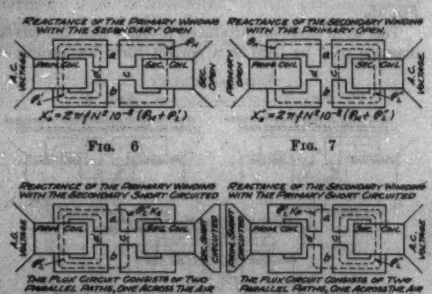



Fig. 6 Fig. 7

Fig. 8 Fig. 9

Figs. 6-9—Reactance Values Used in the System Presented in This Paper

(1) Torque = $H\,P\,\dfrac{5252}{\text{Rev. per min.}}$ (Using test or estimated value of rev. per min.)

(2) Secondary input =

$$\text{Torque}\ \frac{\text{Synchronous rev. per min.}}{7.04}$$

(3) Primary amperes = Secondary input × (*No convenient expression available*)

(4) Secondary amperes = Secondary input × (*No convenient expression available*)

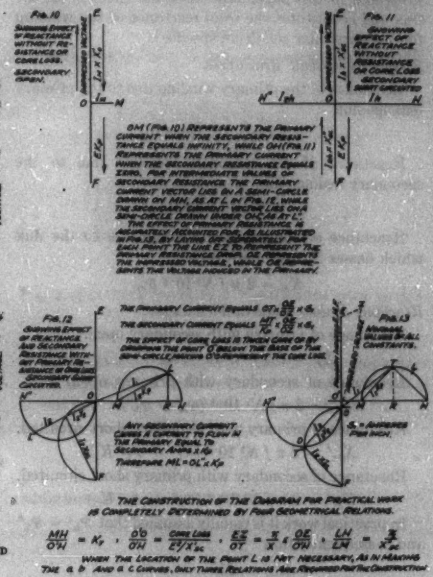
(5) Secondary copper loss = (Secondary amperes)$^2$ × $r_2$ × phases

(6) Secondary output = Secondary input—Secondary copper loss

(7) Output = Secondary output—$F$ and $W$ loss

(8) Rev. per min. = $\dfrac{\text{Secondary output}}{\text{Secondary input}}$ × synchronous rev. per min.

(9) Primary copper loss = (Primary amperes)$^2$ × $r_1$ × phases




Figs. 10-13—Development of the Circle Diagram

(10) Input = Secondary input + primary copper loss + iron loss

(11) Efficiency = $\dfrac{\text{Output}}{\text{Input}}$

(12) Power factor = $\dfrac{\text{Input}}{\text{Primary amperes} \times E \times \text{phases}}$

Starting with the horsepower for which a calculation is desired, the first step gives the torque while the second gives the input to the rotor. The next quantities wanted are the primary and secondary amperes; but the equations which might be written for these steps would be so elaborate and complicated as to involve many times more work than all the other steps in the calculation combined.

This directs attention to the fact that in any *rigorous*

method of calculating polyphase induction motor performance, after the constants are known, the determination of the current values which correspond to any

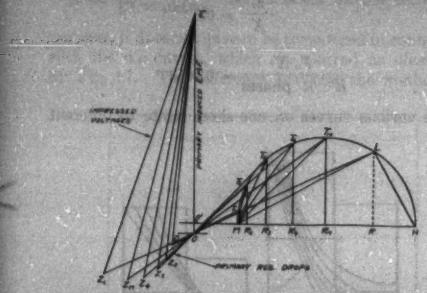



FIG. 14—THE CIRCLE DIAGRAM FOR PRACTICAL WORK

specified input makes nearly all of the work. In the Circle Diagram processes, these relations are determined graphically, while in the Steinmetz System the

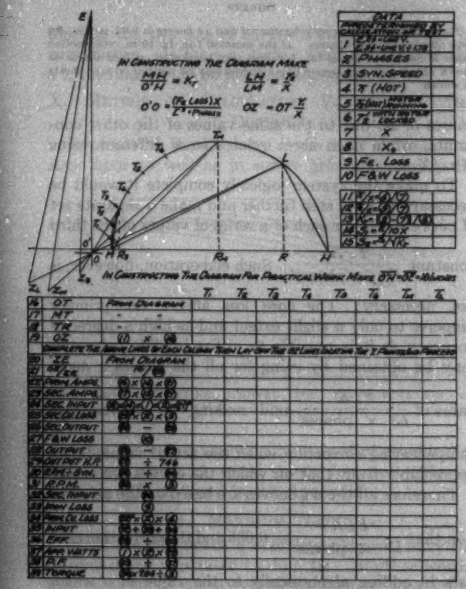



FIG. 15—WORKSHEET FOR CALCULATING PERFORMANCE BY CIRCLE DIAGRAM

results are obtained by lengthy analytical equations.

In the system which this paper describes these tedious and lengthy processes are eliminated. The primary and secondary amperes are obtained with a negligible amount of labor by reference to two sets of curves, reduced examples of which are shown in Figs. 16 and 17.[2] One set, known as the *a b* curves, is used for primary amperes, while the other set known as the *a c* curves, is used for secondary amperes. The values which the curves represent are geometrical relations from the circle diagram shown in Fig. 14, and are mathematical quantities of the same general character as sines or cosines. On both sets of curves the abscissa is marked *a*, while the ordinates are marked *b* on the curves for primary amperes and *c* on the curves for secondary amperes. In terms of the lines on the diagram, in Fig. 14,

$$a = \frac{TR}{O'H} \times \left(\frac{OE}{ZE}\right)^2$$ and *represents* secondary input

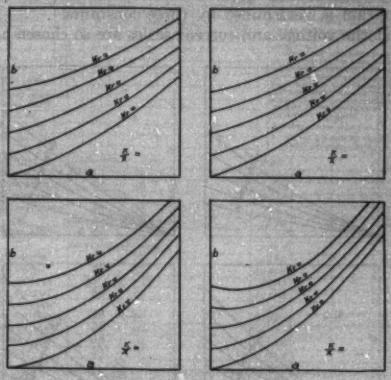



FIG. 16—EXAMPLES OF *a b* CURVES

The most satisfactory scale is 0.02 per in. for ordinates and abscissas See Fig. 17A

$$b = \frac{OT}{O'H} \times \frac{OE}{ZE}$$ and *represents* primary amperes

$$c = \frac{MT}{O'H \times K_p} \times \frac{OE}{ZE}$$ and *represents* secondary amperes

while in terms of the motor values,

$$a = \frac{\text{Secondary input}}{(E^2/X) \times \text{phases}}$$

$$b \times \frac{E}{X} = \text{primary amperes}$$

$$c \times \frac{E}{X} = \text{secondary amperes}$$

2. The author expects to make available in the near future two ful lsets of curves which cover about 100 pages.

In a practical calculation, we complete the first and second items of the procedure outlined above and then obtain

$$a = \frac{\text{Secondary input}}{(E^2/X)\ \text{phases}}$$

Next using $a$ as abscissa we read $b$ and $c$ from the appropriate curves and as stated above

$$b \times \frac{E}{X} = \text{primary amperes}$$

$$c \times \frac{E}{X} = \text{secondary amperes}$$

## IX. Description of the Curve Sheets

In preparing the $a\ b$ and $a\ c$ curves, we take advantage of the fact that the geometrical construction of the circle diagram is determined by three constants.

If the voltage and current scales are so chosen as to

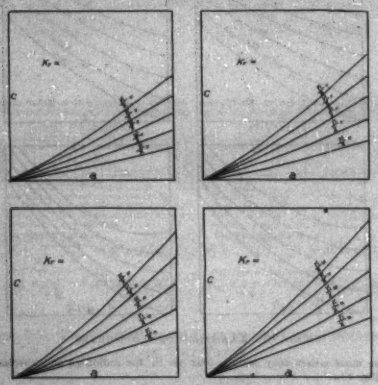



Fig. 17—Examples of $a\ c$ Curves

See Fig. 17A

make the lines $O\,E$ and $O'\,H$ (Fig. 14) of equal length, the only relations involved in the construction are

$$\frac{M\,H}{O'\,H} = \frac{X_o - X}{X_o} = K_p\,K_s = K_r$$

$$\frac{O\,Z}{O\,T} = \frac{r_1}{X}$$

$$\frac{O'\,O}{O'\,H} = \frac{\text{Core loss}}{(E^2/X)\ \text{phases}}$$

The general scheme of the $a\ b$ curves is illustrated by Fig. 16. All of the curves give the values of $b$ corresponding to the variations in the value of $a$ over as wide a range as practical work requires. Each individual curve relates to a particular set of constants, such as

$$K_r = 0.92$$

$$\frac{r_1}{X} = 0.3$$

$$\frac{F_e\,X}{E^2 \times \text{phases}} = 0.005$$

The various curves on one sheet relate to different

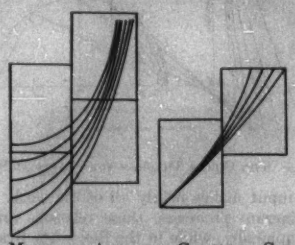


Fig. 17A—Method of Arranging Curves on Cross-Section Sheets

The most satisfactory scale for the $a\ b$ and $a\ c$ curves is 0.02 per in. for both abscissa and ordinates If the common 7-in. by 10-in. cross-section paper is used each group of $a\ b$ curves may be plotted on four sheets as shown above and each group of $a\ c$ curves may be plotted on two sheets as shown

values of $K_r$ but to the same values of the other constants, while each sheet relates to a different value of $r_1/X$.

To make the system logically complete it would be necessary to go a step further and make a separate set of curve sheets for each of a series of values of the third constant $\frac{F_e\,X}{E^2 \times \text{phases}}$. Such elaboration, however, is not necessary. The core loss affects the primary amperes to only a slight extent and as high a degree of accuracy as it is possible to utilize in slide rule work may be obtained by using for all the curves a mean value of $\frac{F_e\,X}{E^2 \times \text{phases}}$ and making an approximate compensating correction when the actual value differs appreciably from that on which the curves are based.

Therefore all the $a\ b$ curves are based on the assumption that $\frac{F_e\,X}{E^2 \times \text{phases}} = 0.005$ and the correction consists in adding algebraically to the value of $a$ which is used as abscissa for the $a\ b$ curve the quantity

$$\left(\frac{F_e\,X}{E^2 \times \text{phases}} - 0.005\right) 0.6$$

When this correction has been applied, the discrep-

ancy in the primary ampere figures will not often exceed one-tenth of one per cent.

Since $\frac{F_1 X}{E^2 \times \text{phases}}$ has no effect on the secondary amperes, it does not have to be considered in connection with the $a\,c$ curves, which are plotted as illustrated by Fig. 17. The difference between the methods of

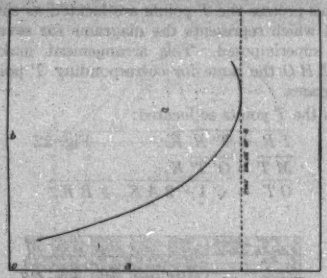


FIG. 18—AN $a\,b$ CURVE, SHOWING THE MAXIMUM VALUE OF $a$

plotting the two sets of curves is simply a matter of convenience. If the a-c. curves were plotted like the $a\,b$, the lines would be too close together.

## X. METHOD OF CALCULATING VALUES FOR THE CURVES

In preparing the $a\,b$ and $a\,c$ curves, it is possible to save labor as well as to secure greater accuracy by

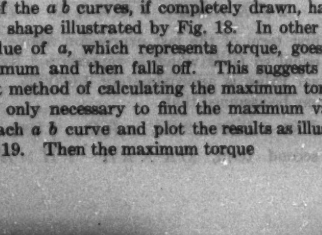


FIG. 19—ILLUSTRATING CURVES FOR DETERMINATION OF MAXIMUM TORQUE

deriving the values analytically instead of graphically. The equations and work sheets for two different methods will be found in the Appendix.

## XI. MAXIMUM TORQUE

All of the $a\,b$ curves, if completely drawn, have the general shape illustrated by Fig. 18. In other words, the value of $a$, which represents torque, goes up to a maximum and then falls off. This suggests a convenient method of calculating the maximum torque.

It is only necessary to find the maximum value of $a$ on each $a\,b$ curve and plot the results as illustrated in Fig. 19. Then the maximum torque

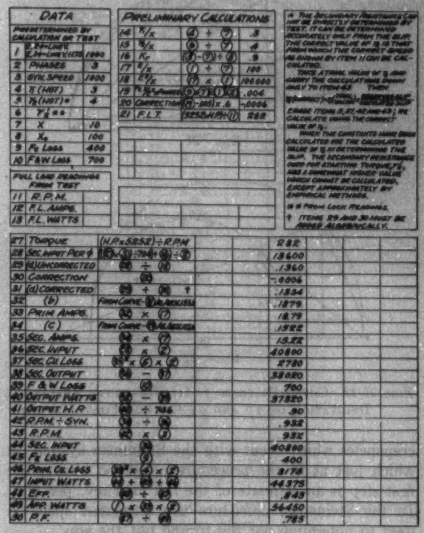
$$T \text{ maximum} = a \text{ (maximum)} \times \frac{E^2 \times 7.04 \times \text{phases}}{X \times \text{synchronous r.p.m.}}$$

Maximum torque curves of this character have not actually been made up to the present time.

## XII. PRACTICAL PROCEDURE BY THE CURVE METHOD

Full directions for making performance calculations from known constants will be found on the work sheet, Fig. 20.

A desirable feature of this system lies in the fact that the output which a calculation will give is known in advance with a high degree of accuracy. Consequently



| DATA | | |
|---|---|---|
| PRE-DETERMINED BY CALCULATION OR TEST | | |
| 1 | $E_1$ = LINE-LINE VOLTS | 1000 |
| 2 | PHASES | 3 |
| 3 | SYN. SPEED | 1800 |
| 4 | X (1-401) | 3 |
| 5 | $R_1$ (1-401)* | 4 |
| 6 | $Y_1$ (*) | |
| 7 | X | 10 |
| 8 | $X_0$ | 100 |
| 9 | $F_0$ LOSS | 400 |
| 10 | F&W LOSS | 700 |
| FULL LOAD READINGS FROM TEST | | |
| 11 | R.P.M. | |
| 12 | F.L. AMPS. | |
| 13 | F.L. WATTS | |

| PRELIMINARY CALCULATIONS | | | |
|---|---|---|---|
| 14 | $Y_1/X$ | (4) ÷ (7) | .3 |
| 15 | $Y_0/X$ | (8) ÷ (7) | .4 |
| 16 | $K_F$ | (9) ÷ (10) = (9) | 3 |
| 17 | $Y_1/X$ | (11) ÷ (7) | 100 |
| 18 | $E_1/X$ | (17) × (1) | 100000 |
| 19 | $\frac{E_1}{X}$ × 2π × phases | (2) × (17) × (3) × 6.28 | .006 |
| 20 | CORRECTION | (19) × .005 × .6 | -.0006 |
| 21 | F.L.I. | (12)×(2)×(13)÷(1) | 282 |

* THE SECONDARY RESISTANCE CAN NOT BE DIRECTLY DETERMINED BY TEST. IT CAN BE DETERMINED ACCURATELY ONLY FROM THE SLIP. THE EFFECTIVE VALUE OF $R_2$ IS SO THAT FOR WHICH THE CAPACITY SPEED AS CALCULATED BY ITEM 11 CAN BE CALCULATED.

THIS A FITTING VALUE OF $R_2$ AND CARRY THE CALCULATION ONLY TO ITEM 43. THEN

$R_2$ = (SLIP) × (SYN. SPEED) × (ITEM 4) / (ITEM 11) − (ITEM 4) − (ITEM 5)

CHANGE ITEMS 5, 21, 40 AND 43, RE CALCULATE USING THE CORRECT VALUE OF $R_2$.

WHEN THE CONSTANTS HAVE BEEN CALCULATED FOR THE CALCULATED VALUE OF $R_2$ BY DETERMINING THE SLIP. THE SECONDARY RESISTANCE HAS A DIFFERENT HIGHER VALUE WHICH CANNOT BE CALCULATED, EXCEPT APPROXIMATELY BY EMPIRICAL METHODS.

(* IS FROM LOCK READINGS.

† ITEMS 29 AND 30 MUST BE ADDED ALGEBRAICALLY.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 27 | TORQUE | (H.P.×5252)÷R.P.M. | | | | 282 | | |
| 28 | SEC. INPUT PER ϕ | (21)×(2)÷(3)=(4)÷(3) | | | | 13600 | | |
| 29 | (a) UNCORRECTED | (4) ÷ (10) | | | | .1360 | | |
| 30 | CORRECTION | (20) | | | | -.0006 | | |
| 31 | (a) CORRECTED | (29) + (30) † | | | | .1354 | | |
| 32 | (b) | FROM CURVE (31) ALGEBRAICALLY | | | | .1879 | | |
| 33 | PRIM. AMPS. | (32) × (7) | | | | 18.79 | | |
| 34 | (c) | FROM CURVE (31) ALGEBRAICALLY | | | | .1922 | | |
| 35 | SEC. AMPS. | (34) × (7) | | | | 19.22 | | |
| 36 | SEC. INPUT | (28) × (10) | | | | 40800 | | |
| 37 | SEC. CU. LOSS | (35)² × (6) × (2) | | | | 2720 | | |
| 38 | SEC. OUTPUT | (36) − (37) | | | | 38080 | | |
| 39 | F & W LOSS | (10) | | | | 700 | | |
| 40 | OUTPUT WATTS | (38) − (39) | | | | 37380 | | |
| 41 | OUTPUT H.P. | (40) ÷ 746 | | | | 50 | | |
| 42 | R.P.M. ÷ SYN. | (43) ÷ (3) | | | | .938 | | |
| 43 | R.P.M. | (42) × (3) | | | | 1688 | | |
| 44 | SEC. INPUT | (36) | | | | 40800 | | |
| 45 | $F_0$ LOSS | (9) | | | | 400 | | |
| 46 | PRIM. CU. LOSS | (33)² × (4) × (2) | | | | 3178 | | |
| 47 | INPUT WATTS | (44) + (45) + (46) | | | | 44379 | | |
| 48 | EFF. | (40) ÷ (47) | | | | .843 | | |
| 49 | APP. WATTS | (7) × (33) × (2) | | | | 54450 | | |
| 50 | P.F. | (47) ÷ (49) | | | | .785 | | |

FIG. 20—WORKSHEET FOR CALCULATING PERFORMANCE BY USE OF $a\,b$ AND $a\,c$ CURVE SHEETS SHOWN IN FIGS. 16 AND 17

when the efficiency, power factor, etc., for rated load are wanted, it is not necessary to go through the calculation two or three times in order to obtain figures for the correct output. This is due to the fact that the calculation begins with the torque which can be determined precisely for any specified load when the speed is known. For example, in the illustrative calculation given on the work sheet, the speed obtained by test is 932 rev. per min. Therefore, the torque for 50 hp. is

$$\frac{50 \times 5252}{932} = 282 \text{ ft. lb.}$$

and starting with 282 ft. lb. in line 27, we obtain in line 41 an output of exactly 50 hp.

When it is necessary to estimate the speed, the error

in the assumed full load torque and consequently the discrepancy between the calculated output and the rated horsepower will be the same in percentage as the error which is made in estimating the speed. From an inspection of the motor constants it is usually possible to estimate the full load speed without an error of more than about ½ per cent. Therefore, without knowing the test value of rev. per min. we could have made the output come within ½ per cent of the rated horsepower, that is between 49.75 hp. and 50.25 hp.

This result should be compared with the wide discrepancies which occur with the Steinmetz system, in which just as in the procedure presented above, the first step is an estimate of the full load rev. per min. In the Steinmetz procedure the estimated speed is used to determine not the torque but the slip.

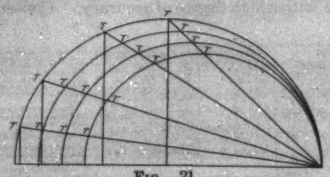


Fig. 21

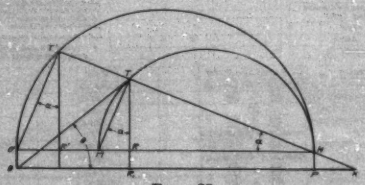


Fig. 22

Figs. 21-22—Circle Diagrams to Illustrate the Analytical Derivation of $a\,b$ and $a\,c$ Curves, First Method

The calculation begins with the slip and the output obtained is that at which the estimated slip would occur. For example, taking the same figures used above, if the estimate of the speed is ½ per cent high or low the slip used in the calculation will be, 1000 − 927 = 73 which is 7 per cent high, or 1000 − 937 = 63 which is 7 per cent low, and the output obtained may be as low as 46½ hp. or as high as 53½ hp.

## Appendix

A complete set of $a\,b$ curves has been prepared by the author covering 56 pages and including values of $r_1/X$ from 0.1 to 1.

A complete set of $a\,c$ curves has been prepared covering 48 pages and including values of $K_r$ from 0.98 to 0.75 inclusive. Both sets of curves may, of course, be expanded to any extent that is found desirable.

The formulas and work sheets for two processes by which the curves may be calculated without graphical work are given below. The process given first is the best for calculating a complete set of curves at one time, while the second process is more convenient when a single curve is to be made for a special motor.

### Analytical Derivation of $a\,b$ and $a\,c$ Curves
First method

In this process the $T$ points are located as shown in Fig. 21 which represents the diagrams for several $K_r$ values superimposed. This arrangement makes the angle $T\,H\,O$ the same for corresponding $T$ points on all diagrams.

With the $T$ points so located:

$$\overline{T\,R} = \overline{T'\,R'\,K_r} \ldots\ldots\ldots \text{Fig. 22}$$

$$\overline{M\,T} = \overline{O'\,T'\,K_r}$$

$$\overline{O\,T} = \sqrt{1 - 2\,A\,K_r + B\,K_r^2}$$

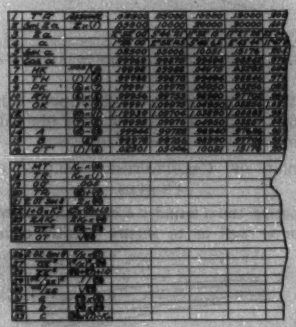


Fig. 23—Worksheet for Calculating $a\,b$ and $a\,c$ Curves, First Method

A separate calculation of items 17-25 is made for each value of $K_r$. A separate calculation of items 26-33 is made for each curve

The expression under the radical is derived as follows:

$$\overline{O\,T}^2 = \overline{O\,K}^2 + \overline{T\,K}^2 - 2\,\overline{O\,K} \times \overline{T\,K} \cos \alpha$$

But

$\overline{T\,K} = \overline{T\,H} + \overline{H\,K}$ and $\overline{T\,K} \cos \alpha = \overline{R_1\,K} = \overline{R\,H} + \overline{P\,K}$

$$\therefore \overline{O\,T}^2 = \overline{O\,K}^2 + \overline{T\,H}^2 + 2\,\overline{T\,H} \times \overline{H\,K} + \overline{H\,K}^2 - 2\,\overline{O\,K} \times \overline{R\,H} - 2\,\overline{O\,K} \times \overline{P\,K}$$

$$= (\overline{O\,K}^2 - 2\,\overline{O\,K} \times \overline{P\,K} + \overline{H\,K}^2) - 2\,(\overline{O\,K} \times \overline{R\,H} - \overline{T\,H} \times \overline{H\,K}) + \overline{T\,H}^2$$

The first term of the last expression above is very nearly equal to $O'\,H$ which is represented by unity. Its actual value is approximately 1.000025. Therefore it may be assumed that

$$\overline{O\,K}^2 + \overline{H\,K}^2 - 2\,\overline{O\,K} \times \overline{P\,K} = 1.0000 \ldots.$$

The second term, $(\overline{O\,K} \times \overline{R\,H} - \overline{T\,H} \times \overline{H\,K})$ is

proportional to $K_r$. If $(\overline{OK} \times \overline{RH} - \overline{TH} \times \overline{HK}) = A$ when $K_r$ = unity, then for any other value of $K_r$

$$\overline{OK} \times \overline{RH} - \overline{TH} \times \overline{HK} = A \times K_r$$

The last term, $\overline{TH}^2$, is proportional to $K_r^2$. If $\overline{TH}^2 = B$ when $K_r$ = unity, then for any other value of $K_r$

$$\overline{TH}^2 = B \times K_r^2$$

For a given value of $T' R'$ the angle $\alpha$ is found from the following relation:

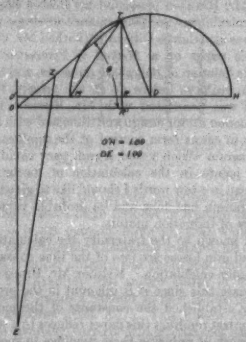



FIG. 24—CIRCLE DIAGRAM TO ILLUSTRATE THE ANALYTICAL DERIVATION OF $a\,b$ AND $a\,c$ CURVES, SECOND METHOD

$$\text{Angle } M\,T\,R = \text{Angle } R\,H\,T = \alpha$$

$$\cos\alpha = \frac{T'\,R'}{O'\,T'};\ \sin\alpha = \frac{O'\,T'}{O'\,H} = O'\,T' \text{ since } O'\,H = 1$$

$$\text{Sin}\ \alpha \cos\alpha = T'\,R' = \frac{\sin 2\,\alpha}{2} \quad \therefore \sin 2\,\alpha = 2\,T'\,R'$$

This explanation covers lines 1-25 of the calculation sheet. The remaining lines relate to the same process as lines 25-36 of the second method.

ANALYTICAL DERIVATION OF $a\,b$ AND $a\,c$ CURVES
Second Method

(1) To obtain $O\,T$

$$\overline{RD}^2 = \overline{TD}^2 - \overline{TR}^2$$

$$\overline{RD}^2 = \overline{MD}^2 - \overline{TR}^2$$

$$\overline{RD} = \sqrt{\overline{MD}^2 - \overline{TR}^2}$$

$$\overline{O'R} = \overline{OR'} = \overline{O'H} - (.5\,K_r + \overline{RD})$$

$$\overline{OT} = \sqrt{\overline{OR'}^2 + \overline{TR'}^2}$$

(2) To obtain $\overline{MT}$

$$\overline{MR} = .5\,K_r - \overline{RD}$$

$$\overline{MT} = \sqrt{\overline{TR}^2 + \overline{MR}^2}$$

(3) To obtain $\overline{ZE}$

$$\overline{OZ} = \overline{OT} \times r_1/X$$

$$\overline{ZE} = \sqrt{\overline{OE}^2 + \overline{OZ}^2 - 2\,\overline{OE} \times \overline{OZ} \times \cos E\,O\,Z}$$

$$= \sqrt{1 + \overline{OZ}^2 - 2\,\overline{OZ} \times \cos E\,O\,Z}$$

$$= \sqrt{1 + \overline{OZ}^2 + 2\,\overline{OZ} \times \sin R'\,O\,T}$$

$$\overline{ZE} = \sqrt{1 + \overline{OZ}^2 + 2\,\overline{OZ}\left(\frac{T\,R'}{O\,T}\right)}$$

(4) $$a = \overline{TR} \times \left(\frac{\overline{OE}}{\overline{ZE}}\right)^2 = \overline{TR} \times \left(\frac{1}{\overline{ZE}}\right)^2$$

$$b = \overline{OT} \times \left(\frac{\overline{OE}}{\overline{ZE}}\right) = \overline{OT} \times \left(\frac{1}{\overline{ZE}}\right)$$

$$c = \overline{MT} \times \left(\frac{\overline{OE}}{\overline{ZE}}\right) \div K_r = \overline{MT} \times \left(\frac{1}{\overline{ZE}}\right) \div K_r$$

FIG. 25—WORK SHEET FOR CALCULATING $a\,b$ AND $a\,c$ CURVES BY SECOND METHOD

TABLE OF SYMBOLS

| | |
|---|---|
| $a$ | = Abscissa for the $a\,b$ and $a\,c$ curves. |
| $b$ | = Ordinate of $a\,b$ curve. |
| $c$ | = Ordinate of $a\,c$ curve. |
| $E$ | = Voltage. (Line voltage for two phase and line voltage ÷ 1.73 for three phase.) |
| $f$ | = Frequency. |
| $F_e$ | = Iron loss in watts. |
| F & W | = Friction and windage loss. |
| F. L. T. | = Full load torque. |
| $I$ | = Amperes. |
| $I_1$ | = Primary amperes. |
| $I_2$ | = Secondary amperes, assuming 1 to 1 ratio. |
| $I_m$ | = Magnetizing amperes. |
| $I_k$ | = Primary locked amperes, when resistances equal zero. |

$I_{2A}$ = Secondary locked amperes when resistances equal zero.

$K_p$ = Flux factor $= \dfrac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L'}$

$K_s$ = Flux factor $\dfrac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L''}$

$K_r$ = Flux factor $= K_p \times K_s$

$N$ = Number of turns.

$\mathcal{P}$ = Permeance, as defined by Karapetoff. $\mathcal{P} = 3.19 \dfrac{\text{Area}}{\text{Length}}$ for an air gap.

$\mathcal{P}_m$ = Permeance of the flux path through both primary and secondary coils.

$\mathcal{P}_L'$ = Permeance of the primary leakage path.

$\mathcal{P}_L''$ = Permeance of the secondary leakage path.

$r$ = Resistance.

$r_1$ = Primary resistance.

$r_2$ = Secondary resistance, assuming a 1 to 1 ratio.

$r_2'$ = Effective secondary resistance of an induction motor under the condition of locked readings, assuming a 1 to 1 ratio.

$R$ = Combined effective resistance of stator and rotor under the condition of locked readings, = locked watts ÷ (primary amperes)$^2$.

$R$.... See equivalent circuit, Fig. 1.

$r_f$.... See equivalent circuit, Fig. 1.

$S_1$ = Primary amperes per inch on circle diagram.

$S_2$ = Secondary amperes per inch $= S_1 \div K_p$.

$x$ = Reactance.

$x_1$ = Reactance of primary winding due to primary leakage flux.

$x_2$ = Reactance of secondary winding due to secondary leakage flux.

$X_m$ = Reactance of primary winding due to the flux which cuts both coils.

$X$ = Reactance—Either $X_{sc}'$ or $X_{sc}''$ when the two are assumed to be equal.

$X_s$ = Either $X_s'$ or $X_s''$ when the two are assumed to be equal.

$X_s'$ = Reactance of the primary with the secondary open, when resistances equal zero.

$X_s''$ = Reactance of the secondary with the primary open, when resistances equal zero.

$X_{sc}'$ = Reactance of the primary with the secondary short circuited, when resistances equal zero.

$X_{sc}''$ = Reactance of the secondary with the primary short circuited, when resistances equal zero.

## Discussion

**A. D. Moore:** The complete and correct analytical method of polyphase induction motor performance calculation is very tedious. The accurately-drawn circle diagram involves laborious methods, and it usually includes inherent inaccuracy due to simplifying assumptions made. The Branson method is very simple and easy to use.

To gain advantage a price is usually paid. The user of this method is freed from the price, for the author has already covered that feature by having done the labor of preparing a complete presentation and system of curves. The advantages are two: speedy calculations, and inherent errors minimized to the degree where they are entirely negligible.

**A. M. Dudley:** Three times in a period of 18 years have I been deeply stirred with a sense of witnessing a distinct advance in the art of calculation and design. The first of these was in 1912 when Mr. Branson presented his Boston paper covering a method of calculating the performance of single-phase motors; the second was at Atlantic City in 1918 when Mr. C. L. Fortescue presented his paper on a *Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks*, and the third is the paper which we have before us at the present time. Several years ago I was associated with Mr. Branson in commercial work on induction motor design and discussed with him his idea of working out in curve form several of the significant relations in the circle diagram which would permit very rapid evaluation of single load points in the calculation of motor performance. As well as I can in a few words I should like to give my estimate of what Mr. Branson has done and its probable value to commercial designers of induction motors.

As is well known to the fraternity the calculation of leakage reactance and iron losses are two of the time consuming items in induction motor calculation. Neither Mr. Branson nor anyone else can obviate this since it is inherent in the problem. However, having established the constants of the motor either by calculation or test readings this paper reduces to a startling extent the further work of reducing these readings to speed-torque and power factor and efficiency curves. It has taken Mr. Branson and his associates several years to produce the required number of *a*, *b*, and *c* curves to which he refers but now that they are produced they become of intense interest to all students and engineers who are working with induction motor calculations. I think it would not be extravagant to say that if a man spent 15 years on this kind of work the use of Mr. Branson's methods ought to add from 1 to 2 years to his working usefulness simply through the item of time saving.

Any discussion of Mr. Branson's paper would be incomplete without reference to the exactness and scientific vigor of his methods. His method of considering the circle diagram seems to me the most exact of all those with which I am familiar and his results are therefore dependable to an extraordinary degree of accuracy.

It is also true that those relations chosen as significant such as $K_r$, $\dfrac{r_1}{X}$, and $\dfrac{P_s X}{E_2 X \text{ Phases}}$ are those which lend themselves best to the reduction to curve form and make possible the simplicity of the method.

To sum up I feel that in this paper Mr. Branson contributes a new and very useful idea in the field of induction motor calculation. I feel that the method is accurate and time saving. In contributing the *a*, *b*, *c* curves, which he says he proposes to, Mr. Branson is putting at the disposal of all engineers who are interested, the result of several years of painstaking and arduous labor and for this I wish to thank him as one engineer who has profited through the use of this system.

**W. J. Morrill:** Mr. Branson has spoken of his method as if it were a circle diagram method but in reality it is an entirely new method. He could have used some other scheme for obtaining the data with which he plots his charts. For example, he could have employed the equivalent circuit in Fig. 1 herewith, which represents exactly the current and output which he obtains, and almost exactly the input watts. Mr. Branson assumes

the core loss to be constant. In the equivalent circuit which I show it is represented by the watts lost in the resistance $R_c$ and is not quite constant.

I am very much pleased with Mr. Branson's method because of the straightforward manner with which it solves the designer's problem. By the use of his charts it is possible to proceed directly to the determination of all the motor characteristics corresponding to a given output.

**C. R. Boothby and C. G. Veinott:** The author is to be highly commended for developing the calculating method given in this paper. Undoubtedly, once such curves as these have

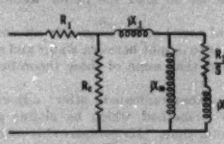


FIG. 1—EQUIVALENT CIRCUIT FOR CURRENT OBTAINED BY BRANSON'S METHOD

been made available, as the author proposes, their use should save much time where a large number of routine calculations is to be made. It is our opinion, however, that while the author has arrived at an admirable calculating method, his development of this method is rather obscure and might lead one to erroneous conclusions. For example, the author states in Fig. 12 "Any secondary current causes a current to flow in the primary equal to secondary amperes times $K_p$." This means that the component of the primary current which balances the secondary current differs from the secondary current by an amount depending upon the leakage coefficient, $K_p$.

The foregoing statement is evidently an attempt to justify the division of the chord $M\ T$ by $K_p$ in order to obtain the actual secondary current. There can be no doubt as to the correctness of this procedure as Mr. Behrend, in his book, "The Induction Motor," p. 27, gives the same diagram used by Mr. Branson and shows that when the flux diagram is replaced by the current diagram the chord $M\ T$ becomes $I_2 \times K_p$.

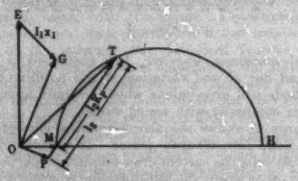


FIG. 2

$O\ G$ voltage impressed across $X_m$
$O\ P$ magnetizing current under load conditions
$O\ M$ no-load magnetizing current

An inspection of the equivalent circuit discloses one fact which is not apparent from the author's circle diagram. It is that the magnetizing current of the motor decreases with an increase in load. In the diagram the magnetizing current is represented as constant for all loads and $I_1 \times K_p$ is added to it to obtain the primary current. However, that the two systems of treatment give identical results has been illustrated by the author by a specific numerical example. The agreement of the two systems can also be shown by a general algebraic proof. For those who are interested, such a demonstration is given at the end of this discussion.

For those who do not care to follow the detailed mathematical work, we are attempting in Fig. 2 herewith to show graphically the equivalence of these two methods in a clearer, though less rigorous manner. This figure shows how the voltage across the magnetizing reactance, $X_m$, decreases and changes in phase under load due to the voltage drop in the primary leakage reactance. This voltage is represented by $O\ G$ in this figure. The magnetizing current, that is, the current flowing through $X_m$, is proportional to this voltage and lags it by 90 deg. This current is represented by $O\ P$. $O\ T$ and $P\ T$ represent the primary and secondary currents, respectively. That the secondary current is larger than the chord of the circle is evident from this figure. That the ratio of the latter to the former is equal to $K_p$, while not directly evident from the figure, is, however, amply shown both by Mr. Behrend from an analysis of the flux conditions in the motor and also by the complex algebra of the equivalent circuit as given at the end of this discussion.

It may also be well to call attention to the fact that the voltage $O\ D$ in Fig. 13 is actually $\frac{I_1 r_2}{S}$ ($S$ = the slip) instead of $I_2\ r_2$ as shown.

The author is to be highly commended for the detailed "worksheet" he has given. This makes it possible to apply the method even if the details of the theory are unknown or forgotten. We should like to offer as a suggestion that the curves in Figs. 16 and 17 might be more useful if plotted on log-log paper as this would enable them to be read with the same percentage of accuracy throughout their entire range.

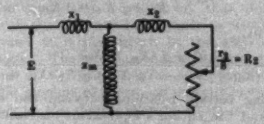


FIG. 3

*Comparison of the Circle Diagram with the Equivalent Circuit.* The circle diagram given by the author depends for its correctness upon the truth of the equation

$$\bar{I}_{mo} + \bar{I}_1 K_p = \bar{I}_1{}^* \tag{1}$$

where $\bar{I}_{mo}$ = no load magnetizing current $= \frac{-jE}{X_m + X_1}$ (2)

Let us investigate the truth of Equation (1) by determining $\bar{I}_1$ and $\bar{I}_2$ from an analysis of the equivalent circuit in which iron loss and primary resistance are neglected. Such a circuit is given in Fig. 3 herewith.

*First let us solve for* $\bar{I}_2$. Applying Kirchoff's laws to the network of reactances and resistances in Fig. 3 the following solution for $\bar{I}_2$ is obtained.

$$\bar{I}_2 = \frac{E}{\left[ jX_1 + \left( \frac{jX_1}{jX_m} + 1 \right) \left( R_2 + jX_2 \right) \right]} \tag{3}$$

$$= \frac{E}{R_2 + j\left( X_2 + \frac{X_1 X_m}{X_m + X_1} \right)} \times \frac{X_m}{X_m + X_1} \tag{4}$$

Certain groups of constants in the above expression can be recognized as the author's "equivalent" constants so that, from (4)

$$\bar{I}_2 = \frac{E K_p}{R_2 + jX_{eq}} \tag{5}$$

*The sign ⌣ over quantity indicates a vector.

Digressing from the main subject for a moment, we think it interesting and worth while to remark that it is evident from Equation (5) that the locus of the secondary current, as $R_2$ is varied, is a semicircle having a diameter of $\frac{E K_p}{X_{sc}''}$. This checks the author's secondary current circle in Fig. 12.

But, returning to our main object,

$$\bar{I}_2 K_p = \frac{E K_p^2}{R_2 + j X_{sc}''} = E\left(\frac{K_p^2 R_2}{R_2^2 + X_{sc}''^2} - j\frac{K_p^2 X_{sc}''}{R_2^2 + X_{sc}''^2}\right) \tag{6}$$

Now, we can evaluate the left member of Equation (1) by taking the value of $\bar{I}_{mo}$ from Equation (2) and adding to Equation (6), obtaining

$$\bar{I}_{mo} + \bar{I}_2 K_p = E\left[\frac{K_p^2 R_2}{R_2^2 + X_{sc}''^2} - j\left(\frac{K_p^2 X_{sc}''}{R_2^2 + X_{sc}''^2} + \frac{1}{X_m + X_1}\right)\right]$$

which reduces to

$$\bar{I}_{mo} + \bar{I}_2 K_p = E\left[\frac{K_p^2 R_2}{R_2^2 + X_{sc}''^2} - j\frac{R_2^2 + X_{sc}''(X_{sc}'' + K_p X_m)}{(R_2^2 + X_{sc}''^2)(X_m + X_1)}\right] \tag{7}$$

Now, let us solve directly for $\bar{I}_1$ from the equivalent circuit. It is evident from Fig. 3 that

$$\bar{I}_1 = \frac{E}{j X_1 + \frac{j X_m (R_2 + j X_2)}{R_2 + j X_2 + j X_m}}$$

which reduces to

$$\bar{I}_1 = E\frac{R_2 + j(X_m + X_2)}{-X_2(X_m + X_1) - X_m X_1 + j R_2 (X_m + X_1)} \tag{8}$$

By again noting certain relations between the constants in Equation (8) and the author's equivalent constants, Equation (8) may be reduced, with a little manipulation, to

$$\bar{I}_1 = \frac{-E K_p}{X_m}\,\frac{R_2 + j(X_m + X_2)}{(X_{sc}'' - j R_2)} \tag{9}$$

This equation, when rationalized, becomes

$$\bar{I}_1 = E\left[\frac{K_p^2 R_2}{R_2^2 + X_{sc}''^2} - j\frac{R_2^2 + X_{sc}''(X_m + X_2)}{(X_{sc}''^2 + R_2^2)(X_m + X_1)}\right] \tag{10}$$

At first sight it may not appear that the right members of (10) and (7) are identical; noting, however, that

$$X_{sc}'' + K_p X_m = X_m + X_2$$

Equation (7) becomes

$$\bar{I}_{mo} + \bar{I}_2 K_p = E\left[\frac{K_p^2 R_2}{R_2^2 + X_{sc}''^2} - j\frac{R_2^2 + X_{sc}''(X_m + X_2)}{(X_{sc}''^2 + R_2^2)(X_m + X_1)}\right]$$

Thus the truth of the relation expressed by Equation (1) is demonstrated.

**J. F. H. Douglas:** I wish to offer my tribute to the excellent paper and point out that I think charts similar to Figs. 16 and 17 could probably be derived and used with great advantage for other types of motors. Of course the analytical method of obtaining these figures would have to be adjusted to suit the circuit of the motor in question.

In deriving these curves a certain simplification in the "exact equivalent circuit" is made. In particular, the no load resistance $r_0$ is transferred to a point nearer the source of supply than the stator reactance.

Inasmuch as stator slots have reactance in proportion to their depth, and in view of the fact that occasionally we run across circle diagrams that are skewed in an opposite sense which regarding the stator resistance only would give, I think that perhaps in some cases the core losses are sufficiently large taken in conjunction with the stator reactance to warrant further consideration of this problem.

The charts were computed on the basis of the assumption of a constancy of core loss. Without attempting to criticise this statement from the practical point of view, I wish to say that there are some theoretical elements involved that are of great importance. I do not recall having seen in print the intimate connection between hysteresis torque and the friction loss of an induction motor. If hysteresis torque is less than friction torque, the losses represented by $R_0$ should decrease with speed but it should be possible to raise the voltage on the stator to such a point that at no load the motor would run in exact synchronism.

The constancy of core loss is also greatly affected by the ratio in which the reactance is split between stator and rotor windings.

It is to be hoped that some of these theoretical points may soon be clarified.

**H. Weichsel:** (communicated after adjournment) Mr. Branson presents a method which he claims gives accurate results in a minimum time. He compares his with the graphical and analytical methods. The comparison between Mr. Branson's and the analytic method has been carried to a large degree of accuracy. All three methods are based on the assumption that the self-induction coefficient or leakage coefficient is constant and is independent of the current draw of the machine.

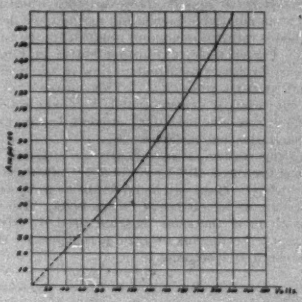



FIG. 4

In practical machines, however, this coefficient is far from constant, and due to the variation of this coefficient any one of the methods will give values which are only approximately correct when compared with tested values.

Fig. 4 herewith shows the short-circuiting current of an 8-pole, 10-hp., 220-volt, 60-cycle motor. It will be noticed that up to about 80 volts the current draw appears proportional to the voltage. In other words the self-induction coefficient up to this voltage is approximately constant. At values above this voltage, the current increases rapidly with increasing voltage, indicating that the self-induction coefficient decreased with increasing voltage.

As Mr. Branson points out, the graphical and analytical ways must give the same results, because they are both based on the same assumption, which means the two methods lead to a current locus which is a circle, a well-known condition derived years ago by Heyland, Behrend, and Osana.

Fig. 5 shows the current locus of the same motor for which the short-circuiting current is given in Fig. 4. It will be noticed that this locus, Fig. 5, is anything but a circle. No. 1 is the locked point of the machine, and No. 2 is the point of idle running. If it is attempted to draw a circle through these points, it is evident it would deviate materially from the curve 1–2. A fairly close approximation can be obtained, however, if as locked point

a current value is used obtained at about half voltage and then multiplied by 2; in other words, if the self-induction coefficient is used which exists at about half voltage. It will be seen that even under these conditions, the results obtained from the tests and those obtained from the circle are only in fair agreement and sufficiently accurate for most practical purposes. The curves referred to above have been based on a machine which has, like most modern machines, totally closed rotor slots. The variation of the self-induction coefficient will not be quite as large in machines having semi-closed slots in the rotor and stator, and also the variation is decreased with decreased number of poles.

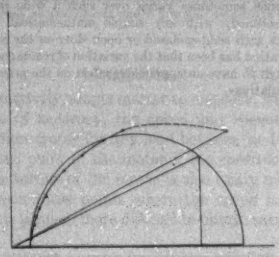


Fig. 5

Nevertheless, the fact remains that in the majority of cases the self-induction coefficient is not constant, and at the best only a reasonable agreement between test and calculated data can be expected as long as the constant self-induction coefficient is used as a basis.

Mr. Branson's method is based on the diagram shown in Fig. 14. This is in principle a circle diagram for an ideal motor having primary and secondary reactance and secondary resistance but no primary resistance. A constant voltage is supposed to be impressed across its terminals. The omission of the primary resistance is corrected by external resistance in each of the three lines in series with the motor. Consequently the line voltage across these three resistances is not constant, but is a function of the current. For historical reasons it may be pointed out that this method of considering the influence of the primary resistance was published in Heubach's book, p. 83, published 1903; and in the book by De La Tour entitled "The Induction Motor," p. 147, published 1903.

The method proposed by Mr. Branson makes the assumption that the primary leakage coefficient is equal to the secondary leakage coefficient, or using the terms preferred by Mr. Branson, the permeance values $P_L'$ and $P_L''$ are alike. This assumption is more or less correct if the rotor is of the wire-wound type. If it is of the squirrel-cage type, a larger percentage of the leakage exists in the stator than in the rotor.

Heubach also pointed out in his book that for any ratio between stator and rotor leakage, the exact rotor current can be obtained by drawing a diagram as shown in Fig. 6 herewith, where a small circle drawn over the magnetizing current divides this current in the relation of stator leakage to total leakage. The rotor current is vector 1–2 and the stator current vector 0–2 when both are measured with the same scale. If all the leakage is in the stator member, this small circle has a diameter equal to the magnetizing current. As the percentage of the rotor leakage becomes larger and larger, this circle shrinks and finally becomes merely a point located at the end of the magnetizing current vector.

With this diagram as a basis, and to it added the method for considering the primary resistance proposed by Heubach (which is identical to that proposed by De La Tour), a diagram of sufficient accuracy for practical purposes can be obtained. Naturally it has the same shortcoming which was pointed out in the beginning,—it is based on a constant self-induction coefficient. But if desired it can readily be modified to take care of a variable self-induction coefficient by drawing a family of circles for different self-induction coefficients. It is true that this idea can also be followed by any of the methods outlined above. It is more or less a matter of personal preference as to which method is to be used. My opinion is that the graphical method is applicable to any case which may occur and has the advantage that the calculation can be carried out without reference to tables or graphs, which are not always available when calculations are to be made on motors. It further has the advantage that it enables one to visualize the influence of changes in relations of a given design.

In large motors the use of the methods referred to above is rarely justified, because the stator copper loss represents only a small percentage of the total machine input, and in such cases the influence of the ohmic resistance is so small that the simple Heyland diagram is preferred. Generally only in small 60-cycle motors or in medium size low-frequency motors is the stator copper loss a large percentage of the motor input. In such cases any of the above methods can be used to advantage.

**W. J. Branson:** In the discussion of Mr. Boothby, I am not sure that I got all the points. In regard to the use of $K_p$ in Fig. 12 to show the relation between the secondary current and the increase of the primary current due to the demagnetizing action of the secondary, I might say that the mathematical derivation was given in my 1912 paper to which reference has been made and it is also given in the 1923 edition of Mr. Behrend's book. The two demonstrations are entirely different but the result is the same. With any current flowing in the secondary the amount of increased current in the primary that will flow due to the demagnetizing effect of the secondary is equal to the secondary current times $K_p$. That is the exact relation so far as the mathematics is concerned. I did not clearly understand whether Mr. Boothby took exception to that or not.

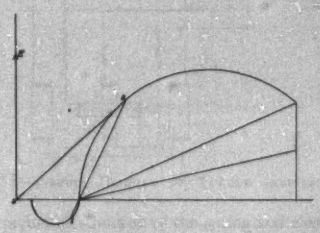


Fig. 6

In reference to Mr. Dudley's statement that it has taken several years to produce a set of *a b* and *a c* curves, it may be well to explain that what has taken the time has not been the actual work of calculating and plotting the curves. The big job was to find a simple and practical way of deriving the values. The first set of curves covering a small range of constants was made by the graphical process about 1910 or 11; and two or three years later a larger set was made in the same way. This method of procedure was very laborious.

The last set of curves, which was made three or four years ago, was plotted from values calculated by the work sheet shown as

Fig. 23. This process requires probably not more than 10 per cent of the labor that would be involved in deriving the values graphically.

Anyone who may wish to try the system before the curves are published can easily make up a small set which will take care of practically all 60 cycle 4-, 6-, and 8-pole motors. Such a set should cover the constants listed below:

$K_r$ 0.94, 0.93, 0.92, 0.91, 0.90, 0.89

$r_1/X$ 0.15, 0.2, 0.25, 0.3, 0.35

It would include five groups of $a\,b$ curves and six groups of $a\,c$ curves, and cover 32 sheets of cross-section paper. A young man who is quick with the slide rule might do all the work in two or three weeks.

Professor Douglas has called attention to the fact that "charts" like Figs. 16 and 17 might be used to advantage for other types of motors. In this connection, I might say that several such "charts" are in regular use. One set of curves has been used for about 15 years to determine the starting torque of split-phase motors while another set has been in use for 6 or 7 years to determine the maximum torque of any single-phase induction motor. In either case the torque values, calculated with the aid of the curves in less than 30 seconds, are exactly the same that would be obtained by constructing a circle diagram in accordance with the directions given in my 1912 paper.

Mr. Weichsel has called attention to the fact that the variation of the leakage coefficient, which corresponds to a decrease in reactance as the load comes on, will cause the actual performance to differ from the calculated performance regardless of the theoretical accuracy with which calculations are made. In the case of motors with closed rotor slots, it is undoubtedly true that the reactance sometimes varies over such a wide range as to interfere seriously with any simple mathematical treatment. For motors with semi-enclosed or open slots on the other hand, my observation has been that the variation of reactance is seldom great enough to have an appreciable effect on the practical value of the calculations.

# A Recording Torque Indicator

## That Records the Torsional Effort of Motors During Acceleration

BY G. R. ANDERSON[1]

Member, A. I. E. E.

*Synopsis.—The measurement of torque under unstable conditions of speed is usually extremely difficult and inaccurate when a dynamometer, prony brake, or similar torque measuring equipment is used. The device described in this paper was developed primarily to obtain torque measurements under unstable conditions as well as under stable conditions, and to obtain a permanent record of these measurements. It has been particularly successful in recording speed-torque curves of motors during acceleration and it can also be applied very effectively to other fields.*

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### Introduction

It is a relatively simple matter to measure, with a fair degree of accuracy, the speed and torque of an induction motor for any load between no-load and the pull-out point of the motor if the speed is steady. The static torque of the motor is also easily measured, but between these points where the speed is usually unstable, it is much more difficult to obtain satisfactory measurement. With the development of line-start motors, condenser motors, etc., it is becoming increasingly more important to know exactly the torque characteristics that the motor will develop. Dips in torque due to harmonics or other causes may be present in sufficient magnitude to seriously hinder the motor in accelerating its load. A device that will quickly and accurately record this torque should therefore find many uses in analyzing and improving motor characteristics. Such a device is described in this paper.

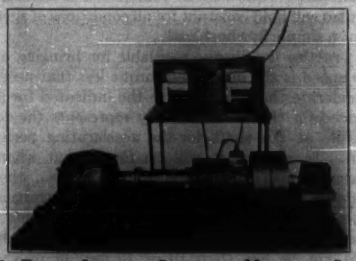

Fig. 1—Torque Indicator Set-up for Measuring Starting Torque of Induction Motor

### Description of Torsional Indicator

Fig. 1 illustrates the torsional indicator set up to take speed and torque curves on a squirrel-cage induction motor. The device consists of (1) a helical spring capable of transmitting the torque of the motor and giving an angular deflection proportional to the torque, and (2) an electromagnetic circuit of two elements that are displaced from each other by an angle equal to the deflection of the spring. A recording electrically-operated position finder is connected to the device to record the amount of angular deflection, which is proportional to the torque.

The helical torsion spring is accurately finished and is mounted so as to eliminate any distortion due to centrifugal forces. The spring is equipped with a damping sleeve that prevents fluctuations due to the natural period of vibration of the spring and elements, from being recorded on the chart. Full-scale deflection on the meter is obtained with a spring deflection of 60 degrees. Several sizes of springs can be interchangeably mounted to take care of various ranges of torque.

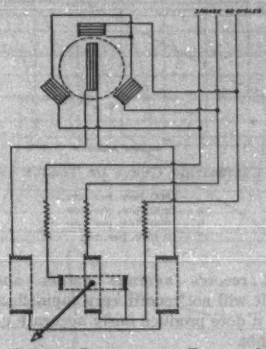

Fig. 2—Circuit Diagram of Torque Indicator

The electromagnetic elements are mounted on two concentric cores, one of which revolves with the motor and the other with the load. The first element consists of a three-phase winding arranged symmetrically outside of the second element. This is shown diagrammatically in Fig. 2. This three-phase winding is

1. Development Engineer, Fairbanks, Morse & Co., Beloit, Wisconsin.

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29-157

excited through slip-rings from an external three-phase source of power. The second element contains a winding which is connected by another set of slip rings to the position finder as shown. The moving coils of the position finder are connected to the external source of power. When the first element is turned with respect to the second, the phase angle of the voltage generated in the second, is changed and this causes a deflection of the position indicator proportional to the torque. A tachometer generator and recording meter are used to measure the speed. The charts for recording both the torque and the speed are mounted on the same shaft in order to provide synchronized readings. Gear combinations in the tachometer generator allow different full-scale values of speed on the chart. It is obvious that the meter circuit can be so designed that the needle deflection is closely proportional to the angular deflection in the electromagnetic circuit of the device, thereby allowing the use of standard chart paper.

The device is similar in action to a d-c. meter

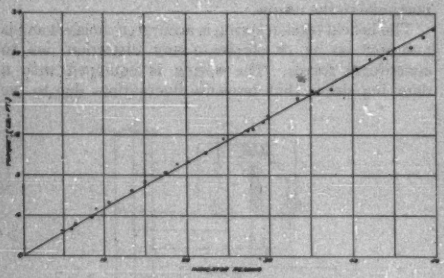

Fig. 3—Calibration Curve of Torque Indicator

. —1800 Rev. per min.
x —1200 Rev. per min.
0 — 600 Rev. per min.
□ — 0 Rev. per min.

in that it records average values and is well damped. It will not record very rapid fluctuations of torque but it does produce fairly accurate quantitative measurements.

## Calibration

Calibration of the device is accomplished by placing it between a dynamometer and a load and recording the torque output of the dynamometer and the instrument reading. Fig. 3 is a calibration curve for a given spring showing the relation between actual torque and instrument reading. The plotted readings were taken over a wide range of speed and of torque and clearly indicate that centrifugal force has no serious influence on the accuracy of the device. While the calibration curve is actually slightly S-shaped, for practical purposes it may be considered a straight line, since the error introduced by such assumption is extremely small.

## Methods of Loading

Since this device indicates transmitted torque and speed simultaneously and records these values on a chart, it is obvious that any suitable method of loading can be applied. In the case of taking speed and torque curves on motors during acceleration it has been found that a simple flywheel load is most satisfactory. Under these conditions, the entire torque output of the motor is utilized to accelerate an inertia load, neglecting friction, and the rate of acceleration is proportional to the torque transmitted at that speed. The rate of acceleration can be readily determined from the speed-time chart. The torque indicated on the chart is the torque transmitted through the spring, and is equal to the torque developed by the motor less that required to accelerate its rotor. Thus the indicated torque during acceleration will be slightly less than that shown at stable speeds and will be proportional at all speeds to the ratio of the $WR^2$ of the flywheel and device to the $WR^2$ of the entire rotating mass. By calculating the $WR^2$ of the rotor and determining the rate of acceleration from the chart, the ratio of developed torque to transmitted torque can be found. It is obvious that this ratio will hold constant for all conditions of acceleration of a simple flywheel load.

In practise the torque available for bringing a load up to speed is the developed torque less that necessary to accelerate the rotor so that the indicated torque as produced on the chart actually represents the torque available at the shaft for the accelerating period as shown. In general it will be found that when the accelerating period exceeds 15 or 20 sec., the difference between the developed torque and transmitted torque will be less than four or five per cent. The necessary time to allow for full acceleration of a motor should not be less than 10 or 15 sec. in order that the pen of the instrument may follow accurately the changes of torque. It has been noted also that accelerating periods of 20 to 30 sec. usually cause such a small change in motor temperature that this factor can be neglected.

In the following examples the instrument chart speed was 12 in. per min., each cross-division representing a time of 3.75 sec.

## Applications

Fig. 4 is an example of speed and torque charts taken on a 5-hp., 1800-rev. per min., 60-cycle, repulsion-induction motor. The variations in torque at start due to the commutator are clearly shown as well as the point of operation of the short-circuiting device and change over from repulsion to induction torques. Charts of this kind were taken to show the effect of setting the short-circuiting device to operate at different speeds.

Other charts taken on repulsion-induction motors, clearly show the change in shape of the repulsion torque curve due to change in brush setting and the lowering

of pull-in torque when the brushes are displaced from neutral by more than the proper angle.

Fig. 5 shows records taken on a line-start squirrel-cage induction motor. In addition to the charts of torque and speed, synchronized charts that recorded the current and power input were also obtained with a constant voltage applied to the terminals of the motor. Several of these motors with different types of rotor construction were tested in order that an accurate comparison of the characteristics of each type might be obtained.

It was noted from the charts that each of these motors having a rotor winding of special shape designed to lower the current drawn by the motor from the line

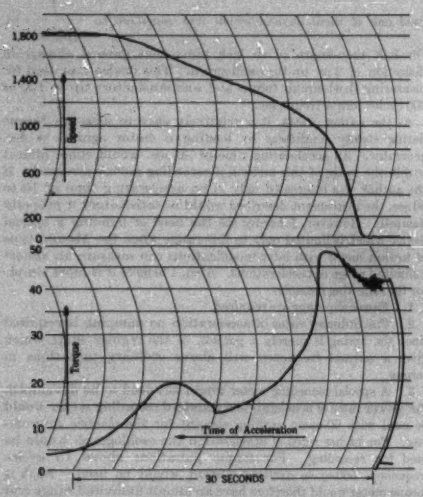


FIG. 4—SPEED AND TORQUE CURVES OF REPULSION-INDUCTION MOTOR DURING STARTING

This is a 5-hp. 1800-rev. per min. 60-cycle, 220-volt single-phase motor

during starting, had an appreciable dip in accelerating torque. The knowledge thus obtained of the exact amount of accelerating torque at all speeds should prevent misapplications of these motors.

By means of the addition of current and wattmeter readings, the factors affecting the developed torque of the motor can be determined from tests for all speeds. The change in rotor resistance and reactance with changes in slip can be calculated and the value of any particular type of rotor construction for a given condition can thereby be determined.

In making tests on squirrel-cage induction motors it was found that invariably the indicator recorded distinct torque pulsations whenever the motor became noisy. Investigation with this device also verified the general belief that dips in torque due to harmonics in squirrel-cage motors are more pronounced at low

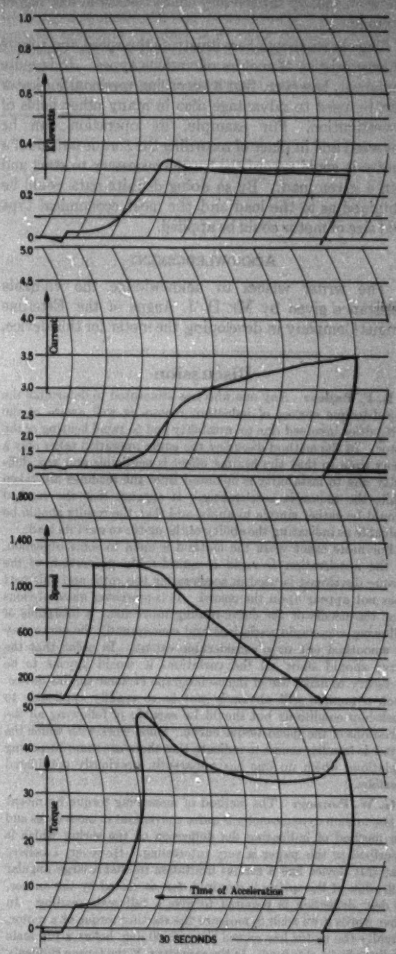


FIG. 5—RECORDS TAKEN DURING ACCELERATION OF A LINE-START INDUCTION MOTOR

Curves are shown for kw., amperes, speed, and torque of a 20-hp. 1200-rev. per min. three-phase 60-cycle motor

voltage than at high voltage. A series of curves taken on a motor with different values of voltage applied to the terminals showed a damping out of harmonics as

the voltage was increased. It seems reasonable therefore to assume that if a motor develops a satisfactory speed-torque characteristic on reduced voltage, it will show an equally satisfactory characteristic at any higher voltage.

The charts shown here illustrate the speed and torque characteristics of motors of various types. It is quite apparent, however, that a recording torsional indicator can be used to advantage also in many other fields of investigation. For example, its operation can be reversed and in place of recording the torque output of a motor it could record the torque necessary to start and run a given load. By so doing definite data could be obtained as to the load and the most economical type and size of motor could be applied.

ACKNOWLEDGEMENT

The writer wishes to acknowledge the valuable assistance given by Mr. D. J. Angus of the Esterline Angus Company in developing the meter for this device.

## Discussion

**B. F. Bailey:** Any one who has attempted to determine the speed-torque curves of induction motors is well aware of the difficulties involved due to instability and to rapid heating of the rotor. In the method discussed the entire operation takes only a short time so that the heating effect is negligible and any difficulty due to instability is obviated since the readings are taken while the motor is accelerating. It appears that the method should be rather simple to apply and that the results should be valuable as indicating the ability of the motor to start its load.

For more exact work the method is open to some objection. If the acceleration is rapid a considerable proportion of the torque developed is used in accelerating the rotor and this part does not appear upon the record. It is moreover quite obvious that the needle of the curve-tracing instrument is incapable of following very rapid variations and consequently the curve may be smoothed out to a considerable extent. In order that the curve should show all the variations it would appear to be necessary to make use of the oscillograph or some similar device. Such a method will obviously not be so readily applicable to workshop conditions but should be capable of following all the variations of the speed-torque curve. Some work with which the writer is familiar seems to indicate that there are some surprising variations which no one has apparently previously considered possible.

**G. W. Penney:** The method of measuring torque by means of the torsion dynamometer is quite convenient in most cases and the method of indicating the deflection of the spring which is described in this paper is very interesting. However, I believe that this device has a serious limitation in that a large angular deflection of the spring is required, for, as stated by the author, 60 deg. deflection is required to give a full scale reading. In other words if we wish to measure the starting torque of a motor, actually the motor has moved through 60 deg. before a full scale reading can be obtained. In the same way, if the torque suddenly changes this change cannot be indicated until the spring has deflected.

This helical spring between the motor and the load gives a natural period of oscillation between the two rotors which is inherently low so that the damping device becomes of considerable importance. An ordinary friction device having sufficient friction to prevent oscillations of the rotor would tend to restrict the deflection of the spring, giving a reading which is too low in case the torque is increasing and too high if decreasing. The details of the damping device used would, therefore, be interesting and especially test results showing whether the calibration is the same for both increasing and decreasing torque.

This principle of using the deflection of a spring as a measure of torque transmitted has frequently been used and devices described in the literature for measuring the torsional deflection. I believe that one of the best of these devices is the "Moulin Torsion Meter."[1] In this torsion meter the deflection of the spring was measured by measuring the change in impedance of two coils as the air-gap between the cores changes. In this way very small movements can be measured so that the spring of the dynamometer can be very stiff. Several modifications of this magnetic device have been described in the literature recently [2,3] which reduce the size of this instrument and increase its sensitivity to a point where ordinary shafting can be used as the dynamometer spring. At the Westinghouse works a few years ago, we used one of these devices which was sensitive to $\frac{1}{100{,}000}$ in. One-half thousandth of an inch movement gave a change in deflection of 2 in. on the oscillogram. This device was used for measuring short-circuit torque and was satisfactory up to 120 or 200 cycles torque frequency.

As the author states, it is relatively easy to measure torque during steady conditions by loading a motor against a d-c. generator. An accelerating time of 30 sec. would come almost within the range of this method if recording meters are used. If the author was interested only in an accelerating time of 10 to 30 sec. the instrument described would be satisfactory if properly damped. However, I hardly see the need of building a special device which is limited only to this range when the Moulin type of torsion meter with later modifications can measure an almost unlimited range of accelerations. Also, I believe it is more simple for the following reasons:

1. Fewer slip rings are required.
2. For ordinary rates of acceleration no damping is required since the spring is merely a portion of the regular shaft which gives a natural frequency well above ordinary pulsations in torque.
3. A special recording meter would not need to be developed. For slower rates of acceleration a standard recording meter would be used with 60-cycle exciting current for the electric micrometer. For higher rates of acceleration the oscillograph would be used for recording. For torque pulsations above 15 cycles frequency, 500-cycle exciting current would be used. Such a torque meter would therefore have an almost unlimited range and would require only standard recording devices.

**G. R. Anderson:** Professor Bailey is perfectly correct in that the instrument is simply a commercial piece of apparatus convenient for production testing. I should certainly like to see a torque meter with such a small inertia in its moving elements that it could follow any minute variation such as an oscillograph does in recording electrical units.

In regard to the damping device that was on the spring, it was a friction device, but no friction was applied to the spring unless the torque was actually reversed. In other words, as long as there was positive torque transmitted by the spring there was no damping.

I think that this will answer Mr. Penney's criticism of the inaccuracy that might be caused due to damping. If the torque happened to go to a negative direction damping would occur and the inaccuracy would be there, but no readings would be obtained.

1. *Engineering*, June 13, 1924, p. 764.
2. *Vibration Recorder*, by A. V. Meraho, A. I. E. E. TRANS., Vol. XLV, 1926, p. 1007.
3. *An Instrument for Measuring Short-Circuit Torque*, by G. W. Penney, A. I. E. E. JOURNAL, Nov. 1926, p. 1151.

Several different kinds of damping means were considered. We were interested mainly in one thing, and that was eliminating the natural period of oscillation that might be set up in the spring.

Engine builders have for a great many years studied the problem of measuring torque and torque vibrations. A number of different devices has been used for recording of Diesel engine torque variations and it has been the experience of the company with which I am connected that none has been entirely satisfactory. There are certain features about such measuring devices similar to the Moulin Torsionmeter described by Mr. Peuney, that may work out in the laboratory but are unsuitable for commercial work. However, I do know that we did not consider them for the measurement of torque of motors, simply because we wanted a fairly reliable commercial piece of apparatus by which we could test all kinds of motors and use a standard recording instrument. If the measurement of torque under unstable conditions of speed is so easily obtained, I cannot understand why it is that authors in the past have drawn such smooth curves for line-start motors in which there were no depressions in torque between starting and maximum.

# Stability of Synchronous Machines

## Effect of Armature Circuit Resistance

BY C. A. NICKLE* and C. A. PIERCE*

Associate, A. I. E. E. Non-member

*Synopsis.—The theory of synchronous machines as developed by Doherty and Nickle[1] has been extended to include a determination of the effect of armature circuit resistance on damping torque. Equations are developed for the damping torque of synchronous machines in general, i. e., both the salient-pole and round rotor types. These equations assume an exciting winding in the direct axis and an amortisseur winding in the quadrature axis, and further assume that all damping is due to currents induced in these two windings. The effect of an amortisseur winding in the direct axis is not considered because its damping action at the low frequency of hunting is small compared to that of the exciting winding. It is shown that the damping torque of any synchronous machine can become negative, giving instability, if the armature resistance is increased beyond a critical limiting value. This fact has been known,[2] but an actual determination of the value of the critical resistance in terms of constants of the machine has not, to the authors' knowledge, been available. This value, for a salient-pole generator with normal excitation and no amortisseur winding, is*

$$r = x_q \tan \delta'$$

*where r is armature circuit resistance†, $x_q$ is quadrature synchronous reactance, and $\delta'$ is the steady-state displacement angle. If r is less than the critical limiting value, the damping torque is positive; if greater, negative.*

*The damping of a generator increases in the positive direction with increase in load. Thus a salient-pole generator with amortisseur winding, if stable at no load, will be stable under any steady load within its steady-state power limit. With $\delta' = 0$, and normal excitation, the critical limiting value of armature resistance for a machine with an amortisseur winding is*

$$r = \sqrt{b\,d + \frac{d}{b}(x_d - a)^2}$$

*where $x_d$ is the direct synchronous reactance and a, b, d are constants depending upon the design of the machine. This formula is useful for determining the constants of an amortisseur winding which would prevent sustained or cumulative oscillations of a generator.*

*The analysis also shows that a round-rotor generator with identical field windings in the direct and quadrature axes may be made unstable by too much resistance in the armature circuits. This fact had been previously established by Dreyfus.[2]*

*The relations for inherent stability in synchronous motors are not so simple as for generators, but definite relations involving armature resistance will be found in the article.*

*The mathematical analysis is checked with laboratory experiments.*

### Introduction

THE problem of sustained and cumulative oscillations due to an impressed periodic exciting torque has been fully treated in the literature of synchronous machines.[1] It is further known, as shown by Dr. Ludwig Dreyfus,[2] that sustained and cumulative oscillations can occur without the presence of a periodic exciting torque. He called these oscillations self excited, because they can be started by an impulse of momentary duration; and once started become self sustaining, provided conditions favorable to such oscillations exist in the circuits of the machine.

His method of attack was to set up and solve the differential equations for the magnetic fields of a round-rotor machine under the conditions of small forced oscillations. The final equations of this analysis are based on a round-rotor machine with a damping winding in the quadrature axis having the same constants as the d-c. field winding. He showed by means of these equations that self-excited oscillations may be set up, *i. e.*, that negative damping is possible. He showed, furthermore, that the conditions favorable for negative damping are high excitation, low line frequency, and a large value of armature resistance. In the conclusion to the paper, it is stated that the oscillations of the exciting current due to transformer action between armature and field help to stabilize the machine, and a well-designed amortisseur winding in the quadrature axis will completely suppress the self-excited oscillations.

While Dr. Dreyfus initially considers both salient-pole and round-rotor machines in his paper, the part of the mathematical analysis dealing with self-excited oscillations in an actual machine is based on a machine with a uniform air gap. It is desirable to extend the analysis to include salient-pole machines. The necessity for considering this type is proved by engineering experience. Certain instances of troublesome hunting with salient-pole generators have come to notice from time to time that were difficult to explain. It was believed that too large armature resistance was to blame, but no analysis of the effect of this resistance was available with which to check the belief. This paper is the direct outcome of this problem. It takes up the mathematical analysis and solution for the effect of armature circuit resistance on damping torque of the salient-pole machine, and includes experimental verification of the mathematical solution, as well as application of the conclusion to a practical problem.

The mathematical analysis is based on the vector

*Both of the Engineering General Dept. of the General Electric Company, Schenectady, N. Y.

†Armature circuit resistance includes the resistance of armature phase and line wire back to the system bus. Likewise, synchronous reactance includes the reactance of line wire as well as the synchronous reactance of the phase. These quantities will usually be referred to as armature resistance and synchronous reactance.

1. For references see Bibliography.

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29-152

diagram rather than on the original differential equations for the machine, and is an extension of an Institute paper[1b] on torque-angle characteristics of synchronous machines under transient conditions. In the paper just referred to, equations for both synchronizing and damping torque were developed for salient-pole machines based on the assumption of zero armature circuit resistance. This assumption, in so far as it affects torque angle characteristics, had been justified in an earlier Institute paper[1a] by the same authors. The mathematical analysis will now be extended to show the effect of armature circuit resistance on damping torque.

In the mathematical analysis, the synchronous machine is considered to have a main-field winding in the direct axis and a damping winding in the quadrature axis. Although the ordinary amortisseur winding gives damping in both axes, its effect in the direct axis is neglected, since at the low frequency of oscillation usually encountered, the damping of the main-field winding predominates. This method of attack gives a solution that can be readily simplified to apply when there is no amortisseur winding. Since a great many machines have no amortisseur winding, this case has been considered in some detail.

Damping due to means other than the main-field winding and the amortisseur winding is not considered. Any external damping that may exist can be added to the inherent damping of the two windings if it is desired to determine the total damping acting on the rotor.

Saturation of the magnetic circuits is not considered. To include the effects of saturation would unduly complicate the mathematical analysis, if it did not make a solution impossible.

## Assumptions

In order to simplify the mathematical work, certain assumptions are made which do not seriously impair the usefulness of the conclusions derived. The assumptions are:

1. The machine is assumed to be connected to a relatively large power system so that hunting of the machine will cause no appreciable variation in the bus voltage; *i. e.*, an infinite bus is assumed.

2. The polyphase voltages impressed on the armature circuits of the machine and the currents flowing therein are assumed to be balanced and to vary sinusoidally with respect to time. Thus the usual vector diagram for voltage and current per phase may be used to represent the steady-value voltages and currents of the machine.

3. The machine is assumed to be in a state of sustained oscillation about a constant average value of displacement angle. The electromagnetic torque is then a function of time and contains two components, *viz.*, one component in time phase with the angular velocity of oscillation, and the other in phase with the angular displacement. These components are the damping torque and the synchronizing torque, respectively. The assumption is further made that the differential equations at the point considered are linear. Thus this analysis of damping applies rigorously only when the oscillations are of very small amplitude, *i. e.*, when voltage, current, torque, etc., vary proportionately. The motion of the rotor is assumed to consist, then, of a steady rotation at synchronous speed upon which is superimposed a sinusoidal oscillatory, or alternating motion.

4. The angular velocity of oscillation is assumed to be very small compared with the steady-value angular velocity; hence torque and power may be assumed numerically equal in the per-unit system.[4]

5. The alternating component of motion of the rotor causes the amplitude of the polyphase currents to vary periodically in time at the frequency of oscillation. It is assumed that the peak value of the armature current pulsates, or is modulated, in such manner that the envelope of the peak values can be represented as a sinusoidal function with respect to time, having a period equal to the period of hunting. If the actual modulation is more complex than assumed, the analysis will hold in so far as the fundamental of the modulation is concerned.

## Preliminary Analysis

An outline of the reactions produced by the modulated polyphase armature currents is set down in order that the mathematical analysis may be more easily followed. The currents in the several phases produce the armature reaction, or armature m. m. f., which can be resolved under steady-state conditions into space fundamental and space harmonic components.[1a] Only the space fundamental component will be considered.

The steady-value space fundamental component of armature reaction revolves around the air gap synchronously with the field poles, and cannot induce current in either of the two field windings. But the modulated armature reaction does induce current by transformer action in each of the rotor windings. The current in the main field winding, *i. e.*, in the direct axis, is made up of two components. One component is the steady-value current which is set up by the exciter; and the second component is alternating current induced by the modulated armature reaction. Only alternating current flows in the quadrature winding. The frequency of the currents induced in both windings is the same as the frequency of hunting of the machine. Thus the modulation of the peak value of the armature current produces a modulation of the total rotor voltage, *i. e.*, of the nominal voltage of the armature winding.

As the permeance of the air gap of a salient-pole machine is different in the two axes, in order to make the analysis perfectly general, it is necessary to deal with the direct and quadrature components of voltage and current.[1a] It is evident that these components of the armature current will be modulated if the total current is modulated, and that the modulation will

appear in the direct and quadrature components of the nominal voltage by transformer action.

Since the modulation of the steady peak value $i_d'$ of the direct component of armature current causes its amplitude to vary sinusoidally at the frequency of hunting, the peak value $i_d$ at any instant is a function of time and can be represented as

$$i_d = i_d' + \Delta i_d \cos s t = i_d' + [\Delta i_d] \tag{1}$$

where $s$ is the angular velocity of modulation expressed as a fraction of normal angular velocity, and $[\Delta i_d] = \Delta i_d \cos s t$ is the value of the modulating wave at any instant. Using the per-unit system of units,

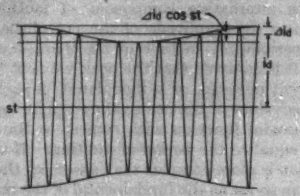


Fig. 1—Armature Current with Harmonic Modulation

frequency and its corresponding angular velocity are numerically equal. Fig. 1 shows the current represented by Equation (1). It will be assumed that the angular velocity $s$ is small compared with $\omega$, the angular velocity corresponding to line frequency, so that the modulation will not distort the wave form of the current during a cycle enough to make the use of the usual vector representation of polyphase currents inaccurate.

In like manner the peak value $i_q$ of the quadrature component of armature current is a function of time and can be represented as

$$i_q = i_q' + \Delta i_q \cos (s t + \alpha) = i_q' + [\Delta i_q] \tag{2}$$

introducing the time-phase angle $\alpha$ because the modulating waves for the direct and quadrature components of current will not in general vary in time phase with each other. In Equation (2) $i_q'$ is the average value of $i_q$ and $[\Delta i_q] = \Delta i_q \cos (s t + \alpha)$ is the value of the modulating wave.

The peak value of the nominal voltage, $e_d$, due to the main field winding, is a function of time and can be represented as

$$e_d = e_d' + [\Delta e_d] \tag{3}$$

where $e_d'$ is the average peak value and $[\Delta e_d]$ is the modulation, or alternating, component introduced by the hunting. As there is no d-c. excitation in the quadrature axis, the peak value of the nominal voltage $e_q$ can be represented as

$$e_q = [\Delta e_q] \tag{4}$$

where $[\Delta e_q]$ is a function of time.

The displacement angle $\delta$, which is made up of two component angles, the steady value $\delta'$ corresponding to the average load, and an alternating value $[\Delta \delta]$ corresponding to the hunting, can be represented as

$$\delta = \delta' + [\Delta \delta] \tag{5}$$

The alternating components $[\Delta i_d]$, $[\Delta i_q]$, $[\Delta e_d]$, $[\Delta e_q]$, and $[\Delta \delta]$ all vary in time with the frequency of hunting.

These values of armature current, nominal voltage, and load angle can be combined by means of the relations shown in the vector diagram, Fig. 2, for a salient-pole machine to give relations from which the damping torque can be determined. The mathematical analysis is given in Appendix I. Equation (56) of Appendix I gives the value of damping torque for a synchronous machine having an exciting winding in the direct axis of the rotor and an amortisseur winding in the quadrature axis.

## Study of Damping Torque

It is not immediately apparent from inspection of Equation (56) how much effect armature resistance $r$ has on damping torque $T_d$, because $r$ appears not only as seen in the equation, but also in the equations for the constants, $\alpha$, $B$, $C$, and $D$. Equation (56) can be reduced to a simpler form, however, by letting $c = 0 = d$ (compare (26) and (27)), which means considering a machine that has no amortisseur winding,

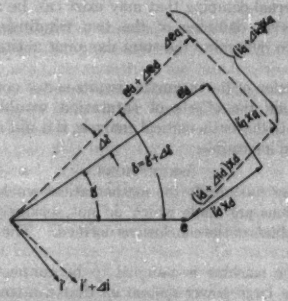


Fig. 2—Vector Diagram for Salient Pole Machine on Infinite Bus under Conditions of Mechanical Oscillation

in which case damping is due to the current induced in the main field winding.

Substituting $c = 0 = d$ in (50), (41), and (56),

$$D = \frac{r \sin \alpha - x_d \tan \delta' \sin \alpha}{b} \tag{58}$$

$$\cos \alpha = \frac{r \tan \delta' + (x_d - a)}{-b} \tag{59}$$

$$T_d = \frac{B\,D\,e \sin \delta' \,[D\,b\,x_d + r\,(b \cos \alpha - a \sin \alpha)]}{s[(r \sin \alpha - b\,D)^2 + \{r \cos \alpha + D(x_d - a)\}^2]} \tag{60}$$

The damping torque for this case can be written more

simply by substituting (58) and (59) in (60) and reducing; thus obtaining

$$T_d = \frac{B b e\,(r^2 + x_d x_q)\,(x_q \tan \delta' - r) \cos \delta'}{s\,[(b\,x_q)^2 + (r^2 + x_q\,(x_d - a))^2]} \qquad (61)$$

The quantities $e$, $a$, $b$, $x_d$, $x_q$, $r$, $s$, and $\cos \delta'$ are all positive. Thus the sign of the damping torque is determined by the quantities $B$ and $(x_q \tan \delta' - r)$. Hence Equation (61) for damping torque of a synchronous machine can be rewritten as

$$T_d = K\,B\,(x_q \tan \delta' - r) \qquad (62)$$

where $K$ is a positive constant including various constants of the machine.

Inspection of Equation (47) shows that the quantity $B$ can become negative in value with positive values of displacement angle $\delta'$ if the nominal voltage $e'_d$ is sufficiently small, *i. e.*, if the excitation is sufficiently reduced. However, under usual conditions of operation as a generator, the quantity $B$ is positive in value. Thus Equation (62) shows that a generator without amortisseur winding will be negatively damped and will oscillate at no load unless stabilized by positive damping external to the main-field winding. The relation that must exist in order for the machine to show inherent positive damping, *i. e.*, damping due to the main field winding, is

$$r < x_q \tan \delta' \qquad (63)$$

The critical value of resistance is $r = x_q \tan \delta'$; if the resistance is greater than this value, the inherent damping becomes negative in value.

The case is somewhat different for a synchronous motor. Inspection of Equation (47) shows that the constant $B$ may be positive or negative in value depending on the values of the armature resistance $r$, displacement angle $\delta'$, which is negative for a motor, and the amount of excitation, which determines $e_d'$. With negative values of $\delta'$, the quantity $(x_q \tan \delta' - r)$ is negative in value. Thus for a motor in which all damping is due to current induced in the main field winding, the damping will be positive or negative as determined by the value of $B$. If $B$ is negative, the damping is positive; if $B$ is positive, the damping is negative. Further inspection of Equation (47) shows that the character of the damping in a motor also depends on the armature resistance $r$; compare Fig. 6.

The difference between the action of positive and of negative damping should be clearly understood. The action of positive damping tends to reduce the magnitude of the oscillation. Cumulative hunting can occur with positive damping only when the power which sets up the oscillation is greater than the power dissipated as heat. But negative damping acts otherwise. If an oscillation is started, as by a change in load, for instance, it will be cumulative unless the action of the negative damping is neutralized by other sources of positive damping.

## Graphical Illustration of Results of Mathematical Analysis

Several curves have been determined by means of the preceding equations to show the effect that armature resistance has on damping torque of a synchronous machine which is connected to an infinite bus and carries a constant load. The machine constants were chosen for illustrative purposes alone, and do not represent an actual machine. The two curves in Fig. 3 show the variation of damping torque for a synchronous generator which has no amortisseur winding, when the armature resistance is varied from zero to 0.75, *i. e.*, to 75 per cent. The values in the per unit system[4] of the constants

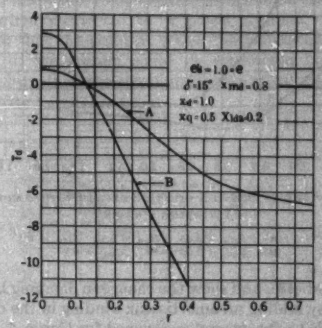


Fig. 3—Curves of Damping Torque as a Function of Armature Resistance—No Damping Winding

(A) Field resistance, $R_{dd}$, in armature terms = 0.05
(B) Field resistance = 0.01

which were used for the curves are $s = 0.02$, $e_d' = 1 = e$, $x_d = 1$, $x_q = 0.5$, $x_{md} = 0.8$, $X_{ldd} = 0.2$, $\delta' = 15$ deg. Curve $A$ is for a main field resistance of $R_{dd} = 0.05$ and Curve $B$ is for $R_{dd} = 0.01$. These curves are computed by means of Equations (61) and (47).

Since the damping for the conditions of Fig. 3 is caused by absorption of power in resistance loss due to current induced in the main field winding, it is to be expected that less resistance in the field circuit will give greater damping, as shown by the two curves. But until Equations (62) and (63) were derived, there had been no way of determining, so far as the authors know, that the damping of a salient-pole machine would become negative in value for an armature resistance greater than a certain critical value which the analysis shows to be $r = x_q \tan \delta'$. The value of main-field resistance is important in determining the amount of damping but does not determine whether it is positive or negative in value; this is determined by the value of the armature resistance.

The critical armature resistance for the constants assumed is $r = 0.134$, which is a much larger value than would be found in the windings of an armature, but is not an unusual value when the line back to the infinite bus is considered. Furthermore, Equation (63) shows that the critical value is increased proportionally to the increase in the tangent of the steady-load displacement angle. Thus a generator may hunt badly on light loads and yet run satisfactorily under larger loads.

The curves in Fig. 4 are based on Equations (56),

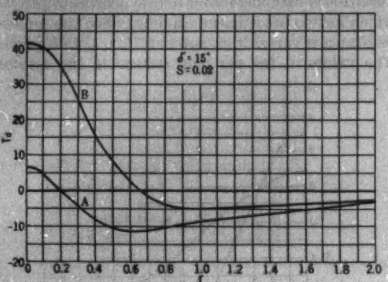


Fig. 4—Same as Curve *A* of Fig. 3 except with Amortisseur Winding Present

(A) $R_{de} = 0.05$, $R_{qe} = 0.1$, $X_{lqe} = 0.1$
(B) $R_{de} = 0.05 = R_{qe}$ $X_{lqe} = 0.2$

(47), and (48), and show the change in damping brought about by adding an amortisseur winding in the quadrature axis to the generator assumed for Curve *A*, Fig. 3. The constants of the damping winding for Curve *A*, Fig. 4, are $R_{qe} = 0.1$, $x_{mq} = 0.3$, and $X_{lqe} = 0.1$. For Curve *B* the quadrature damping winding is given the same constants as the main field circuit. The effect of the amortisseur winding is seen to be two fold; namely, to increase the amount of positive damping, and to increase the critical value of the armature resistance. But comparison of Fig. 4 with Fig. 3 shows that the general form of the damping torque-armature resistance characteristic has not been changed by the addition of the damping winding. Evidently, any synchronous generator can be made unstable by adding enough resistance to the armature circuits. Compare, Hunting of Round-Rotor Synchronous Machines.

Curve $T_d$ in Fig. 5 was computed for conditions and constants the same as for Curve *B*, Fig. 4, except that the excitation was removed, the field winding remaining short-circuited through the exciter. This curve is based on Equations (56), (47), and (48). The curve shows that there is no value of armature resistance which will cause hunting. This condition is easily understood, because the generator is operating essentially as an induction machine.

Fig. 6 is based on Equations (61) and (47), and shows the change in the values of damping torque and the constant *B* when the load, which is a function of $\delta'$, is varied from large positive values to zero, the generator range, and from zero to large negative values, the motor range. The five curves are based on armature resistance $r = 0$, $r = 0.05$, $r = 0.1$, $r = 0.2$, and $r = 0.4$. The other constants are the same as in Curve *A*, Fig. 3. The excitation is held constant at unit value, $e_d' = 1$.

These curves show that the damping torque passes through zero to negative values at $(x_q \tan \delta' - r) = 0$ in the generator range, and passes through zero to positive values when $B = 0$ in the motor range, as the displacement angle changes from large positive values through zero to large negative values. Compare Equation (62) for the relation between damping torque, the constant *B*, and the displacement angle $\delta'$. Under normal conditions of excitation the constant *B* is a positive quantity throughout the generator range of load; but passes from positive to negative values somewhere in the motor range of load. So long as *B* is a positive quantity, the damping of motor or generator has the sign of $(x_q \tan \delta' - r)$. Therefore, to obtain positive damping in a motor, where $\delta'$ is negative, *B* must be a negative quantity.

Fig. 7 is similar to Fig. 6 and is based on Equations (61) and (47); but the four curves are for different amounts of excitation; namely, $e_d' = 0.25$, $e'_d = 0.5$, $e_d' = 1$, and $e_d' = 1.5$. The armature resistance is $r = 0.1$ for all the curves. The other constants are the same as for Fig. 6. These curves bring out the fact that the general deductions as to damping based on Fig. 6 are

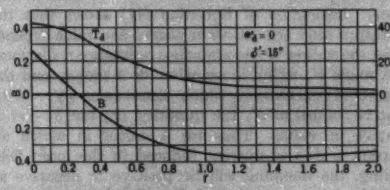


Fig. 5—Curves of Damping Torque and Factor *B* as Functions of Armature Resistance

Conditions same as for Curve *A*, Fig. 4, except that the excitation is zero and the field winding is short-circuited

independent of the value of the excitation in the range covered. Calculations show that the constant *B* can become negative in the generator range of load only for exceedingly low values of excitation.

## Damping at Zero Load

The design engineer is occasionally asked if an amortisseur winding will prevent some particular generator from hunting. The generator will probably have been in service for some years, and the instability develops when the machine is used under new

conditions. The new conditions may be brought about by connecting it to a power system through a transmission line. The problem is to determine whether an amortisseur winding can be added which can be guaranteed to make the machine run without hunting.

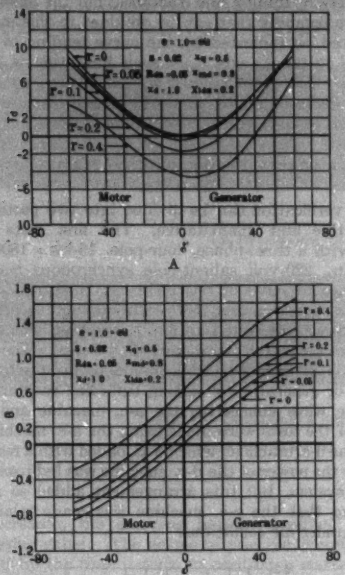


Fig. 6—Curves of Damping Torque and the Factor $B$ as Functions of Load Angle with Armature Resistance as a Parameter. Constant Excitation and No Amortisseur Winding

A study of Equation (56) shows that if the damping of a generator is positive at zero displacement angle, it will remain positive at all angles. Thus the problem can be reduced to adding an amortisseur winding which will eliminate hunting under no-load conditions. Equation (56), when used to determine the value of the damping torque at zero load, gives an indeterminate form which must be evaluated. Equations (56) for damping torque, $T_d$, (41) for cot $\alpha$, and (50) for the constant $D$, can be combined for the condition $e_d' = e$, *i. e.*, for normal excitation, to give a determinate result at no load.

The equation thus obtained is

$$T_d = -\frac{e^2}{s}\left[\frac{b\,r^2 - b^2\,d - d\,(x_d - a)^2}{[b(x_q - c) + d(x_d - a)]^2 + [b\,d - r^2 - (x_q - c)(x_d - a)]^2}\right] \tag{64}$$

This equation shows that the critical value of armature resistance for zero damping can be found by equating the numerator to zero; giving

$$r = \sqrt{b\,d + \frac{d}{b}\,(x_d - a)^2} \tag{65}$$

If the armature resistance is less than this critical value, the damping is positive. Thus the condition for no sustained or cumulative hunting is

$$r < \sqrt{b\,d + \frac{d}{b}\,(x_d - a)^2} \tag{66}$$

As an example of the use of Equation (64), an old three-phase salient-pole synchronous generator, rated at 312 kw. and 2300 volts, became unstable on fractional loads when connected to a power system. It was assumed that the point at which the generator is connected to the system could be considered to be an infinite bus; then the combined constants of alternator

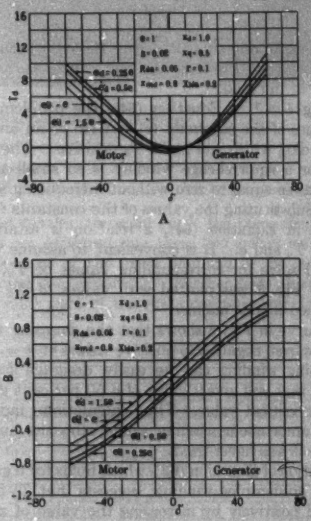


Fig. 7—Curves of Damping Torque and the Factor $B$ as Functions of Load Angle with Excitation as a Parameter. Constant Armature Resistance and No Amortisseur Winding

and connecting line were measured and found to have the following values, *viz.*,

| | |
|---|---|
| $x_d = 1.12$ | $a = 0.370$ |
| $x_q = 0.92$ | $b = 0.0256$ |
| $r = 0.73$ | $s = 0.04$ |

As the machine had no damping winding, Equation (62) could be used to determine whether the generator might be expected to operate without hunting. Substituting the values of the constants for the machine, Equation (62) shows that the machine has negative damping for all load angles below $\delta' = 38$ deg. A generator will have some positive damping due to losses in pole faces, etc.; but even with an allowance

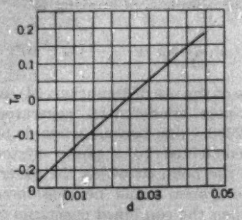


Fig. 8—Variation of Damping Torque with the Factor $d$ for Machine Rated

for this extra damping, it seems that the generator might be expected to hunt for loads up to perhaps 50 per cent of full load.

Setting $e = 1$ in Equation (64), the problem is to find values of the constants ($c$) and ($d$) of an amortisseur winding which will make $T_d$ positive. The value of ($c$) for a squirrel-cage winding is so small that it can be taken equal to zero without introducing serious error. Substituting the values of the constants for the machine in Equation (64), a relation is established between $T_d$ and $d$. It is convenient to assume values of $d$ and solve for corresponding values of $T_d$. The curve in Fig. 8 was plotted with values of $T_d$ and $d$ determined in this manner.

The curve in Fig. 8 shows that the damping torque $T_d$ passes from negative to positive values at $d = 0.024$. A damping winding can be easily designed for this machine that will give a value of $d$ 50 per cent greater than the critical value. Thus calculations indicated that an amortisseur winding would stop the hunting, although it was never tried.

Inspection of Equation (62), which holds for a generator with no damping winding, suggests that $T_d$ can be increased positively by increasing the value of $x_q$, the quadrature synchronous reactance of the generator. Inspection of Equation (64) suggests that an increase in $x_d$ and $x_q$ might increase $T_d$ positively in a generator with an amortisseur winding. These values cannot be changed after a generator is built, but reactance can be added in the line. The effect of adding line inductive reactance is to increase $x_d$ and $x_q$ by the same amount.

The curve in Fig. 9 shows the variation of damping torque $T_d$ of the generator for which an amortisseur winding was recommended when the line reactance is varied, if the machine is assumed to be equipped with an amortisseur winding which will make the damping torque zero, without the added line reactance. The curve is plotted between values of $T_d$ and equivalent $x_d$ of line and alternator for $e_d' = 1 = e$. The direct synchronous reactance of the machine is $x_d = 1.12$. The curve shows that the damping can be increased positively by adding line reactance; but the amount of positive damping that can be obtained in this manner is limited, as indicated by the curve tending to bend parallel to the $x_d$ axis. No such limitation is found to exist when an amortisseur winding is used, as shown by the curve in Fig. 8, where $T_d$ is seen to increase in direct proportion with the constant $d$ of the amortisseur winding.

## Experimental Verification of Mathematical Analysis

The verification can be divided into two parts, *viz.*, qualitative and quantitative. The first tests were made with a three-phase, four-pole, 15-kw., 1800-rev. per min., 220-volt salient-pole synchronous machine connected to a bus of relatively large power capacity. The machine was used both as motor and generator, being direct connected to a d-c. machine which was used as generator or motor, as needed. The synchronous machine could be made to hunt either as motor or generator by adding sufficient resistance in the line wires connecting the a-c. machine and bus. Most of the tests were made using the a-c. machine to drive the d-c. machine, which was loaded with a resistor. At first the power of the d-c. machine was fed back into a d-c. system, but this arrangement added so much damping that the a-c. machine was made relatively stable under all conditions.

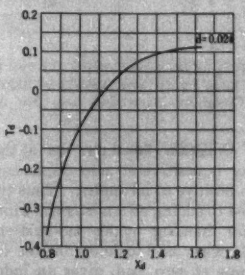


Fig. 9—Curve Showing Effect of Line Reactance on Damping Torque. Same Machine as for Fig. 8

A series of tests was run to show the effect of varying the excitation with a constant value of armature line resistance and with a constant input of 6 kw. to the synchronous motor. The line resistance was chosen of such value that one extreme of excitation gave high positive damping and the other extreme gave high negative damping. Hunting was determined by inspecting indicating instruments connected in the a-c. leads and by taking oscillograms of armature and field

currents. An excitation of 1.100, the per unit system, gave high negative damping; an excitation of 0.641 gave high positive damping. An excitation of 0.458 gave so high positive damping that an initial swing was damped out aperiodically. Critical excitation was 0.814. As the excitation was increased over this value, the damping became negative and of increasing value; as the load is increased, the value of excitation necessary to just make the machine stable also increases.

As a quantitative check, the critical excitation as the load is changed was determined by test and compared with values determined by substituting constants of the machine in equations developed by the mathematical analysis. The broken curve in Fig. 12 shows

Fig. 10—Oscillogram Showing Cumulative Hunting Produced by Introduction of Resistance in the Armature Lines of a Motor

Fig. 11—Oscillogram Showing Effect of Excitation upon Damping

Conditions the same as for Fig. 10 except that excitation was reduced from 1.1 to 0.733.

curve (a)—armature current
curve (b)—field current

as decreased, the damping became positive and of increasing value. The degree of positive damping was judged by the time it took an oscillation started by a definite impulse to die away, or to become of constant amplitude. The degree of negative damping was judged either by the amount of hunting developed, or by the time it took the machine to drop out of step, after the extra line resistance was connected into the circuit.

The oscillogram in Fig. 10 indicates the degree of cumulative hunting when the excitation was 1.1. The machine started hunting as the extra line resistance was connected into the circuit. The oscillogram in Fig. 11 for an excitation of 0.733 shows positive damping; but the damping is small enough so that there is practically sustained hunting.

Further tests showed that the value of excitation which would just make the motor stable for a constant value of line resistance increased as the load was increased. That tests would show these results could be anticipated from the mathematical analysis of damping torque. In Fig. 7A, where load can be assumed proportional to displacement angle $\delta'$, since the curves are for a salient-pole machine, the curves for negative values of $\delta'$, the motor range, show that with a constant load damping increases positively with a decrease in excitation. And furthermore, these curves show that the test results; the solid curve the theoretical results. It was not expected that these two curves would coincide because of the extra damping in the motor and connected d-c. generator. Further tests showed that the greater part of the extra damping was due to the

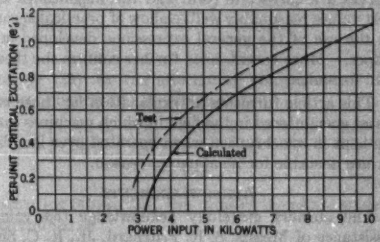


Fig. 12—Test and Calculated Curves of Excitation, for Zero Damping, as a Function of Power Input. Armature Resistance Constant

d-c. generator and did not vary with load. The amount of this constant extra damping was not determined; but inspection of Fig. 12 shows that if the whole calculated curve, the solid curve, is moved up on the sheet by a constant amount, the two curves can be made to come

into fairly close agreement. That extra damping will raise the solid curve in Fig. 12 is seen to be true by inspection of Fig. 7A, which shows that if the damping torque $T_d$ is increased by a constant amount, higher excitation will be needed to produce a given amount of negative damping for a constant load.

A further quantitative check will be found under Hunting of Round-Rotor Synchronous Machines.

### Hunting of Round-Rotor Synchronous Machines

The mathematical analysis, with $x_d = x_q$, indicates that a round-rotor synchronous machine can be made unstable by increasing the armature resistance. For a round-rotor machine symmetrical with respect to both axes, Equation (66) becomes,

$$r < \sqrt{b^2 + (x_d - a)^2} \tag{67}$$

since $b = d$. To show by test that such a machine can be made unstable by adding line resistance, a 20-hp. induction motor, with wound rotor as well as wound stator, was run as a synchronous motor. The rotor was wound two-phase, and d-c. excitation was supplied to both phases of the rotor from a storage battery. This machine with not too high excitation was very stable with minimum resistance between stator and a-c. bus; but it could be made very unstable without changing the excitation by increasing the a-c. line resistance sufficiently. Using adjustable resistors in the line, the degree of stability or instability was under complete control. With sufficient line resistance, the machine was so unstable that it could not be kept on the line.

### Summary

The results given in the paper show that the calculated curves of negative damping under various conditions of loading, excitation, etc., are in essential agreement with results obtained from test. The calculated curves are correct in form and the magnitudes check test values reasonably well to allow of practical accuracy in the use of the general expressions developed in the paper. More recent tests further confirm the theoretical formulas.

This article furnishes an explanation for those many cases encountered in the field in which machines cannot be kept in synchronism when operated over long lines, or are unstable for no apparent reason.

### Acknowledgments

The authors gratefully acknowledge the valuable assistance of Messrs. S. R. Pritchard, Jr., R. C. Small, and S. A. Loukomsky in the preparation of experimental data on the salient pole machine. They also wish to acknowledge the helpful suggestions of Messrs. R. E. Doherty and R. H. Park.

## Appendix I

## MATHEMATICAL ANALYSIS

### Determination of the Phase Angle $\alpha$

The mathematical analysis which follows is divided into two parts. The value of the phase angle $\alpha$, which is the angle between the currents induced in the rotor windings in the direct and quadrature axes by the modulated armature current, will be derived first. Then the values of the damping and synchronizing components of torque will be determined.

Referring to Fig. 2, which shows the peak values of armature voltage and current for a salient-pole synchronous generator with no excitation in the quadrature axis, it is seen that the nominal voltages are

$$e_d = e \cos \delta + i_q r + i_d x_d \tag{6}$$

and,

$$e_q = i_q x_q - e \sin \delta - i_d r = 0 \tag{7}$$

where $r$ is armature resistance, $x_d$ and $x_q$ are the direct and quadrature synchronous reactances, and $e$ is terminal voltage.

Since the modulation is assumed to be slow enough so that the voltage and current are accurately represented at each instant by vectors, as in Fig. 2, Equations (1), (2), (3), and (5) may be substituted in (6) giving

$$e \cos \delta' \cos [\Delta \delta] - e \sin \delta' \sin [\Delta \delta]$$
$$= e_d' + [\Delta e_d] - i_q' r - [\Delta i_q] r - i_d' x_d - [\Delta i_d] x_d \tag{8}$$

If the alternating component of the displacement angle is assumed to be small, meaning that the rotor hunts through a small angle, then at any instant

$$\cos [\Delta \delta] = 1 \tag{9}$$

and

$$\sin [\Delta \delta] = [\Delta \delta] \tag{10}$$

Substituting (9) and (10) in (8) and solving, the alternating component of the torque angle is

$$[\Delta \delta] = \frac{e \cos \delta' - e_d' + i_q' r + i_d' x_d - [\Delta e_d] + [\Delta i_q] r + [\Delta i_d] x_d}{e \sin \delta'} \tag{11}$$

The vector diagram in Fig. 2 shows that

$$e \cos \delta' - e_d' + i_q' r + i_d' x_d = 0 \tag{12}$$

whence (11) reduces to

$$[\Delta \delta] = \frac{[\Delta i_q] r + [\Delta i_d] x_d - [\Delta e_d]}{e \sin \delta'} \tag{13}$$

Substituting the values given in (1), (2), (4), and (5) in (7),

$$e \sin \delta' \cos [\Delta \delta] + e \cos \delta' \sin \Delta \delta$$
$$= i_q' x_q + [\Delta i_q] x_q - i_d' r - [\Delta i_d] r - [\Delta e_q] \tag{14}$$

Substituting (9) and (10) in (14) and solving for the modulating angle,

$$[\Delta \delta] = \frac{i_q' x_q - i_d' r - e \sin \delta' + [i_q] x_q - [\Delta i_d] r - [\Delta e_q]}{e \cos \delta'} \tag{15}$$

The vector diagram in Fig. 2 shows that

$$i_q' x_q - i_d' r - e \sin \delta' = 0 \tag{16}$$

whence (15) reduces to

$$[\Delta \delta] = \frac{[\Delta i_q] x_q - [\Delta i_d] r - [\Delta e_q]}{e \cos \delta'} \tag{17}$$

The modulating components of the direct component of current $i_d$ and the quadrature component $i_q$, from (1) and (2), are

$$[\Delta i_d] = \Delta i_d \cos s t \tag{18}$$

and

$$[\Delta i_q] = \Delta i_q \cos (s t + \alpha) \tag{19}$$

Changing from instantaneous to vector notation, and choosing $[\Delta i_d]$ as the reference vector, (18) and (19) become

$$\Delta \dot{i}_d = \Delta i_d < 0 = \Delta i_d \tag{20}$$

and,

$$\Delta \dot{i}_q = \Delta i_q < \alpha = \Delta i_q (\cos \alpha + j \sin \alpha) \tag{21}$$

These modulating components of current flow in the armature windings and induce alternating components of current $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$, in the two field windings. It has been shown[1b] that

$$\Delta \dot{I}_d = \Delta \dot{i}_d (a + j b) = \Delta i_d (a + j b) \tag{22}$$

and

$$\Delta \dot{I}_q = \Delta \dot{i}_q (c + j d) \tag{23}$$

where the values of the constants are

$$a = \frac{s^2 x_{md}^2 (x_{md} + X_{1da})}{R_{da}^2 + s^2 (x_{md} + X_{1da})^2} = \frac{(x_d - x_d') s^2 T_{do}^2}{1 + s^2 T_{do}^2} \tag{24}$$

$$b = \frac{s x_{md}^2 R_{do}}{R_{da}^2 + s^2 (x_{md} + X_{1da})^2} = \frac{(x_d - x_d') s T_{do}}{1 + s^2 T_{do}^2} \tag{25}$$

$$c = \frac{s^2 x_{mq}^2 (x_{mq} + X_{1qa})}{R_{qa}^2 + s^2 (x_{mq} + X_{1qa})^2} = \frac{(x_q - x_q') s^2 T_{qo}^2}{1 + s^2 T_{qo}^2} \tag{26}$$

$$d = \frac{s x_{mq}^2 R_{qa}}{R_{qa}^2 + s^2 (x_{mq} + X_{1qa})^2} = \frac{(x_q - x_q') s T_{qo}}{1 + s^2 T_{qo}^2} \tag{27}$$

$$\frac{x_{md} + X_{1da}}{R_{da}} = T_{do} \text{ and } x_{md}^2 = (x_{md} + X_{1da})(x_d - x_d')$$

In these equations $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$ are the alternating currents in the two field windings, $x_{md}$ and $x_{mq}$ are the mutual reactances between the armature winding and the two field windings, $X_{1da}$ and $X_{1qa}$ are the leakage reactances of the two field windings in armature terms, and $R_{da}$ and $R_{qa}$ are the resistances of the two field windings in armature terms, $R_{da}$ including the resistance of the armature circuit of the exciter.

The modulating components of field current, $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$, induce modulating components of nominal voltage, $\Delta \dot{e}_d$ and $\Delta \dot{e}_q$, therein. Using per unit quantities,

$$\Delta \dot{e}_d = \Delta \dot{I}_d \tag{28}$$

and

$$\Delta \dot{e}_q = \Delta \dot{I}_q \tag{29}$$

Substituting these values of $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$ in (22) and (23),

$$\Delta \dot{e}_d = \Delta \dot{i}_d (a + j b) \tag{30}$$

and

$$\Delta \dot{e}_q = \Delta \dot{i}_q (c + j d) \tag{31}$$

Substituting (20) in (30) and (21) in (31),

$$\Delta \dot{e}_d = \Delta i_d (a + j b) \tag{32}$$

$$\Delta \dot{e}_q = \Delta i_q (c + j d) (\cos \alpha + j \sin \alpha)$$

$$= \Delta i_q [c \cos \alpha - d \sin \alpha + j (c \sin \alpha + d \cos \alpha)] \tag{33}$$

These equations determine the values of the modulated nominal voltages in the direct and quadrature axes in terms of the corresponding modulating components of current.

Writing (13) in vector notation, the value of the alternating component of the torque angle is

$$\Delta \dot{\delta} = \frac{\Delta \dot{i}_q r + \Delta \dot{i}_d x_d - \Delta \dot{e}_d}{e \sin \delta'} \tag{34}$$

Substituting (20), (21), and (32) in (34),

$$\Delta \dot{\delta} = \frac{\Delta i_q r \cos \alpha + \Delta i_d x_d - \Delta i_d a + j(\Delta i_q r \sin \alpha - \Delta i_d b)}{e \sin \delta'} \tag{35}$$

Changing (17) to vector notation,

$$\Delta \dot{\delta} = \frac{\Delta \dot{i}_q x_q - \Delta \dot{i}_d r - \Delta \dot{e}_q}{e \cos \delta'} \tag{36}$$

Substituting (20), (21), and (33) in (36),

$$\Delta \dot{\delta} = \frac{\Delta i_q x_q \cos \alpha - \Delta i_d r - \Delta i_q (c \cos \alpha - d \sin \alpha)}{e \cos \delta'}$$

$$+ j \frac{\Delta i_q x_q \sin \alpha - \Delta i_q (c \sin \alpha + d \cos \alpha)}{e \cos \delta'} \tag{37}$$

Equations (35) and (37) give two relations for $\Delta \dot{\delta}$. Equating the real terms in the two equations,

$$\frac{\Delta i_q r \cos \alpha + \Delta i_d x_d - \Delta i_d a}{e \sin \delta'}$$

$$= \frac{\Delta i_q [(x_q - c) \cos \alpha + d \sin \alpha] - \Delta i_d r}{e \cos \delta'} \tag{38}$$

and equating the imaginary terms in the same two equations,

$$\frac{\Delta i_q r \sin \alpha - \Delta i_d b}{e \sin \delta'} = \frac{\Delta i_q [(x_q - c) \sin \alpha - d \cos \alpha]}{e \cos \delta'} \tag{39}$$

Solving (39) for the alternating component of the armature current in the direct axis,

$$\Delta i_d = \Delta i_q \left[ \frac{r \sin \alpha}{b} - \frac{\{(x_q - c) \sin \alpha - d \cos \alpha\} \tan \delta'}{b} \right] \tag{40}$$

Substituting (40) in (38), the value of the phase angle $\alpha$ is determined as

$$\cot \alpha =$$

$$\frac{[b d - r^2 + (x_d - a)(x_q - c)] \tan \delta' - r(x_d - a) + r(x_q - c) \tan^2 \delta'}{[d (x_d - a) - b (x_q - c)] \tan \delta' + b r + d r \tan^2 \delta'} \tag{41}$$

## Determination of Damping and Synchronizing Torques

Equations for the electrical output and armature copper loss of a synchronous machine connected to an

infinite bus have been previously developed.[1a] Since in the per unit system of units torque and power are numerically equal, if the angular velocity of rotation is substantially constant at normal value, these equations can be used to determine torque. Letting $T$ represent the torque due to the combined electrical output and copper loss in the machine,

$$T = \frac{(e\,e_d\,e_q - e\,e_q\,r)\sin\delta + (e\,e_d\,r + e\,e_q\,x_d)\cos\delta + \frac{e^2}{2}(x_d - x_q)\sin 2\delta - e^2\,r}{r^2 + x_d\,x_q}$$

$$+ \frac{r(r^2+x_q^2)(e_d - e\cos\delta)^2 + r(r^2+x_d^2)(e_q + e\sin\delta)^2}{(r^2 + x_d\,x_q)^2}$$

$$+ \frac{2\,r^2\,(x_d - x_q)\,(e_d - e\cos\delta)\,(e_q + e\sin\delta)}{(r^2 + x_d\,x_q)^2} \qquad (42)$$

where the term with $r^2 + x_d\,x_q$ in the denominator is the torque corresponding to the electrical output, and the other terms give the torque corresponding to copper loss in the armature.

The modulation of angular velocity of the machine causes a modulation $[\Delta\,T]$ of the steady-value torque $T'$, so that the torque at any instant is

$$T = T' + [\Delta\,T] \qquad (43)$$

The value of $T$ may be found by substituting (3), (4), and (5) in (42) and then placing $\cos[\Delta\,\delta] = 1$ and $\sin\,[\Delta\,\delta] = [\Delta\,\delta]$, which means that the machine is assumed to hunt through a small angle only. Making the substitutions indicated, neglecting all products such as $[\Delta\,e_d] \times [\Delta\,\delta]$, because they are infinitesimals of second order, the remaining terms may be grouped to give $T'$ and $[\Delta\,T]$. The value of the alternating component of torque is

$$[\Delta\,T] = \frac{e\,e_d'\,x_q[\Delta\,\delta]\cos\delta' + e\,x_q[\Delta\,e_d]\sin\delta' - e\,r[\Delta\,e_q]\sin\delta'}{r^2 + x_d\,x_q}$$

$$+ \frac{e\,e_d'\,r\,[\Delta\,\delta]\sin\delta' + e\,r\,[\Delta\,e_d]\cos\delta' + e\,x_d\,[\Delta\,e_q]\cos\delta'}{r^2 + x_d\,x_q}$$

$$+ \frac{e^2\,(x_d - x_q)\,[\Delta\,\delta]\cos 2\,\delta'}{r^2 + x_d\,x_q}$$

$$+ \frac{r\,(r^2 + x_q^2)\,[[\Delta\,e_d]\,(2\,e_d' - 2\,e\cos\delta') + [\Delta\,\delta](2\,e\,e_d'\sin\delta' - 2\,e^2\sin\delta'\cos\delta')]}{(r^2 + x_d\,x_q)^2}$$

$$+ \frac{r\,(r^2 + x_d^2)\,[2\,[\Delta\,e_q]\,e\sin\delta' + 2\,e^2\,[\Delta\,\delta]\sin\delta'\cos\delta']}{(r^2 + x_d\,x_q)^2}$$

$$+ \frac{2\,r^2\,(x_d - x_q)\,[[\Delta\,e_q]\,(e_d' - e\cos\delta') + [\Delta\,e_d]\,e\sin\delta' + [\Delta\,\delta]\,(e^2\sin^2\delta' - e^2\cos^2\delta' + e\,e_d'\cos\delta')]}{(r^2 + x_d\,x_q)^2} \qquad (44)$$

Changing the quantities $[\Delta\,T]$, $[\Delta\,\delta]$, $[\Delta\,e_d]$, and $[\Delta\,e_q]$ to vector notation and collecting terms, (44) becomes

$$\Delta\,T = A\,\Delta\,\delta + B\,\Delta\,e_d + C\,\Delta\,e_q \qquad (45)$$

where the constants $A$, $B$, and $C$ have the following values:

$$A = \frac{e\,e_d'\,(x_q\cos\delta' - r\sin\delta') + e^2\,(x_d - x_q)\cos 2\,\delta'}{r^2 + x_d\,x_q}$$

$$+ \frac{2\,r\,(r^2 + x_q^2)\,(e\,e_d'\sin\delta' - e^2\sin\delta'\cos\delta') + 2\,r\,(r^2 + x_d^2)\,e^2\sin\delta'\cos\delta'}{(r^2 + x_d\,x_q)^2}$$

$$+ \frac{2\,r^2\,(x_d - x_q)\,(e^2\sin^2\delta' - e^2\cos^2\delta' + e\,e_d'\cos\delta')}{(r^2 + x_d\,x_q)^2} \qquad (46)$$

$$B = \frac{e\,(x_q\sin\delta' + r\cos\delta')}{r^2 + x_d\,x_q} + \frac{2\,r(r^2+x_q^2)(e_d' - e\cos\delta') + 2\,r^2(x_d - x_q)\,e\sin\delta'}{(r^2 + x_d\,x_q)^2} \qquad (47)$$

$$C = \frac{e\,(x_d\cos\delta' - r\sin\delta')}{r^2 + x_d\,x_q} + \frac{2\,r(r^2+x_d^2)\,e\sin\delta' + 2\,r^2(x_d - x_q)(e_d' - e\cos\delta')}{(r^2 + x_d\,x_q)^2} \qquad (48)$$

A physical meaning can be ascribed to the constants $A$, $B$, and $C$ if they are derived directly by differentiation. The complete differential of $T$ in (42) is,

$$d\,T = \frac{\partial\,T}{\partial\,\delta}\,d\,\delta + \frac{\partial\,T}{\partial\,e_d}\,d\,e_d + \frac{\partial\,T}{\partial\,e_q}\,d\,e_q$$

$$= A\,d\,\delta + B\,d\,e_d + C\,d\,e_q$$

which can be written

$$d\,T = A\,\Delta\,\delta + B\,\Delta\,e_d + C\,\Delta\,e_q$$

to correspond to the form used in Equation (45). Thus the constant $A$ is equal to the variation in the torque $T$ when the angle $\delta$ is varied and the voltages $e_d$ and $e_q$ are held constant. Similar meanings can be ascribed to the constants $B$ and $C$.

Equation (40) can be written in the form,

$$\Delta\,i_d = D\,\Delta\,i_q \qquad (49)$$

where the constant $D$ has the value

$$D = \frac{r\sin\alpha}{b} - \frac{[(x_q - c)\sin\alpha - d\cos\alpha]\tan\delta'}{b} \qquad (50)$$

Substituting (49) in (30),

$$\Delta\,e_d = D\,\Delta\,i_q\,(a + j\,b) \qquad (51)$$

Substituting (49) in (35),

$$\Delta\,\delta = \Delta\,i_q\left[\frac{r\cos\alpha + D\,(x_d - a) + j\,(r\sin\alpha - b\,D)}{e\sin\delta'}\right] \qquad (52)$$

Substituting (51), (33), and (52), in (45), the value of the alternating component of the torque is

$$\Delta T = A\,\Delta i_q\left[\frac{r\cos\alpha + D(x_d - a) + j(r\sin\alpha - b\,D)}{e\sin\delta'}\right]$$

$$+ B\,D\,\Delta i_q\,(a + j\,b)$$

$$+ C\,\Delta i_q\,[(c\cos\alpha - d\sin\alpha) + j\,(c\sin\alpha + d\cos\alpha)]$$

$$= \frac{A\,\Delta i_q\,[r\cos\alpha + D\,(x_d - a)]}{e\sin\delta'}$$

$$+ B\,D\,a\,\Delta i_q + C\,\Delta i_q\,(c\cos\alpha - d\sin\alpha)$$

$$+ j\left[\frac{A\,\Delta i_q\,[r\sin\alpha - b\,D]}{e\sin\delta'}\right.$$

$$\left. + B\,D\,b\,\Delta i_q + C\,\Delta i_q\,(c\sin\alpha + d\cos\alpha)\right] \quad (53)$$

The damping and synchronizing components of torque may be determined from the electromagnetic motional impedance[1b] of the generator to hunting. The real part of the vector expression for motional impedance is equal to the damping torque $T_d$, and the imaginary part is equal to $-\frac{T_s}{s}$ where $T_s$ is the synchronizing torque. The motional impedance $Z_m$ can be found by dividing the alternating component of torque $\Delta T$ by the corresponding angular velocity $\omega_1$ of hunting. The angular velocity can be found as the time rate of change of the alternating component, $\Delta\delta$, of displacement angle. Thus differentiating (52) with respect to time,

$$\omega_1 = \frac{d}{dt}\,\Delta\delta$$

$$= -\,s\,\Delta i_q\left[\frac{(r\sin\alpha - b\,D) - j\,[r\cos\alpha + D\,(x_d - a)]}{e\sin\delta'}\right] \quad (54)$$

The motional impedance is, then,

$$Z_m = \frac{\Delta T}{\omega_1} = T_d - j\,\frac{T_s}{s} \quad (55)$$

Now dividing (53) by (54), the damping torque is

$$T_d = \frac{B\,D\,e\sin\delta'\,[D\,b\,x_d + r\,(b\cos\alpha - a\sin\alpha)]}{s\,[(r\sin\alpha - b\,D)^2 + \{r\cos\alpha + D(x_d - a)\}^2]}$$

$$+ \frac{C\,e\sin\delta'\,[D\,b\,(c\cos\alpha - d\sin\alpha) + D\,(x_d - a)\,(c\sin\alpha + d\cos\alpha) + r\,d]}{s[(r\sin\alpha - b\,D)^2 + \{r\cos\alpha + D(x_d - a)\}^2]} \quad (56)$$

and the synchronizing torque is

$$T_s = T_s'$$

$$+ \frac{B\,D\,e\sin\delta'[D\{a(x_d - a) - b^2\} + r(a\cos\alpha + b\sin\alpha)]}{(r\sin\alpha - b\,D)^2 + \{r\cos\alpha + D(x_d - a)\}^2}$$

$$+ \frac{C\,e\sin\delta'\,[D\,\{c\,(x_d - a) - b\,d\}\cos\alpha - D\,\{d\,(x_d - a) + b\,c\}\sin\alpha + r\,c]}{(r\sin\alpha - b\,D)^2 + \{r\cos\alpha + D\,(x_d - a)\}^2} \quad (57)$$

where $T_s'$ is equal to the synchronizing torque at the average displacement angle $\delta'$ due to steady-state conditions. It is interesting to note that the synchronizing torque of a machine in a sustained state of oscillation is equal to the value for zero frequency of oscillation, *i. e.*, steady-state value, plus an increment which is a function of the actual frequency of oscillation. Equation (56) gives the value of the damping torque of a polyphase synchronous machine which is connected to a bus with large enough power capacity to maintain the bus voltage constant when the machine hunts. The damping is assumed to be due entirely to currents induced in the main field winding in the direct axis and in the amortisseur winding in the quadrature axis by the modulated armature currents.

## Nomenclature

Peak values are used for voltage and current. Primed quantities indicate steady-state values. The symbol $\Delta$ indicates variation of the quantity which follows the symbol. Per unit values are used for all equations and numerical work.

$e$ = terminal voltage.
$e_d$ = nominal voltage due to excitation in the direct axis.
$e_q$ = nominal voltage due to excitation in the quadrature axis.
$i$ = armature current.
$i_d$ = direct component of armature current.
$i_q$ = quadrature component of armature current.
$I_d$ = field current, direct axis, in field terms.
$I_q$ = field current, quadrature axis, in field terms.
$t$ = time.
$s$ = angular velocity of modulation.
$\omega_1$ = angular velocity hunting.
$\omega$ = angular velocity at line frequency.
$r$ = armature circuit resistance; includes resistance of line wire, back to the infinite bus.
$R_{dm}$ = field resistance, direct axis, in armature terms.
$R_{qm}$ = field resistance, quadrature axis, in armature terms.
$x_d$ = synchronous reactance, direct axis includes reactance of line wire back to the infinite bus.
$x_q$ = synchronous reactance, quadrature axis; includes reactance of line wire back to the infinite bus.
$x_{md}$ = mutual reactance, direct axis.
$x_{mq}$ = mutual reactance, quadrature axis.
$X_{ldm}$ = field leakage reactance, direct axis, in armature terms.
$X_{lqm}$ = field leakage reactance, quadrature axis, in armature terms.
$T$ = torque.
$T_d$ = damping torque.

$T_s$ = synchronizing torque.

$\alpha$ = time phase displacement between direct and quadrature components of modulated armature current.

$\delta$ = angular displacement between the axes of rotor and rotating magnetic field; a plus angle indicates generator; a negative angle indicates motor.

$Z_m$ = electromagnetic motional impedance.

$a$ = see Formula 24.

$b$ = see Formula 25.

$c$ = see Formula 26.

$d$ = see Formula 27.

$A = \dfrac{\partial T}{\partial \delta}$, if $e_d$ and $e_q$ are held constant.

$B = \dfrac{\partial T}{\partial e_d}$, if $\delta$ and $e_q$ are held constant.

$C = \dfrac{\partial T}{\partial e_q}$, if $\delta$ and $e_d$ are held constant.

$D = \Delta i_d / \Delta i_q$.

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4. See 1a, 1b, 1c. Also Park and Robertson, *The Reactances of Synchronous Machines*, A. I. E. E. Quarterly Trans., Vol. 47, April 1928, p. 514.


## Discussion

**C. F. Wagner:** (communicated after adjournment) From time to time an occasional case of spontaneous hunting arises, the cause of which can be traced to an excessive proportion of resistance in the armature circuit, *viz.*, in the transmission line. This phenomenon was particularly evident in the early days of rotary converters. A rough working rule in use at that time was to limit the line resistance to 25 per cent of the reactance. As has been pointed out by the authors, Dreyfus[1] in 1911 showed that the tendency toward hunting decreased with increasing load and with smaller excitation and that the presence of damper windings alleviated this condition. Tests were made on an induction motor to check his theory. In 1924, reporting stability tests made in the works of the Westinghouse Company, Evans and Bergvall[2] likewise demonstrated this same effect using salient-pole generators and condensers. More recently Wennerberg[3] analyzed the same problem as applied to salient pole machines, extending it to include the effect of exciters. Nickle and Pierce in the paper under discussion attack the problem in a somewhat different manner and arrive at some very interesting and simple results. I have also done some work recently of a similar nature and with a somewhat different method of attack which I believe possesses the advantage of a clearer conception of the mechanism involved.

To illustrate the method I shall merely apply the analysis in a qualitative manner to a salient-pole generator without damper windings connected to an infinite bus through a transmission line whose resistance will be varied. Constant excitation of the generator will be assumed. The transient analysis of synchronous machines may be expedited by the use of the so-called "transient reactance" ($x_d'$) and the "transient internal voltage" ($e_d'$), which will be defined as the terminal voltage plus the transient reactance drop at zero power factor. For any other power factor the components in the direct axis must be used. This is the fictitious voltage corresponding to flux linkages with the field, and which remains unchanged for any sudden change in circuit condition. The voltage $e_d$ will be defined in a similar manner except that the synchronous reactance $x_d$ must be used. For steady-state conditions

$$e_d' = e_d - (x_d - x_d')\, i_d$$

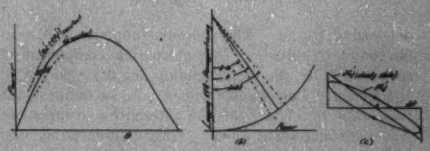


Fig. 1—Pure Line Resistance

in which $i_d$ is the component of armature current in lagging quadrature with $e_d$ and $e_d'$, *i. e.*, it is the demagnetizing component of current.

Consider first the line without resistance. For a given value of $e_d'$ the power-angle curve is somewhat as shown in Fig. 1a herewith. For small positive increments in $e_d'$ the resultant curve will, for nearly all practical cases, lie above the one for $e_d'$. Now assume the generator to be operating at the angle $\theta$, and that the power input from the water wheel is such as to produce a small sinusoidal oscillation of magnitude $\Delta\theta_m$ and frequency $f$. The power-reactive power diagram (similar to the well known power-circle diagram except for effects of saliency) for constant $e_d$ is shown in Fig. 1b and it will be observed that for positive increments in $\theta$ the demagnetizing current, $i_d$, increases so that the steady-state value of $e_d'$ decreases. This relation is shown by the straight line in Fig. 1c which indicates that for positive values of $\Delta\theta$, $\Delta e_d'$ (*steady state*) is negative. If the frequency of oscillation were very slow these are the values which $\Delta e_d'$ would attain. However, in the actual case, due to the time constant of the field circuit, the instantaneous value of $\Delta e_d'$ lags, forming the elliptical loop shown in Fig. 1c. It can further be seen that the motion around the loop is clockwise. Having obtained the instantaneous values of

1. See bibliography (2) of paper.

2. *Experimental Analysis of Stability and Power Limitations*, by R. D. Evans and R. C. Bergvall, A. I. E. E. Trans., Vol. XLIII, 1924, p. 39.

3. "Hunting Characteristics of Synchronous Machines for Oscillations of Small Amplitude," by John Wennerberg. *A. S. E. A. Jl.*, April-May, 1920.

$\Delta e_d'$ as a function of the angle, the instantaneous power-angle relations may be obtained, resulting in the power loop indicated in Fig. 1a, the generating point of which also rotates clockwise around the loop. It can be shown that the area of this loop represents the energy per cycle which must be supplied by the variations in generator input to sustain such oscillations or the energy per cycle which would be absorbed in damping out the oscillations were they once started. It represents a stable operating condition.

Now if the resistance be placed in the line, the power-angle diagram will have the same general shape but the power-reactive power diagram is changed radically as shown in Fig. 2b herewith. It will be observed that for the particular operating angle shown, a positive increment in $\theta$ decreases the demagnetizing effect, so that the steady state value of $\Delta e_d'$, the value which $\Delta e_d'$ tends to approach, increases with $\Delta \theta$. The lag due to the time constant now produces a loop in which the generating point rotates counter-clockwise, resulting in a power loop in which the generating point also rotates counter-clockwise. The area of the power loop now represents the energy per cycle input into the vibrating system and represents an unstable condition. The slightest disturbance results in a condition of "hunting."

As the operating angle, about which the oscillations occur, is increased, a point is reached when no change in demagnetizing current occurs for small changes in $\theta$ and beyond this point the conditions are the same as for the case in which the resistance in the armature is zero, that is, the operation is again stable.

**C. A. Nickle:** The explanation of negative damping of synchronous machines given by Mr. Wagner in his discussion is interesting and is essentially the same as expressed by the author during the presentation of the paper, *i. e.*, the demagnetizing

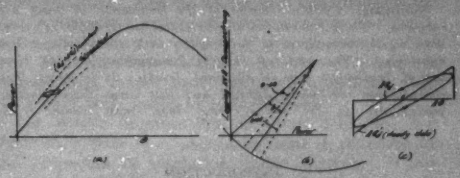


FIG. 2—LINE WITH RESISTANCE

current for a small angular oscillation changes sign for some average operating angle.

As brought out at that time, this change of sign is independent of the frequency of the oscillation. The magnitude of the damping factor does, however, depend upon the frequency of oscillation.

# Ionization Currents and the Breakdown of Insulation

BY J. J. TOROK* and F. D. FIELDER*
Associate, A. I. E. E. Associate, A. I. E. E.

***Synopsis.***—*Certain theories of the breakdown of gases are reviewed. Their limitations or correctness in the light of recent data on the breakdown of large gaps with surge voltages are considered. The work of various investigators on the time lag of breakdown also is discussed briefly. It is shown that comparisons are made difficult and that large discrepancies, particularly at the shorter time lags, may result from variations in the definitions of time lag and breakdown time.*

*The existence of ionization or streamer currents of high magnitude previous to the final breakdown is established and a number of volt—time and ampere—time oscillograms of flashovers on various types of insulation is shown and discussed. The effect of these streamer currents in attenuating a traveling chopped wave is shown.*

* * * * *

## Introduction

ONE of the most perplexing engineering problems is the application of insulation. Continually increasing voltages and higher temperatures, together with economic requirements, have necessitated extensive development and research programs for the study of the properties of insulating materials. However, in spite of much study and ceaseless effort, no exact indisputable laws for the performance of insulation have been discovered. Empirical equations concerning particular applications have been formulated from years of experience, and it is upon these that the designer must rely. A more exact knowledge of the process of breakdown is of prime importance, since other properties of various types of insulation then could be established more readily and applied more effectively.

The dielectric strength of important types of insulation, especially air, has been determined accurately for unidirectional and for low-frequency potentials. However, these determinations have proved insufficient, since transients have caused failure in apparatus even with excessive insulation for its voltage rating. Investigators, who have used voltage impulses of extremely short duration, have shown that breakdown depends upon the rate of voltage application, the magnitude of the voltage, and the duration of the transient. Although these results have been very valuable, it was soon found that there were other considerations involved in the process of breakdown, which, if known, might aid materially in the application of insulation.

Much of the work on the breakdown of air has been done on small sphere-gaps at small spacings. From a practical and engineering standpoint it is necessary to supplement this work with experiments on apparatus where the gaps are long and irregular, with all shapes of electrodes. Entirely different breakdown characteristics may be expected with such differences in the nature of the gaps and electrodes, with the consequent change of dielectric field. In this paper a brief résumé of some of the previous theoretical work will be followed by a discussion of experimental results obtained on commercial apparatus. A new factor in the study of breakdown, heretofore used to a limited extent in the laboratory, will be introduced. The consideration of ionization or streamer currents already has proved valuable in the study of the effect of transients upon insulation.

## Theories of the Breakdown of Air

The first theory to give a satisfactory explanation of the electrical breakdown of air was advanced by Townsend.[1] Briefly this theory may be summarized as follows: Upon the application of sufficient voltage, the free electrons in the field move toward the anode and are swept out of the field. During this movement they collide with the molecules of the gas and produce new ions by collision. The newly created positive ions move toward the cathode, creating more new ions by collision, although the rate of ionization is much less than for the electrons. If the positive ions in their movement toward the cathode produce more electrons than were in the field originally, the discharge will become unstable; that is, the current will continue to increase as long as a constant impressed voltage is maintained.

Two important conclusions may be drawn from this theory. First, breakdown takes place throughout the whole field simultaneously; second, the time of breakdown cannot be any shorter than that required for the movement of an electron from one electrode to the other and for the return movement of the positive ion. Townsend's theory, although checked and proved experimentally at low pressures, appears inadequate at atmospheric pressures. Rogowski[2] has shown that the ionization process according to Townsend's theory requires a time of the order of $10^{-6}$ sec., whereas experimenters,[3,4] agree that with slight overvoltages the spark lag may be as short as $10^{-9}$ sec. Suppressed discharges[5] show that breakdown does not take place simultaneously throughout the whole field. Actually,

*Both of Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., December 2-4, 1929.*

1. See Bibliography for all references.



29-155

streamers form in the most intense parts of the field and these streamers cause breakdown by developing until the two electrodes are linked.

More recently, Slepian[6] presented a new theory which accounts for the streamer currents and according to which spark lags of the order of $10^{-7}$ sec. may be obtained with slight overvoltages. Slepian's theory may be summarized briefly as follows: Upon the application of suitable potential, free electrons in the field move toward the anode and multiply by collision. The rapidly increasing electrons, in forcing their way through the gas, produce sufficient heat to cause thermal ionization, and a streamer is formed. This sequence takes place in the most highly stressed parts of the field, which are usually at the electrode surfaces. Immediately upon the formation of the streamer the gradient at its tip becomes very high, thus increasing its growth in the same manner in which it was formed. One end of the streamer becomes attached to the adjacent electrode; the other end develops at an increasing rate until the gap is spanned. When this occurs the gap may be said to be broken down.

Slepian's theory is based upon the mobility of the electron, and hence, the calculated breakdown time is much shorter than that obtained from theories in which the motion of the more sluggish positive ion is an important factor. However, it must be remembered, in checking these theories quantitatively, that most of the experimental data are only approximate, and at best only the order of magnitude is indicated. On the other hand, these theories serve admirably to guide the experimenter to a logical course of investigation.

A conclusion which might be drawn from both of the above theories is that appreciable currents exist prior to complete breakdown. More specifically, these currents would be expected from the rapid space charge formation of Slepian's theory and from the ionic formation and migration of Townsend's theory. Slepian and Torok[7] have shown that such currents may amount to thousands of amperes in large homogeneous fields.

## The Determination of Breakdown Time

Much of the early work on sparking time has been done on sphere-gaps. Pedersen[8] impressed a flat-topped wave with an abrupt front upon a sphere-gap and determined the time lag by means of a transmission line and Lichtenberg figures. He obtained time lags of the order of $10^{-8}$ sec. with short gaps. Burawoy[3] has shown that the wave-front cannot be perpendicular, and hence, Pedersen's results may be somewhat in error. Peek[9] impressed a highly damped oscillatory wave upon a sphere-gap and found no appreciable time lag. In his tests the wave shape was determined entirely from the constants of the generator. Unfortunately, in many of these cases, the wave probably was distorted by the presence of a second sphere-gap in the circuit.

Burawoy used sinusoidal pulses of short duration by passing surges through a loop in a transmission line. The test gap was placed across the terminals of the loop. In analyzing the data, Burawoy used the entire wave as the time lag and the voltage crest as the breakdown potential. Results procured in this manner show that sphere-gaps separated approximately one centimeter break down in periods of time as short as $10^{-9}$ sec. Data also were obtained on electrodes giving less homogeneous fields; here, however, breakdown took place only with pulses of long duration.

The results obtained by Burawoy, Pedersen, and Peek have been of considerable value in determining the properties of insulation under impulses. These methods, however, can be used only indirectly in investigating the process of breakdown, as it is impossible to ascertain the part of the wave where breakdown starts or where it is complete; also nothing can be learned of the action within the field prior to breakdown.

The cathode ray oscillograph has provided a means of determining the characteristics of breakdown with great exactness; this instrument has been used extensively in Europe and in America. Tamm[4] obtained some excellent volt—time records on sphere-gaps subjected to low-voltage surges with exceedingly abrupt fronts. In interpreting his results he used the point at which the voltage exceeded the steady-state breakdown value as the initial time reference point; the point at which the voltage was suddenly reduced was taken as the breakdown point. The breakdown curve of the sphere-gap was then easily constructed, since these two points were readily established. His results show that time lag is an inverse function of the overvoltages. His experiments with gaps in various gases at low pressures are of special interest. Under these conditions a slight drop in voltage prior to breakdown indicated a preliminary discharge; Tamm expressed the opinion in his conclusions that such preliminary discharges also might occur at atmospheric pressure.

A group of tests on actual transmission line insulation was made by Smith and Wade,[10] who obtained the volt—time characteristics of breakdown of certain suspension and pin-type insulators. For these results the start of the wave was used as the time reference point, instead of where the voltage exceeded the steady-state breakdown value. The flashover was taken as the point where the abrupt drop in voltage occurred.

Torok and Ramberg,[11] in work of a different nature, used the 60-cycle crest breakdown value as a reference. Thus, there appears to be some disagreement as to the start or initial reference point of the breakdown. Although this difference is negligible in the case of long time lags, it might readily cause a large discrepancy when the breakdown time becomes very short. It appears, then, that some other factor must be formed which will establish more definitely an initial time reference point.

### Currents Preliminary to Breakdown

The magnitude of currents prior to breakdown as shown by Slepian and Torok was determined by sphere-gap measurements, and consequently only the crest values of the currents drawn by the streamers were obtained. Although this determination was far from complete quantitatively, since only the approximate form and the magnitude of the applied waves were known, it served to indicate the definiteness of extensive preliminary ionization. This ionization is of vital importance from the standpoint of insulation research and application, since it introduces a new consideration which may help to solve some of the mysteries of the performance of insulation.

### Additional Streamer Current Work

The rapid development and application of the cathode ray oscillograph have made possible a more complete study of these preliminary currents. A special adaptation of the oscillograph was necessary in this work, however, since a practically perfect reproduction of phenomena was essential to obtain both current and voltage traces accurately upon the same film. In this application linear coordinates and a single sweep of the cathode ray across the film were considered most desirable. This required a method of synchronization whereby the cathode ray beam, a timing system, and the test potential were under close control. The final arrangement permitted the whole sequence to be repeated at will with a maximum time variation of one fifth of a microsecond. Fig. 1(a), in which two successive traces superimpose upon each other, and Fig. 3(c) in which five applications at different voltages are recorded, show how closely synchronism may be obtained. Thus, a single oscillograph was employed, and the two traces, which represent current and voltage, were secured by consecutive voltage applications. It is fully realized that a two-element oscillograph, which at the present time would mean two separate cathode ray oscillographs, would meet the requirements of this application much better than a single instrument, and work is under way in this direction. In the present case a slight variation of voltage on consecutive applications might appreciably change the magnitude of the resulting current; this possible error in the current was partially eliminated by averaging results from several oscillograms of each test condition.

The test procedure used to obtain time-lag oscillograms was in general the same for all tests. The voltage of the surge generator was regulated to a critical value barely sufficient to flash over the insulation. Several oscillograms were then obtained at this setting, after which the surge-generator voltage was slightly raised, and more oscillograms were taken. This procedure was continued until the voltage limit of the generator was reached. The voltage was reduced by a potentiometer and transmitted to the oscillograph through a cable to obtain the volt—time traces. Current was determined from the drop across a series resistor, and this drop was also transmitted to the oscillograph through a cable. The latter cable was protected against overvoltage by a small sphere-gap adjusted to break down on excessive currents.

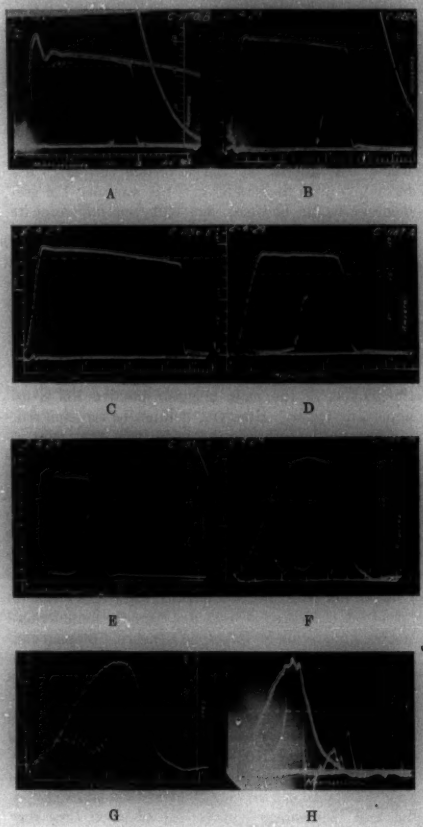



Fig. 1—Cathode Ray Oscillograms of Flashovers on Four Pillar Type Insulators

A The accuracy of the timing arrangement is shown by the manner in which successive voltage waves coincide perfectly up to the point where one resulted in flashover

B Current and voltage relations. Note the abrupt rise of the ionization current

C Completion of the flashover after the voltage dropped below the 60-cycle crest flashover value

D A marked reduction in time lag produced by a higher applied voltage

E The effect of further increasing the voltage is shown

F The streamer currents may be prominent before the crest of the wave is reached

G The phenomenon of F is more apparent here

H Streamer currents limit the maximum voltage reached

### Discussion of Oscillograms

The current drawn by the apparatus under test is the resultant of two distinct components, the charging current and the ionic current. These may be segregated by first determining the charging current from the recorded voltage wave and the capacity of the apparatus and graphically subtracting this current from the total. Unfortunately the majority of the apparatus tested and discussed herein has capacity sufficiently high to draw charging currents of 25 to 75 amperes, thus making the determination of small ionic currents unreliable during the charging period. Another method of obtaining the point at which extensive ionization occurs is to impress a flat-topped wave of such a magnitude that ionic currents start only after the charging period is over. Identical results from these two methods cannot be expected, as the difference in the time involved is quite large. In one case appreciable streamer currents must develop in a few hundredths of a microsecond, whereas with the other method the time for development is limited only by the ability of the generator to maintain the voltage.

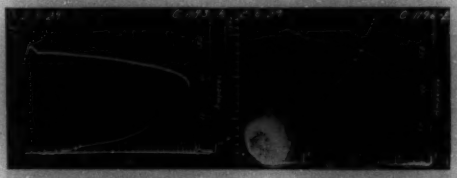
A B

Fig. 2—Surge Flashovers of 16 Suspension Insulators

A Voltage and current relations
B Note the sudden rise and fall of current previous to the normal increase

A close examination of the oscillograms depicting long time lags on pillar type insulators, as in Fig. 1(b), shows the abrupt start of the ionization current. This takes place after an interval of time which depends upon the amount of overvoltage above a critical value, below which ionization currents of appreciable magnitude cannot be obtained. Fig. 1(c) shows a flashover which was completed after the voltage had fallen below the 60-cycle breakdown value. This may be explained by the slow rate of formation of space charges and small streamers when the voltage barely exceeded the 60-cycle value. The formation of streamers decreased the effective spacing between the electrodes; this, together with the needle-gap properties of the streamers, raised the gradient to a value sufficient for the completion of breakdown. This point is substantiated by oscillograms on other apparatus, which follow. A slight increase in the applied voltage produces a marked reduction in time lag, as shown in Figs. 1(d) and 1(e). In Fig. 1(g) the streamer currents were very prominent even before the crest of the wave was reached. Fig. 1(g) shows this effect amplified still further, while in Fig. 1(h) the streamer currents were so large that the voltage wave was limited to 1350 kv. instead of reaching the voltage of the generator, which was 2000 kv.

Tests on a string of 16 suspension insulators showed similar breakdown characteristics, with the exception that at low voltages the current did not rise as abruptly, Fig. 2(a). An interesting phenomenon is shown in Fig. 2(b), where the current remained very low for several microseconds after the voltage reached its crest; then an abrupt rise and fall occurred, after which



A B

C D

E

Fig. 3—Surge Flashovers on a 16-Unit Insulator String Equipped with Arcing Rings of Four-Inch Diameter Pipe

A Voltage and current relations
B The effect of increasing the voltage is shown
C Five successive applications at increasing voltage. The inverse relation between overvoltage and time lag is well illustrated
D The currents corresponding to (C)
E The response of the current to potential variation is shown

the current increased in a normal manner. It is probable that streamers were initiated at the time indicated by the first sudden rise in the current.

Insulator strings equipped with arcing rings behave somewhat differently from plain strings, under surge voltages. The nature of the arcing rings seems to determine almost entirely the resulting characteristics. Fig. 3(a) is an oscillogram of a flashover on a 16-unit

string of insulators equipped with two arcing rings of four-inch pipe. Fig. 3(b) shows the corresponding current and voltage waves with moderate overvoltages. The start of the current wave was modified by high-frequency oscillations, (20,000 kilocycles), which were probably initiated by small rapidly forming streamers and thereafter maintained by leads which could not easily be eliminated. The effect of variation of the applied voltage is shown in Fig. 3(c) where flashover occurred in all but one case. The corresponding currents appear in Fig. 3(d).

Arcing rings of the strap type have somewhat

A B

C

Fig. 4—Surge Flashovers on 16 Suspension Insulator Units Equipped with Circular Arcing Rings of ¼-In. Strap

A Current and voltage relations with a slight overvoltage
B Current and voltage relations with a moderate overvoltage
C Current and voltage relations with a still higher overvoltage

different characteristics. Figs. 4(a), 4(b), and 4(c) are typical oscillograms of the voltage and current waves. The flat portions of the current waves probably were caused by the decreasing voltage waves. In Fig. 3(e), the voltage increased to a high value and then dropped to the 60-cycle flashover value. The large change in current caused by a relatively small potential variation shows clearly that the rate of ionization depends upon the overvoltage above a critical value. It also follows that the rate of ionization depends upon the nature of the stress distribution throughout the field.

In the breakdown of insulation, particularly of the gaseous form, ionization does not start at the time of the sudden reduction in voltage. The process may start 25 or 30 microseconds prior to the instant when the gas becomes highly conducting. In full consideration of this fact such terms as time lag and breakdown time become indefinite and arbitrary unless they are defined very completely. The rate of increase of current near the completion of flashover is so great that the voltage is abruptly reduced to a negligible value in a fraction of a microsecond. Thus for breakdowns where the voltage remains at a high value for considerable time, that is, with long time lags, variations in the determination of the breakdown point will be small in comparison. On the other hand, when breakdown occurs in a short time, as in Fig. 1(g), these variations in the arbitrary points of the start of breakdown and the time of completion are such a large part of the surge duration that the results of different interpretations may deviate as much as 200 per cent.

## Attenuation

Klydonograph data obtained on transmission lines have shown that high-voltage surges which have caused flashover at some point of the line attenuate much more rapidly than low-voltage surges. This high rate of energy dissipation at high voltages commonly is attributed to corona on the line. However, with a chopped wave, which results when the line insulation breaks down on the front of a high overvoltage wave, streamers will form on the succeeding insulators and thereby produce high currents which will reduce the voltage much more rapidly than is possible with corona alone. The space charge and streamers that exist when the current is large, invariably result in flashover, unless the tail of the wave is abrupt or chopped.

## Conclusions

1. The process of breakdown of insulation on surge voltages does not start until the steady voltage breakdown value has been exceeded. Hence, it seems logical to compute time lag of breakdown from the first crossing of the steady breakdown value by the voltage wave instead of from the beginning of the wave.

2. After breakdown has started, ionization or streamer currents increase in magnitude, as the streamers develop between the electrodes, until the gap is spanned, when the current limit is determined by the generator characteristics.

3. The magnitude of the streamer current at any time apparently is a function of the amount of overvoltage above a critical value.

4. Streamer currents are indicative of an unstable condition and therefore cannot be used for protective purposes except against chopped waves.

5. Streamer currents cause faster attenuation of high-voltage chopped waves than can be attributed to corona alone.

6. The rate and amount of energy dissipation prior to complete breakdown between two electrodes is a function of the nature of the electrostatic field.

7. Terms such as time lag, sparking time, and breakdown time are vague unless they are very completely

defined. The time lag (as defined in this paper) of commercial apparatus values from $10^{-7}$ to $10^{-4}$ seconds.

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## Discussion

**K. B. McEachron:** The results of this paper indicate that it is not sufficient merely to test an insulator with a voltage rising at a certain rate but the generator must be capable of supplying sufficient current so that the rate of building up of the streamer currents is not limited by the capability of the impulse generator. I believe that the generators used in the past for determining insulation flashover have been in most cases designed liberally from the standpoint of current. For instance, the 5,000,000-volt generator at Pittsfield is capable of delivering many thousands of amperes during the discharge over an insulator string.

It seems to me however, that some test should be made on insulator strings on transmission lines with the impulse traveling several miles since the surge impedance of the line imposes a limitation on the amount of current available for the formation of streamer currents. It would be interesting if the authors could tell us how the streamer currents compare for one insulator and 16 insulators with the same proportional transient voltage supplied. It may be that only at the lower potentials and with short strings would the surge impedance of the transmission line delay the formation of the streamer currents.

Under the heading of "Attenuation" the authors state that when an insulator flashover chops the traveling wave on a transmission line, the high rate of attenuation is due largely to the formation of streamer currents on succeeding insulators. Tests in Michigan with artificial lightning on transmission line conductors indicate that a wave chopped by a sphere-gap much below the insulator flashover value still attenuates more rapidly than does the full wave of the same potential.

Since streamer currents are required between spheres or other points of opposite potential before actual breakdown occurs, it is reasonable to suppose that the conductors themselves develop streamer currents and that to establish corona considerable starting current must flow, which seems to be the more reasonable explanation of the greater attenuation of chopped waves than of full waves. I should like to compliment the authors on the excellent oscillograph work in this paper although the reproduction makes the study of some of these oscillograms difficult.

**J. T. Tykociner:** The investigations described in this paper throw valuable light on the phenomena of breakdown in gases. As in former experiments the existence of large currents preceding the complete breakdown was found in accordance with Doctor Slepian's theory. In view of these results, who can deny that we possess in the cathode ray oscillograph a powerful instrument of research. We tend, however, to become overenthusiastic as to the possible information we may expect from the cathode ray oscillograph. We must take into consideration that the oscillograms reveal total discharge currents as function of time and voltage. They do not disclose all the information required for the construction of a complete picture of the mechanism of breakdown. We need in addition to these oscillograms knowledge of the distribution of current density and potential along and across the path of breakdown. We can hardly hope that the present-day oscillograph may serve in connection with the determination of electron or ion density distribution. It seems that, in addition to the theory of thermal ionization, we will also have to borrow from astrophysicists the instrument they are using in the study of the radiation emitted by the sun and stars, an instrument older and simpler than the cathode ray oscillograph. I have in mind the spectroscope. The spectra revealed by spectroscope also present oscillograms, but of another type. They indicate the highest frequencies produced in discharges by atoms and molecules in state of excitation. The existence of strong electric fields in an electric discharge is evidenced by splitting and widening of spectral lines and bands. The phenomenon is known as Stark effect. It should also be possible to determine the density of current from point to point all over the area of discharge by making use of the Zeeman effect. Measuring thus the position, width, and intensity of spectral lines may lead to a precise knowledge of the distribution of electric and magnetic fields for all regions and phases of breakdown in gases. The distribution of temperature can be measured by thermopiles subjected to the radiations emitted by different parts of the discharge. The short intervals of time at which a given spectrum will have to be photographed may be controlled by a Kerr cell. Physics, especially astrophysics, has ready for us the methods of investigation. I wish to suggest that the time has come for engineers to apply these powerful means for high-voltage research.

**R. H. George:** There are two questions having to do with discharge phenomena with short gaps which I should like to ask Mr. Torok in connection with this excellent paper.

Did changing the polarity of the electrodes make any difference in the breakdown potential of the gaps, or was this tried? Some investigations conducted by K. A. Oplinger and the writer[1] some years ago on the d-c. breakdown of point-to-plane gaps, showed the breakdown potential to be very much higher with the point negative than with it positive.

Was any reduction in the time lag found with insulators illuminated with ultra-violet light as compared with ordinary laboratory illumination and total darkness? I assume the curves represent an average value of time lag, and I should be interested to know something of the variation found in the lag.

**S. C. Sprague:** I had always understood that a string of insulators might be assumed to approximate a needle-gap and that the time lag of such a gap was variable and quite subject to humidity and other atmospheric conditions. I suppose these several oscillograms were taken all within a very short time of each other and that that is is how they were able to check the theory so well.

**J. J. Torok:** From his first question it appears that Mr. McEachron thought we had tried to attribute all the losses on the line to streamer currents. We did not mean that at all. There is certainly a great deal of energy dissipated through corona. We have done a considerable amount of work on corona and have determined the amount of loss at different voltages. The losses in the formation of streamer currents, however, only appear when the voltage exceeds the steady-state breakdown value of the insulator so we may say this: That the line dissipates a great amount of energy due to corona but at voltages above the breakdown value of the insulators we get a still greater draw of current and consequently a greater loss. For this reason it is not pos-

1. Bulletin No. 19, Purdue University Engineering Experiment Station, Lafayette, Ind. "A Photographic Study of High-Voltage Discharges," by R. H. George, Karl B. McEachron, and K. A. Oplinger, 1925.

sible to send an unlimited current into the substation. The currents due to traveling surges will be modified within the station by the energy dissipation in corona as well as about the insulators on the line.

Professor Tykociner has made a very valuable and interesting suggestion. This would make it feasible to measure the currents at any point within the gap without the introduction of electrodes which would distort the original field. It would be very desirable if this scheme of measurements could be set forth in full detail. The synchronization of the Kerr cell as well as the spectroscope may present some difficulty; however, this scheme is of great value because it offers another means of measuring these currents and thus checking the present methods of determination which are exceedingly difficult to make and in which large errors may appear. Unfortunately all of our measurements on streamer currents have been made with one polarity, that is with the negative grounded. Because of the great amount of work to be done on various different problems, measurements using a positive polarity grounded have not been made. It is intended to continue this investigation with reverse polarities.

The question has been raised concerning the effects produced by variations of free ions within the gap. For small gaps illumination of the electrodes by ultra-violet light produces considerable effect. With large gaps this effect becomes almost negligible. In the laboratory, to produce an increase in density in free ions by means of ultra-violet light, a very powerful source is required as the lamp would necessarily have to be placed about 20 ft. away from the apparatus to be tested and the useful energy would not be very large. We have done some work of this nature in which we used sunlight. With large gaps having spacings greater than 5 cm., the effect of the increased ionization became negligible. Repetition of this test with insulators showed that the effect of ultra-violet light was nil. The application of ultra-violet light did not alter the random element in the phenomena of breakdown when large gaps were used. The variations of time in breakdown under a given voltage remained practically the same.

Because of the variation in breakdown time it is necessary to take many oscillograms at one given voltage to determine a fairly accurate average of the breakdown time; thus instead of making only eight or ten oscillograms to represent a time lag curve it is necessary to obtain 40 or 50.

Mr. Sprague spoke of the variation in results produced by changing humidity. We have not encountered much difficulty from that score as most of the tests were made within a period of time less than four hours; however, we have noticed slight variations in characteristics from day to day but this effect has been so small that it may be entirely neglected.

# Dissipation of Heat by Radiation

BY A. D. MOORE[1]

Member, A. I. E. E.

***Synopsis.***—*Heat dissipation is an ever-present factor affecting the design and operation of many kinds of electrical equipment. Usually, the problem is to get rid of heat due to losses. Sometimes the problem is how to conserve heat. Radiation, or convection, or conduction, or combinations of these, enter into all cases. Engineering literature as a rule presents conduction and convection in sound terms, but in many cases, the treatment of radiation is unsound, misleading, and sometimes in error. This paper is presented with the hope of putting heat radiation in engineering applications on a sounder basis.*

*The usual laws given to cover total heat radiation are stated and discussed, and their limitations brought out. Net heat loss by radiation interchange for the cases of parallel and concentric surfaces are reviewed and stated.*

*The problem of total radiation from a rectangular slot is attacked, the method of solution is indicated by example and discussion, and the results given.*

## Section I

### Introduction

THE term "radiation" has been so thoroughly corrupted by being used to include all forms of heat dissipation, that it needs definition at the outset. Radiation, within this paper, does not include heat dissipation by convection, either natural or forced. It applies only to true radiation, either emitted, reflected, or absorbed by a surface. Radiant heat energy covers the range of the spectrum, including the visible, or light wave energy. Heat waves behave as the more commonly known light waves behave,—they are electromagnetic waves traveling in straight lines; they are reflected by mirror surfaces as light is reflected; a given surface emits, reflects, or absorbs to varying degrees, depending on the character of the surface.

### Stefan's Law of Emission

Stefan formulated the law of radiation emission,

$$R = k\,e\,T^4$$

where $R$ is the rate of heat radiation emission from a unit of surface, $e$ is the emission coefficient for the surface, $k$ is a constant, and $T$ is the temperature in degrees Kelvin (absolute) of the surface.

*Stefan-Boltzmann Law.* When a radiating body is subject to reception of radiation from surrounding radiating bodies, as is usually the case, there is an interchange. The net loss of heat from the body by radiation interchange is perhaps most commonly given in engineering literature in the form of the Stefan-Boltzmann Law,

$$R = S\,k\,e\,(T_1^4 - T_2^4)$$

in which $R$ represents the net rate of losing heat by the body; $S$ is its surface; $k$ is a constant; $e$ is the emission coefficient for the surface; $T_1$ is the temperature (Kelvin) of the surface; and $T_2$ is variously and loosely described.

Let Fig. 1 represent the body, which has an irregular surface. When the above formula is given, it is usually not stated whether $S$ is to be the actual surface, or the enveloping surface. Usually, nothing is said as to why the surface of the surrounding bodies, and their emission coefficient, are omitted. And $T_2$, depending on the writer, is given as being

1. Temperature of surrounding walls
2. Temperature of surrounding air
3. Temperature of surrounding objects
4. Temperature of surrounding space.

In succeeding articles in this section, an attempt will be made to place radiation interchange, in simple cases, on a more definite basis.

*Black-Body Radiation.* At a given temperature a black-body surface radiates more than any other surface. It radiates the maximum possible amount in all wavelengths, although the energy is distributed over the various wavelengths according to a familiar curve. The black-body is the standard of reference, and its total emission coefficient, $e$, is herein taken as unity. When energy falls on a black-body, none is reflected Hence, a small window opening into a large black-lined cavity, being a nearly perfect energy trap, is a nearly perfect equivalent of a black-body surface.

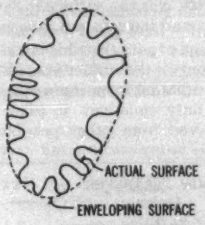


Fig. 1

### Selective Radiation

A given surface may emit selectively; in some wavelengths it may emit (radiate) as much energy as does a black-body, in others, less, and in some, none.

### Gray-Body Radiation

If a surface emits so that the energy of all wavelengths is reduced by the same per cent below that which is

1. Associate Professor of Electrical Engineering, University of Michigan, Ann Arbor, Mich.

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29-163

emitted by a black-body at the same temperature, it is called a gray-body. For example, if its total coefficient is 0.7, it emits seven-tenths as much energy in every wavelength as does the black-body. *In this paper, only black-body and gray-body radiation will be dealt with.* Further, only opaque surfaces will be considered.

### Absorption and Reflection

The absorption ability of a surface depends upon its ability to emit. If it can emit in a given wavelength, it can absorb that wavelength. If it emits completely, as a black-body, it absorbs completely. Incomplete emission, as for a gray-body, is accompanied by incomplete absorption for energy falling upon it. With unity as a base, emission and absorption coefficients are equal. Energy not absorbed is reflected (by opaque surfaces), and the reflection coefficient is $(1 - e)$.

### Prevost's Law of Exchange

By this proposition, radiation emission goes on irrespective of energy that may be absorbed at the same time.

### Stefan's Law Written to Give Watts

Stefan's law of emission is

$$R = S\,e\,36.9\left(\frac{T}{1000}\right)^4$$

where $R$ is watts, $S$ is the surface in square inches, $e$ is based on unity, and the constant is as given.

It is important to note that this law gives initial emission correctly only if the surface is so disposed that none of it receives radiation from some other part of it, and that it gives only emission; it takes no account of radiation received from other possible bodies in the neighborhood.

### Net Radiation Transfer of Heat for Simple Interchange Cases[2]

(*a*) *Parallel Surfaces.* Two parallel surfaces, of the same extent, are placed so close together that escape from edge openings is negligible. $S_1$ has $e_1$ and $T_1$ for emission coefficient and temperature, respectively, and for $S_2$, like quantitites are $e_2$ and $T_2$. The two energies initially emitted by the two surfaces in a given time increment, are inter-reflected, with two infinite series as the result. The net watts lost by $S_1$ will be

$$R = 36.9\,(1000)^{-4}\,S_1\,(T_1^4 - T_2^4)\,\frac{e_1\,e_2}{e_1 + e_2 + e_1\,e_2}$$

(*b*) *Concentric Spheres.* Let $S_1$, $e_1$, and $T_1$ be the surface in square inches, the coefficient, and the temperature, respectively, for the surface of an enclosed sphere, and $S_2$, $e_2$, and $T_2$ like values for the surface of an enclosing spherical wall concentric with the sphere. The net rate of heat loss by $S_1$, in watts, is

$$E = 36.9\,(1000)^{-4}\,(T_1^4\,S_1 - T_2^4\,S_2\,P)\,\frac{e_1\,e_2}{e_1 P + e_2 - e_1 e_2 P}$$

where $P$ is as follows: at any given stage of reflection, when a quantity of heat $H$ leaves the walls, the fraction $P$ is such that $P\,H$ is the part of $H$ that strikes the enclosed sphere. $P$ is determined by the characteristic of the surface, as to what degree heat coming from it is diffused. If we deal with mat surfaces (as described in Section II), the above expression simplifies to

$$R = 36.9(1000)^{-4}S_1(T_1^4 - T_2^4)\,\frac{e_1\,e_2}{e_1\dfrac{S_1}{S_2} + e_2 - e_1\,e_2\dfrac{S_1}{S_2}}$$

(*c*) *Concentric Cylinders.* This case, as to symbols and treatment, is similar to the preceding case; and with similar meanings, and mat surfaces, the expression for the watts lost by the enclosed cylinder is the same as the final expression given above.

If, in the concentric cases, the two radii are allowed to approach equality, the cases approach the case of parallel surfaces, physically; and the expression for the concentric cases then degenerates into the expression for parallel surfaces, as it should.

Again, in the concentric cases, if $S_2$ becomes infinite so that the enclosed body is a very small object in a very large room; or if, with finite dimensions, the coefficient $e_2$ of the enclosing wall is made unity (black-body), the expression degenerates into the Stefan-Boltzmann law. Thus the Stefan-Boltzmann law is correct only under one or the other of the two conditions specified at the beginning of this paragraph.

## Section II

## THE SLOT

### Convolutions

When a body is corrugated, like a transformer tank, or when it is slotted, or when cooling fins are attached to it,—is its radiating ability increased, or is its radiation, effectively, determined by its enveloping surface? Probably the simplest ideal set-up for answering this question is to compare the total radiation of a slot with the radiation from an undisturbed portion of surface that would just cover the slot mouth.

### The Mat Surface

Underlying the development of the concentric cases of Section I, and all of the work in this section, is the assumption of the mat surface. The mat surface is a diffusing surface, both for radiation it may emit, or for that which it may reflect. It obeys the cosine law. Imagine a small increment of such a surface, and erect on its plane a hemisphere with the area at its center. Radiation from the area is most intense through the spherical shell along the normal radius; call this intensity, $I$. Then the intensity at the shell for any other radius is $I \cos \theta$, where $\theta$ is the angle between the selected radius and the normal radius. This is

2. The full development for the cases is given in "Fundamentals of Electrical Design," A. D. Moore, McGraw-Hill.

equivalent to saying that for the mat surface, the intensity in watts per square inch at the point of view is proportional to the projected area as viewed from that position, all positions being at the same radius.

### The Slot

The paper from here on is concerned with finding the total radiation per unit length from a rectangular slot that is infinitely long, 2 in. wide, and 8 in. deep. The solution method is semi-mathematical. The entire slot surface is divided into strips of equal width (1 in.), and accurate "interchange" values are found mathematically.

Fig. 2 shows the slot. Let the strip shown as Level 1 emit uniformly 100 watts per sq. in. Then, by simple mathematical processes not given here, the values to the left of the slot were found. For example, the top

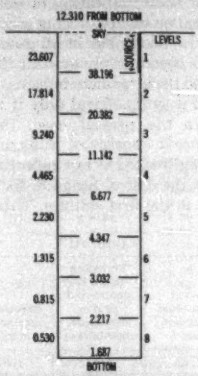


Fig. 2

value is 23.607, which means that of the 100 watts sent out by the right strip, Level 1, the opposite or left strip, Level 1, receives 23.607 watts; and strips at other levels receive less amounts. From these values it is a simple matter of argument and arithmetic to obtain all other values given in Fig. 2.

For example, the figure shows that if a floor were placed 1 in. down the slot, it would receive, out of 100 watts leaving Level 1 strip (at one side only) 38.196 watts; and the true bottom would receive 1.678, as shown.

### Principle of Reciprocity

Suppose a surface of any size, $S_1$, being a uniformly dense source of 100 watts per unit area, sends a total of $W$ watts to another surface of any size, $S_2$. Then if $S_2$ is made a uniformly dense source of 100 watts per unit area, it will send the same, or $W$, watts, to $S_1$. This principle is too well known to prove here, and anyone unfamiliar with it can easily verify it by study of simple cases.

This principle at once gives a double meaning to every value shown on Fig. 2. For example, the interchange value connecting a strip in Level 1, and the entire bottom, which is two strips wide, is 1.687, the meaning of which, in one direction, was given above. In reverse, or by reciprocity, if the bottom is a uniform source of 100 watts per sq. in., it will send to the strip in Level 1, 1.687 watts per sq. in.

Fig. 2 thus gives interchange values between any wall strip and any strip in the opposite wall, and between any wall strip and the bottom. It also gives 12.310 as the interchange between bottom and sky opening, a value easily obtained once the other values were established. All values given on Fig. 2 are, it is believed, correct to one-tenth of one per cent.

### Method of Attack

It is possible, by assuming the slot surface to be at such a temperature as to cause it to be a uniform density source of 100 watts per sq. in., to proceed with the different stages of reflection and eventually, to find the total emission from the slot mouth. Instead, the same result will be found in a different way. A uniform "sky" is placed over the slot mouth, which uniformly sends 100 watts per sq. in. of slot mouth into the slot; and the energy total finding its way out again is determined. From the two values, the result desired can be computed.

A basic set of figures is obtained by using a coefficient $e$ of zero, reflection then being total. Initial reception by different levels on one side, and reception per unit on the bottom, for each 100 watts admitted from sky by the slot opening, are given in Table I.

TABLE I
INITIAL RECEPTIONS FROM SKY

| Level | Received from sky | |
|---|---|---|
| 1 | 38.196 | |
| 2 | 20.382 | |
| 3 | 11.142 | |
| 4 | 6.677 | |
| 5 | 4.347 | |
| 6 | 3.032 | |
| 7 | 2.217 | |
| 8 | 1.687 | |
| | 87.680 | |
| Bottom | 12.310 | |
| | 99.990 | checks 100 |

### First Stage

The set of figures showing a quantity of energy sent out by reflection, and being received or allowed to escape, or both, will be called a stage. Stage 1 is given in Table II. The first two columns of Table II give the figures on the eight levels in the side wall. Level 1 being typical, its group of values will be discussed. At the head of the group is 38.196, the watts received by a strip in Level 1 from the sky. $e$ being zero, and $(1 - e)$ being unity, all this energy is reflected; its

reception by the opposite wall strips is shown by the first of the figures in each of the groups of eight sets of figures for the eight levels. For example, out of 38.196, there is sent to Level 1, 9.02; to Level 2, 6.81; and so on. These two values were obtained by multiplying 38.196 by the proper interchange values, 23.607/100 and 17.814/100, as taken from Fig. 2.

In the group of figures for any level, the values are, in order from the top down, that level's reception from the eight levels, taken from top down. Addition of a group gives total reception by a strip in a level from the complete opposite wall.

TABLE II
STAGE I

| | | | | |
|---|---|---|---|---|
| | 38.196 | | 4.347 | E. S. |
| Level 1 | 9.02 | Level 5 | 0.85 | 14.60 |
| | 3.63 | | 0.91 | 4.15 |
| | 1.03 | | 1.03 | 1.24 |
| | 0.30 | | 1.19 | 0.44 |
| | 0.10 | | 1.02 | 0.19 |
| | 0.04 | | 0.54 | 0.09 |
| | 0.01 | | 0.20 | 0.05 |
| | 0.01 | | 0.07 | 0.03 |
| | 14.14 | | 5.81 | 20.79 |
| | 20.382 | | 3.032 | E. B. |
| Level 2 | 6.81 | Level 6 | 0.50 | 0.644 |
| | 4.82 | | 0.45 | 0.452 |
| | 1.98 | | 0.45 | 0.338 |
| | 0.62 | | 0.62 | 0.290 |
| | 0.19 | | 0.78 | 0.290 |
| | 0.07 | | 0.72 | 0.338 |
| | 0.03 | | 0.39 | 0.452 |
| | 0.01 | | 0.16 | 0.644 |
| | 14.49 | | 4.07 | 3.45 |
| | 11.142 | | 2.217 | Check |
| Level 3 | 3.53 | Level 7 | 0.31 | 14.14 |
| | 3.63 | | 0.27 | 14.49 |
| | 2.64 | | 0.25 | 11.59 |
| | 1.19 | | 0.30 | 8.34 |
| | 0.40 | | 0.40 | 5.81 |
| | 0.13 | | 0.54 | 4.07 |
| | 0.05 | | 0.52 | 2.89 |
| | 0.02 | | 0.30 | 1.93 |
| | 11.59 | | 2.89 | 63.46<br>20.79 E. S.<br>3.45 E. B. |
| | 6.677 | | 1.687 | 87.70 |
| Level 4 | 1.71 | Level 8 | 0.20 | which checks 87.68 from Table I. |
| | 1.88 | | 0.166 | |
| | 1.98 | | 0.146 | |
| | 1.57 | | 0.149 | |
| | 0.78 | | 0.194 | |
| | 0.28 | | 0.28 | |
| | 0.10 | | 0.395 | |
| | 0.04 | | 0.40 | |
| | 8.34 | | 1.93 | |

By appropriate use of other interchange values given in Fig. 2, the "escapes" of energy coming from the wall, to sky and to bottom, are computed. These are shown, Table II, under E. S. (Escape to sky) and E. B. (Escape to bottom).

As an indispensable check, the CHECK column is made out. It shows, for this stage, total reception by the eight levels, and the sum of this, and the two escapes. This total must closely check with the energy initiating this stage, which is 87.68, taken from Table I.

The level receptions, eight in number and totaling 63.46, are now used to initiate Stage 2, where computations are carried out precisely as in Stage 1.

Note that energy falling on the bottom is left there in Stage 1 and succeeding stages like it. This energy will be treated later.

## Self-Repeating Distribution, and Summation

Eight stages were carried out, seven of which are not given here. For the end of Stage 8, the reception values for the eight levels closely approached symmetry.

In any closure, successive reflections achieve more and more closely a distribution which is self-repeating in form; it will not be self-repeating in size unless there is no absorption and no escape. This proposition has not been given general proof, but in all cases worked on by the writer, it has been entirely evident that the proposition has governed the later distributions. The distribution approached is symmetrical only if the enclosure is symmetrical. In the present case, the enclosure is symmetrical, since it consists of walls only, bottom for the moment being treated as not reflecting.

Receptions at the end of Stage 8, for eight levels in order, are given in the first column, Table III. In the next column the total of the first column is re-distributed so as to give a self-repeating distribution. The re-distribution was done by trial and error, only two trys being necessary to get the accuracy shown. Stage 9 consisted of beginning with the values as re-distributed, and finding the receptions of the fourth column. Column 5 shows that every level repeated its energy value by a factor closely approximating to 0.838, the Repeat Factor for the present enclosure of walls only.

TABLE III

| Level | Actual receptions at end of stage 8 | Preceding values re-distributed to give self-repeat. distribution | Receptions at end of stage 9 | Repeat factors |
|---|---|---|---|---|
| 1 | 1.27 | 1.21 | 1.01 | 0.835 |
| 2 | 1.73 | 1.68 | 1.41 | 0.839 |
| 3 | 2.07 | 2.02 | 1.70 | 0.842 |
| 4 | 2.21 | 2.20 | 1.84 | 0.837 |
| 5 | 2.18 | 2.20 | 1.84 | 0.837 |
| 6 | 1.97 | 2.02 | 1.70 | 0.842 |
| 7 | 1.63 | 1.68 | 1.41 | 0.839 |
| 8 | 1.18 | 1.21 | 1.01 | 0.835 |
| Escape to sky or to bottom | | | 1.375 | |
| Average repeat factor | | | | 0.838 |

From here on no more stages are needed, as all terms beyond the self-repeating stage can be handled by summing up an infinite series.

Table IV lists all escapes for an over-all check. Escapes to sky and bottom for the first eight stages are given. For the ninth and succeeding stages, the infinite

series comes in. The repeat factor, 0.838, operates on escapes as well as on side-wall distributions, so that escapes to sky, for instance, would be that occurring in Stage 9, plus another reduced by 0.838, etc., as,
$1.375\,(1 - 0.838 - 0.838^2 - 0.838^3 - \ldots)$

$$= \frac{1.375}{1 - 0.838} = 8.50$$

The sum of all escapes should total 100, as all values have been taken on the basis of 100 original watts entering from the sky, and there has been no absorption. The sum obtained, 103.05, checks satisfactorily, considering all the steps through which reflections have been carried.

### Procedure for Coefficient Other than Zero

Table V carries out the steps required when the emission coefficient is 0.1, reflection coefficient then being 0.9. The first column contains the reflection coefficient raised to a power equal to the number of the stage. The second and fourth columns are copied, for eight stages, from Table IV. Values of the first column are multi-

TABLE IV
ESCAPES

| Stage | E. S. | E. B. |
|---|---|---|
| | | 12.31 |
| 1 | 20.79 | 3.44 |
| 2 | 10.63 | 3.39 |
| 3 | 6.77 | 3.30 |
| 4 | 4.74 | 2.97 |
| 5 | 3.55 | 2.65 |
| 6 | 2.76 | 2.28 |
| 7 | 2.17 | 1.92 |
| 8 | 1.74 | 1.62 |
| $\frac{1.375}{1-0.838}$ = | 8.50 | 8.50 |
| | 60.65 | 42.40 |
| | | 60.65 |
| | | 103.05 |

TABLE V

| $(1-e)^n$ | E. S. $e = 0$ | E. S. $e = 0.1$ | E. S. $e = 0$ | E. S. $e = 0.1$ |
|---|---|---|---|---|
| | | | 12.31 | 12.31 |
| 0.9 | 20.79 | 18.70 | 3.44 | 3.23 |
| 0.81 | 10.63 | 8.61 | 3.39 | 2.75 |
| 0.729 | 6.77 | 4.94 | 3.30 | 2.41 |
| 0.656 | 4.74 | 3.11 | 2.97 | 1.95 |
| 0.59 | 3.55 | 2.10 | 2.65 | 1.56 |
| 0.532 | 2.76 | 1.47 | 2.28 | 1.21 |
| 0.479 | 2.17 | 1.04 | 1.92 | 0.92 |
| 0.431 | 1.74 | 0.75 | 1.62 | 0.70 |
| 0.388 | 1.375 | | | |
| $\frac{0.388 \times 1.375}{1 - 0.838 \times 0.9}$ = | | 2.18 | | 2.18 |
| | | 42.90 | | 29.22 |

plied into the values in the second and fourth, to give the third and fifth columns. An exception is to be noted for the first escape to bottom, which, having come direct from sky, is unmodified.

The escapes for Stage 9 are reduced to $(0.388 \times 1.375)$. Instead of summing up the infinite series by dividing this value by $(1 - 0.838)$, it must be divided by $(1 - 0.838 \times 0.9)$, or $(1 - 0.755)$. This is because successive escapes are now reduced not only by the Repeat Factor, but also by the absorption of 0.1. Total escape to sky is 42.90, and to bottom 29.22.

The energy escaping to the bottom, and its effects, must now be taken care of. The bottom will now be considered as a source the same as the sky was. Its position bears the same relation to the walls and sky, in reverse, as the sky did to the walls and bottom. Therefore, just what the sky did, in toto, must be determined.

The sky admitted 100 watts, and due to inter-reflection by *walls alone*, got back (by escape to it) 42.90. The bottom, due to escape values "saved up" there, is now a source of $0.9 \times 29.22$. But this source, being like a sky source, gets back 42.90 parts in a hundred, or $0.429\ (0.9 \times 29.22)$. Of this, 0.9 will be sent out again,

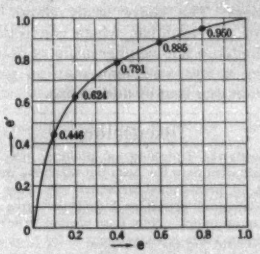


Fig. 3

and some will return, and so on. The total value of the bottom as a source is then, after summing up,

$$0.9\ \frac{29.22}{1 - 0.9 \times 0.429}$$

But what is wanted is the total escape to the sky. If the sky, out of 100, gave an escape of 29.22 to the bottom, the bottom as a source will do likewise for the sky, so the escape to sky due to bottom as source is the above value multiplied by 0.2922, which gives 12.52.

The total escape to sky is then 12.52 plus 42.90, or 55.42, out of 100 originally entering. Or, out of one watt entering the slot mouth, 0.5542 escapes to sky again; this gives a reflection coefficient for the slot mouth. The emission coefficient is $(1 - 0.5542)$ or 0.446. This is called $e'$, the effective emission coefficient for the slot mouth.

### Effective Emission Coefficients for Enveloping Surface

In the case just carried through, for an actual $e$ of 0.1, the enveloping surface (slot mouth area) was found to have an effective, $e'$, of 0.446. This means that if a surface of this kind, being originally flat, is improved by putting on fins to make the surface "all slots" of the 2 x 8 size, its total radiation would be increased over

four times, $e$ being 0.1, and surface temperature being everywhere constant.

Fig. 3 shows the relation of $e'$ to $e$ for this slot proportion over the entire range. Ordinates to the curve are believed to have no errors greater than 4 per cent. The points placed in small circles were computed as in the preceding work.

## Conclusions

Stefan's law of emission holds only for non-interfering surfaces. Where corrugations, convolutions, slots, or fins occur, an effective coefficient used in connection with the enveloping surface must be used.

If the surface is a black-body to begin with, radiation is not increased by slotting or finning it; but if $e$ is unavoidably low, considerable benefit may be derived.

It is probable that cooling fins have been added to hot bodies primarily with the idea of increasing dissipation by convection. The above study shows that in a vacuum tube, for example, where convection cooling may be negligible, a hot member made, of necessity, of a metal having a low coefficient, may be considerably assisted in radiating heat by adding fins.

## Discussion

**Joseph Slepian:** The kind of problem which Professor Moore has dealt with here has been put up to me perhaps half a dozen times in my professional career but except for a statement as to the fundamental principles I could not give much satisfaction to my questioners. Now I am pleased to have this paper on hand and know there is a treatment in his book to meet any future occasion when I shall be consulted on this subject.

I recall an experiment which confirms one of the results that Professor Moore has obtained. This experiment was carried out by Mr. Chubb of the Westinghouse Company some years ago with an unexpected result. The particular problem with which Mr. Chubb was concerned was to heat up a fine filament contained in a cylindrical chamber as rapidly as possible. Having made a first test to determine the length of time for the filament to rise to a certain temperature, it was thought that by polishing the inner surface of the cylinder so as to make it strongly reflecting, the time for heating the filament would be shortened. The experiment was carried out and it was found that in the interior of the highly polished cylinder the filament took just as long to heat up as in the unpolished cylinder.

The explanation appears in Professor Moore's paper, where dealing with cylindrical containers, he points out that if the interior body is small compared to the outer body, the nature of the outer wall of the cylinder makes very little difference in the temperature of the inner body. Thus the apparently paradoxical result of Mr. Chubb's is explained.

**K. W. Miller:** I was under the impression that a slotted surface would not radiate any more heat than the equivalent enveloping area, provided the surface of the material obeys Lambert's law. A piece of porous material at temperature equilibrium in a furnace appears of equal brightness as a smooth surface. If color is an indication of amount of radiation under these circumstances, apparently the porous and smooth surfaces are radiating equal amounts of heat per unit area of enveloping surface at equal temperature. Is there some error in the assumption that a porous body would simulate a slot or is there actually more heat radiated from a porous body?

**B. L. Robertson:** (communicated after adjournment) Work on heat radiation, as applied to the engineering field, has been rather small, and existing information which can be used in attacking problems involving heat radiation is very meager. The dissipation of heat from electrical apparatus has been previously discussed almost wholly from the standpoint of conduction and convection, and more from convection than from conduction. It seems unnecessary to say that the work of Professor Moore furnishes a welcome contribution to the study of heat dissipation by radiation.

Professor Moore takes the black body as the standard of reference for radiation and uses unity as the coefficient of emission. In other words, his case is ideal, but in that he is perfectly justified. Although an open surface, or the face of a slot, having an emissivity coefficient of one does not actually exist, it can be very closely approached, and to such an extent that the difference is only a few per cent and entirely within practical engineering accuracy. R. H. Heilman has very recently investigated the emissivity values for various surfaces and has found that many materials used in engineering practise have coefficients of emissivity about 98 per cent of that for the black body. This may be another case in which a knowledge of the limitations of certain features of a problem may permit an easier calculated result by allowing simplifying assumptions which could not otherwise be made.

As pointed out in the paper, the temperature $T_2$ given in the Stefan-Boltzmann law for radiation is a quite uncertain quantity, as is also the area of the radiating surface which is to be used. Most statements concerning the law, and which are found in college textbooks on physics, simply mention *radiation to surroundings*, with no added thought as to the nature of the surroundings, whether or not the surrounding surfaces are the same materials and at the same initial temperatures, or whether or not it makes any difference. One book implies that the law holds only for two black bodies. It is with difficulty that one can thus use the expression to obtain results for even the most simple cases of radiation. The fact that Professor Moore has found the law to hold for only non-interfering surfaces helps to clarify its interpretation to some extent. Certainly, it shows a limitation in its use.

Some time ago a transformer engineer made the statement that the radiation of heat from a plain transformer tank was the same as that from a corrugated tank having the same envelope, and that the radiation was not dependent in any way upon the configuration. The statement was questioned at the time since it is not apparent, but this impression is somewhat generally existent. The paper notes that such a fact is true for only a surface which is initially a black body, and that for surfaces having lower coefficients of emissivity corrugations may appreciably increase the radiation.

Just recently L. Wetherill and J. V. Montsinger have published the results of the effect of the color of the tank on the temperature of self-cooled transformers operating under service conditions. They have agreed with earlier results presented by E. J. Moore and J. H. Moulton which show that transformer tanks painted light gray reduce the oil temperature 1 or 2 deg. cent. more than tanks painted black, but that this difference is in no way pronounced. The conclusions of the first paper indicate that radiation alone for light colored tanks would perhaps show a pronounced effect upon the oil temperature. That is, by conclusion No. 4 of that article it is shown that using very low emissivities a very great increase in temperature rise was found; therefore, first, radiation instead of convection must have been the chief means of dissipation in the tests here referred to, and second, the profound effect seems to show that low emissivities give high, rather than low rises. Any explanation for these results has been omitted from the above treatments, and I should like to ask Professor Moore if, in any of his work, he has come across a reason for this expected reduction not being found.

Montsinger and Wetherill also conclude from test data taken in the field that as the surface of a transformer tank becomes more and more convoluted, the temperature rise for metallic

paints having low coefficients of emissivity becomes less and less. This result agrees directly with the conclusion given by Professor Moore in which he states that if $e$ is unavoidably low, considerable benefit may be derived by slotting or finning a body in order to increase its rate of heat dissipation by radiation.

**Lynn Wetherill:** (communicated after adjournment) We have done some work on problems of this nature in determining the effect of different kinds of paint on transformer temperatures. It was desired to find the effect of painting a corrugation of 3 in. depth and 2 in. pitch with aluminum (coefficient of emission at operating temperatures about 0.55). A solution similar to that used by Mr. Moore was used except that only three stages were completed instead of eight. At this point it was found that if all the radiation still being reflected were assumed to escape from the corrugation the effective emissivity would be 0.72, while if none of it escaped the effective emissivity would be 0.68. This was considered to give sufficient accuracy. It is interesting to note that the re-entrant portion of the corrugation acted practically like a black body. Only a small amount of time is required to work out such a problem with reasonable accuracy for engineering purposes.

This point illustrates one of the reasons why transformers having a tubular or radiator tank are not much affected by the kind of paint used on the tank, as the effective emissivity is greatly increased by the presence of the convolutions. As a result a paint with comparatively low emissivity will radiate nearly as much heat from a corrugated surface as the customary dark gray paint.

**A. D. Moore:** If you put a slotted object inside a relatively complete enclosure and bring the whole thing up to a given temperature, one way of knowing that everything is at a uniform temperature is to see that everything disappears in outline. There are certain radiation laws that come into the heat balance situation there and you will know that temperature uniformity has been arrived at when you can't see the slot. However, if you get the object hot enough and quickly take it outside of the furnace (remove it from the black-body enclosure, in other words) and observe it before it has a chance to cool off on the corners, then depending on the reflection coefficient, there is a much greater amount of light from the slot. The thing works backward in terms of light. If you take the slot and imagine it to be a light court in a building in something like the proportions 2 by 8, by lining the cavity with black paint you will get a small amount of direct sky illumination on the bottom windows. If you line the side walls only with an 0.8 reflection paint, the illumination on the bottom windows will go up to something like ten times as much. If you then remember to put in a bottom having an 0.8 reflection value, you will get a total increase of 24 or 25 times as much.

**A. D. Moore:** Professor Robertson's question about the Wetherill-Montsinger paper (see p. 41) raises an interesting point or two. Since receiving the discussion I have made a number of calculations on temperature rise of transformer temperatures for various conditions.

The gross heat loss of the transformer is (a) its convection loss, or dissipation, and (b) its emitted radiation loss, or dissipation.

The gross heat gain is (c) incident radiation from the sun that is absorbed; (d) incident radiation from the ground, absorbed; and (e) incident radiation from the atmosphere, absorbed. In general, (e) is probably negligible. None of the other four items can be neglected.

My calculations, as well as simple argument based on theory, show that *for steady conditions*, it would be a rare case indeed in which the use of aluminum paint did not result in higher temperatures. The only exception where the black paint should show a higher rise, is when a disconnected transformer is sitting in strong sunlight, surrounded with air at something like 30 deg. cent., and surrounded by a ground (such as rock, sand) whose surface has gone up to something like 80 deg. cent.

I believe that in all usual conditions the black surface should show the lesser rise.

There are two questions that should be raised about the Wetherill-Montsinger paper. First, if all factors except paint used were made exactly equal, and if the tests were conducted under steady conditions, *in still air*, would not the aluminum and white paints show the higher temperatures in top oil? Second, should not *color* of paint be suppressed in papers dealing with radiation? It is true that when we are concerned with the sun's radiation alone, color is important, simply because so much of the energy is in the visible part of the spectrum; but for ground radiation, and for most cases of low-temperature radiation, the color of the receiving surface is usually one of the least important characteristics of the surface.

If transformers had to do without convection dissipation, an aluminum or white paint (that is, a low-emissivity paint) would cause a higher ascent of temperature over the "black" surface temperature, than would occur with convection present.

# Power Transients in A-C. Motors

## A Watt-Oscillograph Study

BY L. E. A. KELSO[1] and G. F. TRACY[1]

Associate, A. I. E. E. Associate, A. I. E. E.

***Synopsis.***—*The purpose of this paper is to describe the application of the watt-oscillograph to the study of the performance of rotating a-c. machinery under transient conditions. Some typical transient cases are presented with a view to illustrating the possibilities of such an application. The analysis of a film taken with the watt-oscillograph yields not only power, but also current and power factor. It is thus possible, for the case of sinusoidal voltages and currents, to determine the locus of the current vector as it changes from one position to another.*

*The paper also describes the watt elements of the oscillograph developed for this study, with data as to the degree of accuracy that may be expected from them. An outline of the method of analyzing an oscillogram so as to obtain the performance curves and the current locus is also given.*

### I. The Watt-Element and Its Use

*1. Introduction.* The watt-oscillograph not only serves the primary purpose for which it has been developed, namely, that of recording the instantaneous values of power in an a-c. circuit; but, in the case of sinusoidal voltages and currents, its records also permit of the determination of the magnitude and the phase relation of the current with respect to the voltage. This determination may be made for transient as well as steady-state conditions, and therefore the locus of the current vector as it changes from one position to another may be determined. Such an analysis has proved to be particularly applicable to the study of transient conditions in three-phase a-c. motors, as, for example, the behavior of a synchronous motor following a change of mechanical load. The changes in the magnitudes and in the phase relations of the currents in such transients take place relatively slowly so that a reliable analysis may be made throughout the whole of the transient period. In cases where the duration of the transient is only a very few cycles it is difficult to obtain reliable analyses by means of the watt-oscillograph.

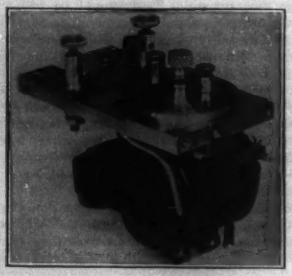

Fig. 1A—Illustration of Watt Element

*2. Description of the Watt-Element.* Illustrations of a single-phase watt-element as developed for these studies are shown in Figs. 1A and 1B. The magnetic circuit consists of twelve strips of 14-mil silicon steel, each strip being 1.43 cm. wide. The length of the iron path is 12 cm., and that of the air-gap 0.07 cm. In order to minimize leakage flux and iron loss, the two exciting coils of 37 turns each are placed close to the air-gap as shown in Figs. 1A and 1B. The rated field current is 3.54 amperes (peak value) and the corresponding exciting m. m. f. is 262 ampere-turns (peak value). At this excitation the flux density in the air gap is approximately 4700 maxwells per sq. cm., and in the iron it does not exceed 5000 maxwells per sq. cm. The volt-ampere load of the field winding at rated excitation is only 1.5 volt-amperes. An element, therefore, can be connected in the secondary circuit of a standard current transformer without imposing any appreciable additional burden on the transformer.

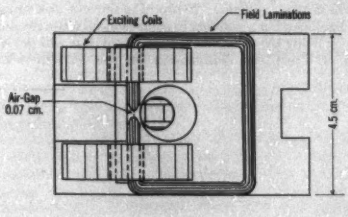


Fig. 1B—Plan View of Watt Element (from below)

Three elements are mounted in a holder which is easily interchangeable with the standard holder in a three-element Westinghouse portable oscillograph. In order to obtain sufficient deflection the vibrators used are the Westinghouse super-sensitive vibrators rather than the standard vibrators. These are oil damped. The full scale deflection of 4.5 cm. peak to peak is obtained with a field excitation of 3.54 amperes (peak value) and 0.0424 ampere (peak value) in the vibrator.

The accuracy of the instrument was tested by

1. Assistant Professor, University of Wisconsin, Madison, Wis.



29-160

connecting each element in a simple a-c. circuit in which both the magnitude of the current and its phase with respect to the voltage could be varied at will. Two groups of films were taken, and the results obtained from these were checked against the readings of calibrated meters. One group consisted of a series of records at unity power factor and various values of field current; the other, at a given field current and various power factors. The current through the vibrator was held constant. The former test showed that the values of volt-amperes as calculated from the oscillograph records were within 1.4 per cent of the corresponding meter readings. The latter test showed that with phase angles from about 30 deg. to 90 deg. the maximum error was less than 4 deg. The accuracy with which the phase angle may be determined decreases, however, as the angle approaches zero; and in the neighborhood of zero the phase angle cannot be found within about 10 deg. This is not a disadvantage in the case of three-phase power measurement as will be pointed out later. It was apparent from these results that with suitable ranges of field and vibrator currents any errors caused

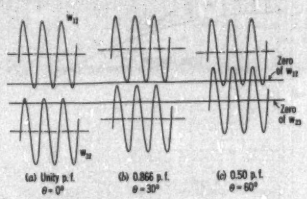


FIG. 2—TYPICAL THREE-PHASE POWER CURVES

by magnetic saturation and hysteresis in the iron circuit are no greater than those ordinarily incurred in measuring distances on an oscillogram. It may be said, then, that the flux densities in the air-gap are substantially proportional to the current in the main circuit, and that the deflection of the vibrator is substantially proportional to the instantaneous power.

*3. Interpretation of the Oscillograms.* It will be recalled that if the voltage and current in a single-phase circuit vary sinusoidally the instantaneous power curve is a double-frequency sinusoid the peak value of which is proportional to the volt-amperes and the axis of which is displaced from the zero line of the power curve by a distance proportional to the average power. Since the ratio of average power to volt-amperes is the power factor, the latter may be found by taking the ratio of the displacement of the axis of the power curve to the peak value of the double-frequency sinusoid. If an oscillogram of a power curve is taken during a transient condition so that power, power-factor, and current are varying, the value of these quantities may be found for all points on the film provided that the vibrator has been properly calibrated.

Either two or three single-phase elements may be used to measure power in three-phase circuits. When two elements are used they are connected in the same way that two single-phase wattmeters would be used to measure three-phase power, with the exception that it is preferable to reverse the potential connections of one element. The two elements trace out two power curves, each having the same characteristics as the single-phase curve. The total power is the sum of the powers indicated by each element, irrespective of load balance.

If the voltages and currents are sinusoidal and balanced, the expressions for the two power curves are:

$$w_{12} = E\,I\,[\cos(\theta - 30°) - \cos(2\,\omega\,t - 30° - \theta)]$$

$$w_{32} = E\,I\,[-\cos(\theta + 30°) - \cos(2\,\omega\,t - 30° - \theta)]$$

where $E$ is the r. m. s. voltage between lines, $I$ is the r. m. s. line current, and $\theta$ is the angle between phase current and phase voltage. The double-frequency components of the two curves are in phase with each other, and have the same amplitudes. The axis of the curve $w_{12}$ is displaced *above* its zero line by a distance proportional to cos $(\theta - 30°)$ while the axis of the curve $w_{32}$ is displaced *below* its zero line by a distance proportional to cos $(\theta + 30°)$. The phase angle, $\theta$, at any point on an oscillogram may therefore be found from either power curve. The value found from one curve may be checked against that found from the other, as the two values should be the same for balanced conditions. The angle between the current in the field and the voltage across the potential terminals in one element differs by 60 deg. from the angle between the current and the voltage in the other element. Therefore, when that angle in one element is in the neighborhood of zero degrees so that it cannot be determined accurately as previously pointed out, the corresponding angle in the other element is in the neighborhood of 60 deg. at the same time, and may be determined accurately.

The disposition of the two power curves for three typical power factors in a balanced three-phase circuit is shown in Fig. 2. When the power factor is unity both curves are displaced from their zero lines by equal distances, the first up and the second down, as in Fig. 2A. When the phase angle is 30 deg., as in Fig. 2B, the displacement of one of the curves is a maximum, *i. e.*, the tips of the double-frequency sinusoid just touch the zero line. In Fig. 2C the axis of one of the power curves is not displaced at all. If the potential terminals of one of the elements had not been reversed the two curves would have been 180 deg. out of phase, and the tips of the curves would overlap, making it more difficult to distinguish them clearly.

## II. TYPICAL CURRENT LOCI

The following section of the paper contains the results obtained from the analyses of the watt-oscillograph records taken of a few typical transient conditions in three-phase induction and synchronous motors. The performance curves and current locus corresponding to each case are shown. On each oscillogram are three

curves, two of power and one of line voltage. In analyzing an oscillogram the envelopes of the two curves were drawn and ordinates were erected at suitable equal intervals, usually at every cycle on the voltage wave. The peak values of the double-frequency com-

FIG. 3A—RATED LOAD THROWN ON INDUCTION MOTOR (FILM 30)

ponents of the power curves and their displacements from their respective zero lines were measured at each ordinate. A calibration film was taken to accompany each film of a transient condition, and the volt-ampere constant and voltage constant were obtained from it.

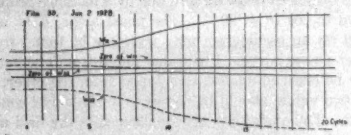


FIG. 3B—POWER CURVE ENVELOPES OF FILM 30

The calibration film was taken with a steady-state load and corresponding meter readings were obtained. In the following discussion each oscillogram is accompanied by a tracing of the envelopes of the power curves

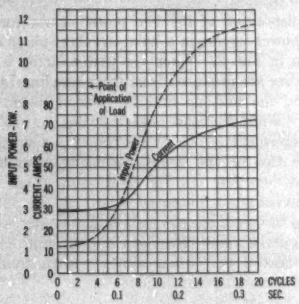


FIG. 3C—PERFORMANCE CURVES FROM FILM 30

15-hp. induction motor, 110–220-volt, 78.8-ampere, 60-cycle, 1200-rev. per min.

showing the ordinates at which the measurements were made. In each case the envelope of one curve has been shown by full lines and that of the other by dotted lines.

4. *Induction Motor Transients.* Power curves taken while rated load was being thrown on a 15-hp. induction motor are shown in Figs. 3A and 3B. The corresponding performance curves and current locus are shown in Figs. 3C and 3D. The load, which consisted of a generator direct-connected to the motor, was thrown on at about ordinate 2 and the current and power then increased steadily from their no-load values to approximately their full-load values at ordinate 20. The magnitude of the current and its phase angle with respect to the voltage were determined at each of the ordinates 1 to 20. Only the no-load and the full-load current vectors have been drawn, but the locus of the end of the current vector as it moves from one of these positions to the other has been shown. The numbered positions on this current locus correspond to the numbers of the ordinates on Fig. 3A. Since these ordinates were erected at equidistant intervals on the oscillogram

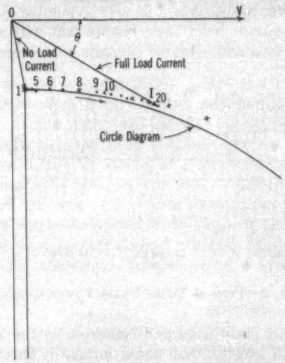


FIG. 3D—CURRENT LOCUS FROM FILM 30

Points marked (·) from Film 30
Points marked (x) from load test data

it means that the corresponding points on the current locus represent equal intervals of time. An indication, therefore, of the rate at which the phase position of the current vector changes, may be obtained from the distances between the points on the current locus. The phase position changes most rapidly, for example, in the vicinity of ordinate 8.

A check on the current locus as obtained from the oscillogram was made by laying out a similar locus from an ordinary load test in which the points were obtained from meter readings. It will be noticed that the two loci coincide. This is to be expected in the case of an induction motor in which the load is gradually applied, since there should be no tendency toward oscillations. The circle diagram of the motor, constructed in the usual way, is also shown.

Figs. 4A to 4D show the case of the breakdown of a

7.5-hp. induction motor. A heavy overload was thrown on the motor so that the speed dropped nearly to zero by the time the film exposure was completed. The circle diagram of this machine is also shown.

*5. Synchronous Motor Transients.* Figs. 5A and 5B show the power curves taken while rated load was being thrown on a 15-kv-a. synchronous motor. The load consisted of a d-c. generator as in the induction

FIG. 4A—BREAKDOWN OF INDUCTION MOTOR (FILM 109)

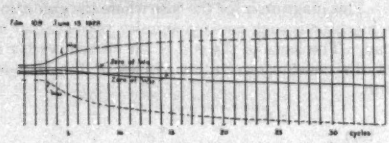

FIG. 4B—POWER CURVE ENVELOPES OF FILM 109

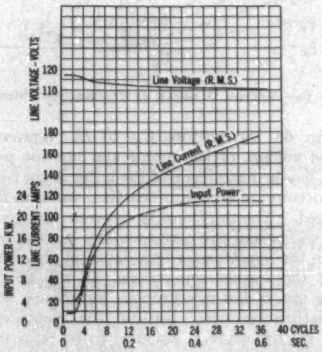


FIG. 4C—PERFORMANCE CURVES FROM FILM 109

7.5-hp. "Self-Start" motor, 1160-rev. per min., 110-volts, 39-amperes, 60-cycles

motor case. The excitation of the motor was adjusted so that the power factor was unity at full load. The power and current start to increase at about ordinate 6 and build up to values that are greater than the ultimate steady-state values. After two or three oscillations both settle down into their steady-state, full-load values. The actual point of throwing the load on was about ordinate 2 and not at ordinate 6. There is a dip in both the power and current curves which is caused, presumably, by a disturbance in the circuit which was used to excite the fields of both the motor and the d-c. generator, when the field circuit of the latter was closed.

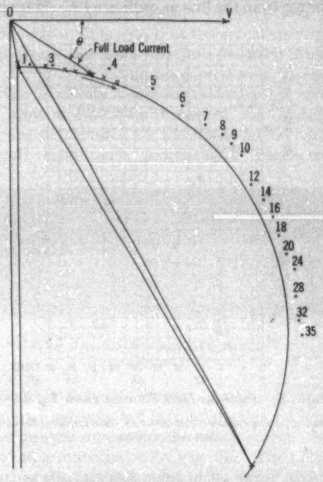


FIG. 4D—CURRENT LOCUS FROM FILM 109

Points marked (.) from Film 109
Points marked (x) from load test data

The current locus in Fig. 5D corresponds to Fig. 5A, and is a peculiar curve which roughly resembles an elongated spiral. Ordinate 1 is the position of the

FIG. 5A—RATED LOAD THROWN ON SYNCHRONOUS MOTOR (FILM 68)

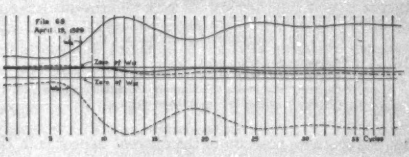

FIG. 5B—POWER CURVE ENVELOPES OF FILM 68

current vector $I$ at no load. It is seen that the locus has a small hook in it which corresponds to the initial dip in the current and power curves. The vector then

travels out along a smooth curve through ordinates 7 to 12 as the load builds up. Its angular velocity is high in the vicinity of ordinates 8, 9, and 10 as indicated by the interval between these points. Maximum power is being drawn from the line at ordinate 12. It is apparent

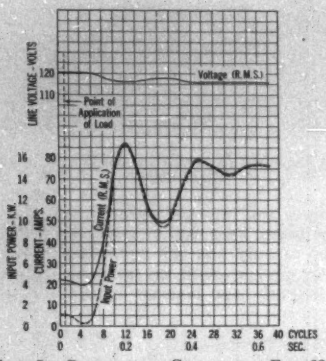


FIG. 5C—PERFORMANCE CURVES FROM FILM 68

15-kv-a., a-c. generator, 110–220-volt, 78.8 ampere, 60-cycle 1200-rev. per min.

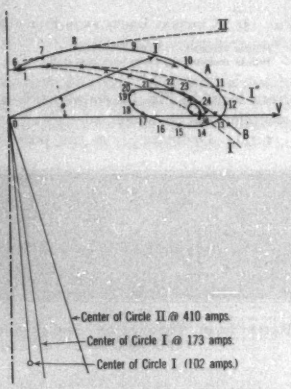


FIG. 5D—CURRENT LOCUS FROM FILM 68

Curve *A* from Film 68
Curve *B* from load test data
Circles *I'* and *I''* are synchronous impedance circles
Circle *II* is a leakage impedance circle

that the ultimate position of the current vector is in the vicinity of ordinate 38, *i. e.*, in phase with the voltage vector. On the same diagram has been shown the corresponding current locus as computed from load test data. These points fall on the familiar circular locus, and since the excitation was adjusted for unity power factor at full load the angle $\theta$ is nearly 90 deg. leading at no-load.

An explanation of the peculiar shape of the current locus in Fig. 5D may be given, by using the same methods and approximations as those of the Blondel circle diagram. When the motor is running at no-load its generated voltage vector is almost in phase opposition to the impressed voltage; while if the load is increased, the generated voltage vector lags farther behind its position at no-load. In the former case the resultant voltage acting across the impedance of the armature is very small, while in the latter case it is quite large (assuming that the magnitudes of the generated and impressed voltages are approximately the same). The current in each case is proportional in magnitude to the resultant voltage and lags behind it by an angle of nearly 90 deg. The vector diagram of Fig. 6A shows the position of the vectors for five different steady-state loads. This diagram is for the case where the excitation of the machine is such as to give unity power factor at full load. The locus of the end of the current vector is one of the constant-excitation circles of the Blondel diagram.

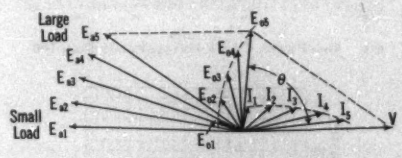


FIG. 6A—VECTOR DIAGRAM OF SYNCHRONOUS MOTOR

In Fig. 6A the vectors $E_{a1}$ to $E_{a5}$ represent the *excitation* voltage of the motor and not the *generated* voltage, for the magnitude of the latter is not constant; but, on account of armature reaction, varies as the load is changed. The relationship between any resultant-voltage vector and the corresponding current vector is therefore the *synchronous* impedance of the armature, and not the *leakage* impedance. It will be recalled that the use of the synchronous impedance accounts for armature reaction, because the magnetomotive force of the armature is assumed to be replaced by a fictitious reactance which is added to the leakage reactance of the armature, the combination of the two reactances being called the synchronous reactance. Thus in Fig. 6A, $I = E_0/z_s$ and $\theta = \tan^{-1} x_s/r_s$; where $z_s$ is the synchronous impedance, $x_s$ is the synchronous reactance, and $r_s$ is the effective resistance. One of the constant-excitation current loci of the Blondel diagram is shown by circle $I$ in Fig. 6B. This current locus corresponds to that shown in Fig. 6A. The center of circle $I$ is at point $C$ which is distant from $O$ by an amount equal to $V/z_s$, and the angle between $O\,V$ and $O\,C$ is $\tan^{-1} x_s/r_s$. The vector $V$ represents the impressed voltage.

Suppose that the armature reaction could be prevented in some way from changing the flux in the field poles. Such would be the case, for example, if either the field circuit or the damping grids had zero resistance so that the field flux were not allowed to change for an infinitely long time. This condition would mean that the additional fictitious reactance that replaces armature reaction is zero. The relation between the resultant voltage and the current is now $E_0/z_s$ instead of $E_0/z_a$ as it was before, where $z_s$ is the transient or leakage impedance of the machine; and the currents, therefore, will be correspondingly larger and will not lag behind the corresponding resultant voltages by so large an angle because $x_s$ is smaller than $x_a$. The current locus can now be shown to be another circle such as circle $I\,I$ in Fig. 6B with center $C'$ on a line $O\,C'$ which is displaced from the voltage vector by an angle $\tan^{-1} x_s/r_s$ and at a distance from $O$ equal to $V/z_s$.

The two circles $I$ and $I\,I$ of Fig. 6B represent two extreme conditions. Circle $I\,I$ is the locus of the

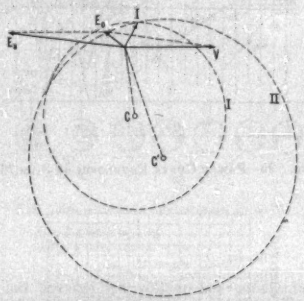


FIG. 6B—CURRENT LOCI OF SYNCHRONOUS MOTOR

current vector if the flux is prevented in some way from changing at all under the influence of armature reaction. Circle $I$ is the locus if the flux readily follows the changes in resultant magnetomotive force. This latter locus is the one that would be traced out if the data from an ordinary load test are plotted; for in such a test the load is increased in steps and there is plenty of time for the flux to change to a new steady value between each step. This circle, then, might be thought of as the current locus when the load is very slowly increased. When full load is applied all in one step, however, the current at first will tend to follow circle $I\,I$ because the flux cannot change readily on account of the damping action of the field circuit and of the damping grids. Then, as the flux gradually yields to the effects of the armature magnetomotive force the current vector will gradually move across to circle $I$.

Referring again to Fig. 5D, circles similar to those which have just been discussed are shown on this figure. Circles $I'$ and $I''$ on Fig. 5D both correspond to circle $I$ on Fig. 6B; *i. e.*, they are both synchronous impedance circles, but the value of the synchronous impedance was measured by two different methods. The value of $z_s$ for circle $I'$ was obtained from short-circuit test data while that for circle $I''$ from the zero power-factor test data. It is seen that the actual current locus as found from the load test falls between these two circles. Circle $I\,I$ of Fig. 5D corresponds to circle $I\,I$ in Fig. 6B; *i. e.*, its center was found by using the leakage impedance. The value of the leakage impedance was determined by the Potier method from the open-circuit and zero power-factor characteristics.

FIG. 7A—RATED LOAD THROWN OFF SYNCHRONOUS MOTOR (FILM 71)

It can be seen that the current locus for a rapidly increasing load actually tends to follow this circle at first, and then moves across to the other current locus as predicted in connection with Fig. 6B. The field structure reaches the farthest point in its swing about ordinate 12, at which point the voltage vector comes to rest; and starts to swing back again because it has overshot its ultimate position. During this time the armature reaction has had time to change the field flux and bring the current vector completely over to its steady-state locus. However, as the field structure swings back again the flux is again slow in changing, this time in the

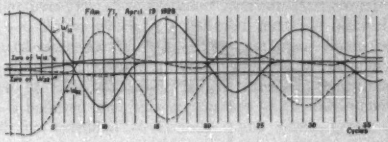


FIG. 7B—POWER CURVE ENVELOPES OF FILM 71

opposite direction; and so the current vector swings down below its steady-state locus. After two or three oscillations the hunting of the field structure dies out and the flux and current settle into their steady-state full-load positions.

Figs. 7A to 7D are for the case of rated load being thrown off a 15 kv-a. synchronous motor. The hunting is very apparent in this case as it persists for a long time. The field structure swings backwards and forwards around its no-load position going alternately into the region of generator action and the region of motor action. The power bands cross and re-cross each other in Figs. 7A and 7B, and the power curve in Fig. 7C goes

alternately positive and negative. The current locus shows characteristics similar to the one for the case of load thrown on the motor. It is obvious that the current vector will ultimately settle down into its no-load position as shown by position 1 in Fig. 5D.

Figs. 8A to 8E are for the case of a 15-kv-a. synchronous motor pulling out of step. The load was allowed to build up to a value which was beyond the maximum torque of the motor. In this case a contactor, mounted on the shaft of the motor, was connected so as to momentarily short circuit the voltage element at one point in each revolution of the motor shaft. As the machine was a six-pole machine this momentary short circuit would occur once every third cycle on the voltage wave if the machine were running in synchronism. The discontinuities in the voltage wave can be seen in Fig. 8A. After the application of load the intervals become greater than three cycles, indicating that the machine is slowing down. These marks afford a means of checking roughly the phase position of the field structure and of the excitation voltage, $E_a$, at the points at which they occur. If normal load had been applied these marks would have shifted to a new steady position on the voltage wave, the distance between the old and new positions being the angle of coupling for that load.

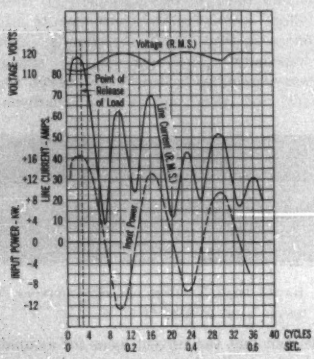


FIG. 7C—PERFORMANCE CURVES FROM FILM 71

15-kv-a., a-c. generator, 110-220-volt, 78.8-39.4-ampere, 60-cycle, 1200-rev. per min.

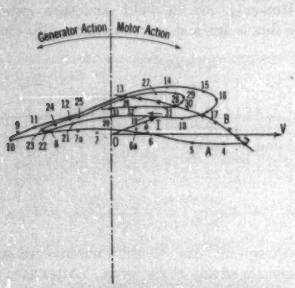


FIG. 7D—CURRENT LOCUS FROM FILM 71

Curve *A* from Film 71
Curve *B* from load test data

FIG. 8A—SYNCHRONOUS MOTOR PULLING OUT OF STEP (FILM 76)

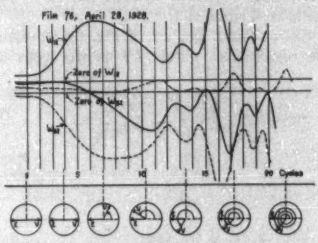


FIG. 8B—POWER CURVE ENVELOPES OF FILM 76

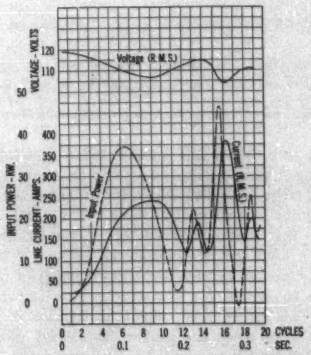


FIG. 8C—PERFORMANCE CURVES FROM FILM 76

15-kv-a., a-c. generator, 110-220-volt, 78.8-39.4-ampere, 60-cycle, 1200-rev. per min.

A group of vector diagrams is shown beneath the curve in Fig. 8B which indicate the phase position of the field structure (as shown by the excitation voltage vector $E$) at the points of discontinuity on the voltage wave. In these diagrams the vector $E$ has been made the reference vector because the points of short-circuit were made at even revolutions of the motor shaft; *i. e.*, at integral numbers of cycles of $E$. Thus at point 7 the motor shaft has made exactly two revolutions after passing point 1; *i. e.*, $E$ has gone through exactly 6

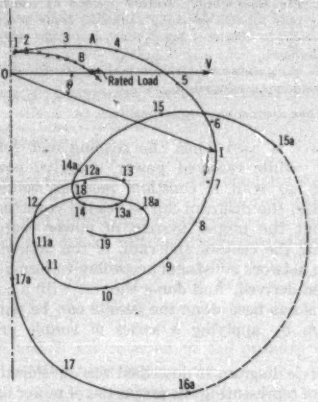


FIG. 8D—CURRENT LOCUS FROM FILM 76

Curve *A* from Film 76
Curve *B* from load test data

cycles, but the applied voltage has gone through 6 cycles and about 60 deg. in addition.

By referring to the power curve in Fig. 8C it is seen that the power reaches its first maximum about point 7. The phase relation between $-E$ and $V$ is about 60 deg. in this position. The power does not reach its first minimum value until about point 12 at which the angle between $-E$ and $V$ is about 180 deg. Then there is a small increase in power to point 13 after which it again passes through a minimum at point 14. The vector diagrams show the angle between $-E$ and $V$ to be roughly 360 deg. at point 14, indicating that the rotor has dropped back a whole pair of poles and the power cycle is about to repeat itself. The second power cycle is similar to the first, the difference being that the power rises to a higher maximum value and the time of the power cycle is much less than that of the first cycle because the rotor is now slipping back at a greater rate. The most noticeable feature of this current locus is its departure from the circular locus of the Blondel circle diagram according to which the current should traverse a true circle (see circle $I$, Fig. 6B) for this case.

Fig. 8E was taken under the same conditions as Fig. 8A, except that the third element was used to record field current. The variations in field current show in a striking way how the field circuit is attempting to prevent the flux from changing. When the load first increases the field current also increases in an effort to counteract the increasing demagnetizing effect of the

FIG. 8E—FIELD CURRENT UNDER SAME CONDITIONS AS FILM 76

armature current. This sudden increase in field current is repeated every time the field structure pulls away from a pair of armature poles of the correct polarity to produce motoring torque.

## III. CONCLUSION

The foregoing illustrations demonstrate a field of usefulness for the watt-oscillograph which is much broader than merely that of recording instantaneous power. The current loci show graphically certain characteristics of a-c. motors which, it is believed, have not been obtained experimentally by other methods. Such loci should prove useful in a theoretical study of the operation of these machines under transient conditions. It is believed that this application of the instrument will be extended to include many other types of transients.

The authors gratefully acknowledge the many suggestions given them by Professor Edward Bennett and Professor J. R. Price of the Department of Electrical Engineering, University of Wisconsin.

# The General Circle Diagram of Electrical Machinery

BY FREDERICK EMMONS TERMAN,*
Associate, A. I. E. E.

CECIL LOUIS FREEDMAN,†
Non-member

THEODORE LOUIS LENZEN,†
Associate, A. I. E. E.

and

KENNETH ALFRED ROGERS†
Non-member

*Synopsis.—The well known circle diagram of a transmission network is applied to electrical machinery, giving circle diagrams of alternators, synchronous motors, synchronous condensers, and transformers. These diagrams give a graphical representation of the machine performance under all possible conditions. Such quantities as power loss, power input, power output, field current, etc., for any operating condition can be obtained by inspection. These diagrams have the same field of usefulness as the circle diagram of the induction motor.*

*The transmission network circle diagram can be applied to the induction motor, yielding in the approximate representation the Heyland diagram, which is merely a special case of the more general diagram. The transmission network method of attack gives a straight-forward solution of many induction motor problems that would otherwise be difficult to handle, such as a motor equipped with a phase advancer.*

*Methods of obtaining network constants by measurements rather than computations are described.*

## Introduction

ANY electrical network connecting two pairs of terminals can have its electrical characteristic expressed in terms of four constants $A$, $B$, $C$, and $D$ through the equations

$$E_s = A\,E_r + B\,I_r$$
$$I_s = C\,E_r + D\,I_r \qquad (1)$$

or the equivalent equations

$$E_r = D\,E_s - B\,I_s$$
$$I_r = A\,I_s - C\,E_s \qquad (2)$$

The subscripts $s$ and $r$ denote sending and receiving and quantities, respectively. The coefficients $A$, $B$, $C$, and $D$, which are known as *network constants*, take into account the composition of the transmitting network and the frequency. They can be readily obtained for any particular case by methods and formulas that have been worked out by Evans and Sels,[1] or by the measurements described in Appendix I. Only three of the four constants are independent, since the relationship $A\,D = I + B\,C$ must always exist between them. For a symmetrical network $A = D$.

When either the sending end or the receiving end voltage is constant, the electrical properties of the network can be represented graphically by a circle diagram consisting of families of circular loci drawn on a power—reactive power coordinate system. This circle diagram is a graphical representation of Equations (1) and (2), and when once drawn, an inspection of the one diagram will give such quantities as power, current, admittance, and power factor at both sending and receiving ends of the network, also efficiency of transmission, power lost in transmission, and so on almost without limit.

A coordinate system of sending end power and reactive power is used when the sending end voltage is constant, while received power—reactive power coordinates go with a constant receiver voltage. In either case, the diagram can be readily constructed by laying out the proper system of power coordinates, computing the centers and radii of the desired circles from the network constants according to formulas that have been derived,[2] and doing the rest with a compass. After this has been done the results can be gone over for errors by applying a series of simple graphical checks.

The circle diagram as described was developed for the purpose of representing the properties of power lines and transmission networks. In a highly specialized form this general circle diagram becomes the well known induction motor circle diagram. In both applications this graphical method has been of inestimable value because it shows on one drawing all possible conditions. After the circles have once been laid out no further computations are necessary, and a complete visualization of the network performance is easily obtained.

The circle diagram method of graphical representation can be used to show the performance of alternators, synchronous motors, transformers, and synchronous condensers with the same advantages that are already well known in the cases of the transmission line and the induction motor. The transmission network circle diagram is applied to such electrical equipment by substituting for the actual machine an equivalent electrical network for which a circle diagram is then drawn. The details of the transformation from machine to electrical network, and the special problems involved are taken up in the following sections.

## Circle Diagram of the Transformer

The action that takes place in a transformer is

*Assistant Professor, Stanford University, Calif.
†Graduate Student, Stanford University, Calif.

1. Evans and Sels, *Power Limitations of Transmission Systems*, A. I. E. E. Trans., Vol. 43, 1926, p. 26. Also a series of articles by Evans and Sels in *Electric Journal*, 1921.

2. F. E. Terman, *The Circle Diagram of a Transmission Network*, A. I. E. E. Trans., Vol. 45, 1926, p. 1081.

accurately given by the well known network shown in Fig. 1, which has the network constants

$$A = D = 1 + Z\,Y/2$$
$$B = Z\,(1 + Z\,Y/4)$$
$$C = Y \qquad (3)$$

Ratios of voltage transformation other than the unity value to which Equations (3) apply can be taken into account in the network constants. Calling the ratio of primary to secondary voltage $N$ ($N$ more than one

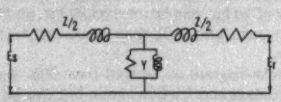


FIG. 1—EQUIVALENT CIRCUIT OF TRANSFORMER

Z-Series resistance and reactance representing primary and secondary copper losses and leakage reactance

Y-Shunt admittance representing core loss and magnetizing current

for a step-up ratio and $N$ less than one for a step-down transformer), then when the transformer leakage reactance $Z$ and admittance $Y$ are referred to the secondary side, the network constants have the values

$$A = N\,(1 + Z\,Y/2)$$
$$B = N\,Z\,(1 + Z\,Y/4)$$
$$C = Y/N$$
$$D = (1 + Z\,Y/2)/N \qquad (4a)$$

When $Z$ and $Y$ are referred to the primary side the network constants become

$$A = N\,(1 + Z\,Y/2)$$
$$B = Z\,(1 + Z\,Y/4)/N$$
$$C = Y\,N$$
$$D = (1 + Z\,Y/2)/N \qquad (4b)$$

Equations (3) and (4) consider the leakage reactance equally distributed between primary and secondary, which is the usual assumption. Network constants for other divisions are readily obtained by using methods outlined by Evans and Sels.

The circle diagram of the transformer is a transmission line type of circle diagram drawn for the network constants given in Equations (4). When applied to an actual example the result is as shown in Fig. 2, which has been drawn for a 1000 kv-a. transformer operating with constant primary voltage. To avoid confusion, only power loss, power factor, and voltage circles are shown, although of course many other types of loci can be drawn when desired.

The transformer circle diagram gives a complete and *exact* graphical representation of the properties of the network shown in Fig. 1, and therefore shows the transformer performance to the same degree of precision as does the usual equivalent circuit. In constructing a circle diagram it is necessary that either the sending end (primary) voltage or the receiving end (secondary) voltage be kept constant. This restriction ordinarily involves no limitation to the usefulness of the diagram because transformers are normally supposed to operate with substantially constant voltage at one terminal.

The transformer is a very efficient piece of equipment, with small voltage drops and low losses. As a consequence some of the circles have large radii and appear to be almost straight lines on the diagram. This is the case with the secondary voltage and load power factor loci in Fig. 2, and is ordinarily to be expected. Circles too large for a beam compass can be readily drawn with the aid of a piano wire.

In drawing circles giving power dissipated in the transformer, great care must be taken in computing the circle radii, and it is necessary that the network constants $A$ and $D$ be known to a number of significant figures sufficient to incorporate to a fair accuracy the effect of the $Z\,Y$ term which they contain. Logarithm tables of at least five places are usually advisable in computations leading to the loss circles. Instead of computing the loss circles in the usual manner, it is more satisfactory under ordinary circumstances to obtain them by the much simpler method described in Appendix II.

It is of course possible to use equivalent transformer circuits other than that shown in Fig. 1. For example, the impedance $Z$ can be considered as lumped in one piece, and placed either on the sending or receiving side

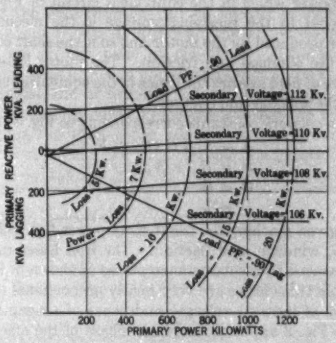


FIG. 2—CIRCLE DIAGRAM OF 1000-KV-A. TRANSFORMER WITH PRIMARY VOLTAGE KEPT CONSTANT WITH 110 KV.

of the admittance $Y$. Such an equivalent circuit has slightly simpler expressions for network constants than does Fig. 1, and involves only a slight approximation. In making approximations it is very necessary that the network constants be *exactly* the constants of the network in question. Simplifying the formulas for network constants by dropping apparently insignificant terms will sometimes yield amazing results. Thus dropping the $Z\,Y$ terms of $A$, $B$, and $D$ in Equations (3) introduces an error in these constants of only about one per cent, but this omission is equivalent to neglecting *all* of the iron loss, and affects practically nothing else.

### Circle Diagram of the Synchronous Motor

The performance of a synchronous motor can be shown by a circle diagram based on the equivalent circuit of Fig. 3, which represents one phase of the machine. In this figure $E_r$ is the actual induced phase voltage, as determined by air-gap flux, $E_s$ is the sending or terminal phase voltage, which is constant in the case of a motor, $X_a$ and $R_a$ are the armature leakage reactance and effective a-c. resistance (including armature copper and stray load losses), respectively, per phase,

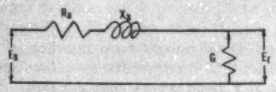


Fig. 3—Equivalent Circuit of Synchronous Motor and Synchronous Condenser

$R_a$ – Series resistance representing armature copper and load losses
$X_a$ – Series reactance representing armature reactance
$G$ – Shunt conductance representing iron losses
$E_s$ – Terminal voltage
$E_r$ – Induced voltage

while the iron losses are accounted for by the conductance $G$. The motor is thus reduced to a transmission network through which power is transmitted with a sending end voltage of $E_s$ and a receiving voltage of $E_r$. The power which in the equivalent circuit of Fig. 3 is delivered to the receiving voltage is the mechanical power produced by the motor and so is the shaft output plus the windage and friction. The motor losses exclusive of field loss are the losses in the equivalent circuit plus the windage and friction.

The network constants corresponding to Fig. 3 are

$$\begin{aligned} A &= 1 + G\,(R_a + X_a) \\ B &= R_a + X_a \\ C &= G \\ D &= 1 \end{aligned} \qquad (5)$$

In a given machine the usual stray power test will give $R_a$, $G$, windage, and friction. The iron losses can be represented by a conductance placed as shown in Fig. 3 because these losses are very nearly proportional to the square of induced voltage (and hence of air-gap flux). Since Fig. 3 applies to only one phase of the machine, in a polyphase motor the total iron losses are divided equally among the phases. An iron loss of $P_i$ watts at an induced voltage of $E_r$ accordingly leads to a conductance $G = (P_i/N)/E_r'^2$ in a machine with $N$ phases. The leakage reactance $X_a$ can be computed, or can be obtained approximately by measurement. The fidelity of the circle diagram is fortunately not appreciably affected by reasonable uncertainties in the value of $X_a$.

The circle diagram of the synchronous motor is based on the network constants of Equations (5), and is constructed in the usual way using a constant terminal voltage and a system of input power—reactive power coordinates. There is, however, considerable flexibility possible in the labeling of the diagram. Thus, although the equivalent circuit and hence the diagram obtained from it apply only to a single phase, it is possible to label this single-phase diagram with the corresponding three-phase quantities. The practical way of doing this is to compute the circle centers and radii on the single-phase basis, then lay out a coordinate system calibrated directly in three-phase power quantities and draw the circles using radii and center coordinates three times the calculated single-phase values. The circles themselves can also be marked with the corresponding three-phase values. Thus a circle representing a single-phase loss of 10 kw. can be marked 30 kw. on the three-phase diagram, and will then represent total three-phase loss.

The circle diagram as derived from Fig. 3 does not include windage and friction losses, but can be made to do so by a simple expedient. Since these losses represent mechanical power developed in the machine, but not available at the shaft, they can be taken into account by suitably labeling the diagram. That is, a loss circle would be drawn to represent a certain network loss but would be labeled with this loss plus the windage and friction loss, and an output power (receiver power) circle drawn representing a certain mechanical power output would be labeled with this power minus windage and friction, to give actual net shaft power.

The circle diagram of a 100-hp. synchronous motor is shown in Figs. 4 and 5, in which the labeling is in terms of three-phase quantities, and concludes windage and

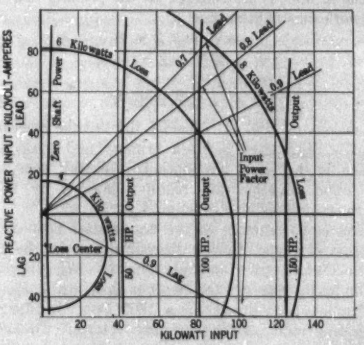


Fig. 4—Circle Diagram of 100-Hp. Synchronous Motor

friction. The motor diagram has been divided into two parts to avoid confusion, but by the use of colored inks all necessary loci could satisfactorily go on one figure. It is of course understood that Figs. 4 and 5 do not show all the circular loci that could be drawn. Loci giving input current, induced voltage, angle between terminal and induced voltage, etc., could have been included.

The usefulness of the synchronous motor circle diagram is greatly increased by superimposing constant field current lines upon the power—reactive power

coordinate system, as has been done in Fig. 5. The location of these lines can be obtained by either measuring or computing the combinations of reactive and real power that with the field current in question will give the terminal voltage for which the diagram is drawn. The field current loci are approximately circular arcs, and would be exactly circles if the armature reaction could be truly replaced by an armature reactance of constant value.

The circle diagram as described does not take into account field copper loss. It is possible, however, to mark each field current line with the corresponding

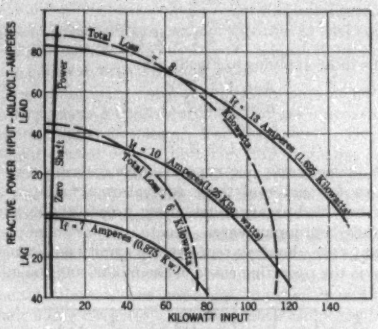


FIG. 5—CIRCLE DIAGRAM OF 100-HP. SYNCHRONOUS MOTOR (FIG. 4 CONTINUED)

field loss, and in this way to obtain from the circle diagram the total power loss of the alternator for a given load power and power factor. The procedure is to locate the point on the coordinate system corresponding to the desired load conditions. The field current line passing through this point shows the field power and the loss circle at the point gives the other losses (*i. e.*, windage, friction, armature copper, load, and iron) so that the total loss is the sum of these components. It is also possible to draw total loss loci, several of which are shown in Fig. 5. These lines are computed point by point from the loss circles and field current lines, and are almost but not exactly circular.

The accuracy of the motor circle diagram is approximately that of the usual stray power test method. The fundamental assumptions are: (1) iron losses are considered proportional to the square of the induced voltage and independent of armature current; (2) load losses are assumed proportional to the square of the armature current; and (3) the armature is assumed to have a constant leakage reactance. None of these assumptions introduces appreciable error.

In constructing the motor circle diagram some difficulty will be experienced in determining the radii of loss circles unless at least five place tables are used in computing radii and network constants. In most cases the approximate and simple method of drawing loss circles, given in Appendix II, is recommended as being the most satisfactory.

## CIRCLE DIAGRAM OF THE SYNCHRONOUS CONDENSER

Since the synchronous condenser is a synchronous motor operated without a shaft load, the circle in Figs. 4 and 5 for zero output represents synchronous condenser action. The entire discussion on the motor applies here without change, and so need not be repeated.

## CIRCLE DIAGRAM OF THE ALTERNATOR

Since an alternator is merely a synchronous motor operated backwards, that is with power supplied to the shaft rather than taken from it, a circle diagram similar to that of the motor can be drawn for the alternator.

The equivalent circuit of the alternator is given in Fig. 6, and the corresponding network constants are

$$A = 1$$
$$B = R_a + X_a$$
$$C = G$$
$$D = 1 + G\,(R_a + X_a) \qquad (6)$$

The notation is the same as explained in connection with Equations (5).

The alternator circle diagram is drawn from these network constants in a manner similar to that followed with the synchronous motor. As in the case of the motor the final diagram can be labeled to represent three-phase quantities although the actual computations are on the basis of one-phase. Windage and friction losses, although not taken care of in the equivalent circuit, can be included by proper labeling. Thus the shaft driving power equals the windage and friction loss plus the three-phase sending end power of the equivalent circuit, and the total machine power loss is

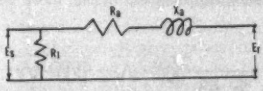


FIG. 6—EQUIVALENT CIRCUIT OF ALTERNATOR

$R_a$ – Series resistance representing armature copper and load losses
$X_a$ – Series reactance representing armature reactance
$G$ – Shunt conductance representing iron losses
$E_s$ – Induced voltage
$E_r$ – Terminal voltage

the windage and friction plus the three-phase loss indicated on the loss circle.

As in the case of the motor, lines of constant field current can be drawn on the coordinate system. These lines must be computed point by point, and are approximately but not exactly circular arcs. They can be marked with the field copper loss they represent, and in this way the diagram readily gives total loss exactly as in the case of the motor.

The circle diagram of a 25,000-kv-a. alternator is shown in Fig. 7. This diagram is drawn for a constant terminal voltage and so utilizes a coordinate system of

load (or receiver) power and reactive power. The labeling gives three-phase quantities and takes into account windage and friction losses. Thus, as the windage and friction is 122 kw., a loss circle computed for a single-phase loss of 76 kw. is marked as $3 \times 76 + 122 = 350$ kw. Only power loss and induced voltage circles are shown on Fig. 7, although many other types of circles could be added if desired.

The entire discussion given in connection with the motor circle diagram applies to the alternator diagram

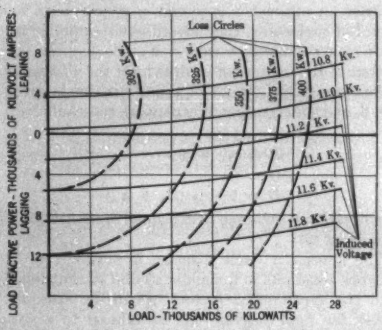


FIG. 7—CIRCLE DIAGRAM OF 25,000-KV-A. ALTERNATOR

with only minor and obvious modifications. In particular, the method given in Appendix II will generally be of considerable assistance in drawing loss circles.

## CIRCLE DIAGRAM OF THE INDUCTOR MOTOR

The classical induction motor circle diagram is merely a special application of the more general circle

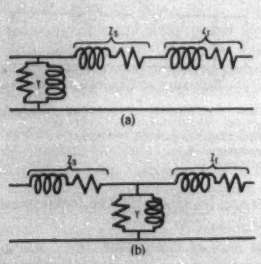


FIG. 8—EQUIVALENT INDUCTION MOTOR NETWORKS

$Z_s$ = Stator impedance
$Z_r$ = Rotor impedance reduced to stator side
$Y$ = Shunt admittance representing iron losses, windage, and friction

diagram of a transmission network. This follows from the fact that the equivalent circuit of the induction motor is that of a transformer operating with a resistance load. Starting with the network constants of the equivalent induction motor circuit, a circle drawn for a unity power factor load is the operating circle of the usual motor diagram.

The equivalent circuit of the induction motor as used by different investigators varies somewhat, according to the assumptions made. The basis of the Heyland diagram is the equivalent circuit of Fig. 8A, which is only approximately correct. The more correct equivalent circuit of Fig. 8B also leads to a circle diagram, but one more difficult to draw.

The network constants corresponding to Fig. 8A are

$$\begin{aligned} A &= 1 \\ B &= Z \\ C &= Y \\ D &= 1 + Z\,Y \end{aligned} \tag{7a}$$

while those applying to Fig. 8B are

$$\begin{aligned} A &= 1 + Z_s Y \\ B &= Z + Z_r (1 + Z_s Y) \\ C &= Y \\ D &= 1 + Z_r Y \end{aligned} \tag{7b}$$

A transmission line type of circle diagram may be drawn for either of these equivalent circuits, or for any modified arrangement, using a constant terminal voltage, and input power—reactive power coordinates. In any case, the circle representing a unity power factor load is the operating circle of the motor, and the inter-

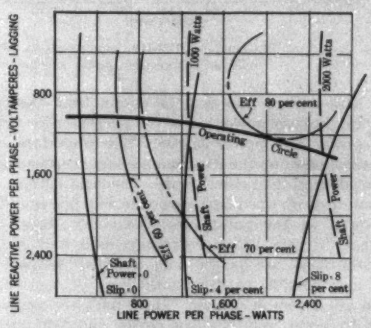


FIG. 9—CIRCLE DIAGRAM OF A SMALL INDUCTION MOTOR

sections of this circle with efficiency, power loss, power output, etc., circles give the motor performance. Also, since each load resistance in the equivalent circuit corresponds to a certain value of slip, load resistance (or conductance) circles can be labeled to give slip.

When the network of Fig. 8A and the network constants of Equations (7c) are used, the resulting diagram is exactly the well known Heyland diagram, which is accordingly only a special case of the general transmission network diagram, and the geometrical constructions commonly used to get slip, efficiency, etc., on the Heyland diagram are merely graphical means of

determining where different power loss, slip, and other circles intersect the unity power factor load arc.

A typical example of an induction motor circle diagram drawn by the transmission network method is shown in Fig. 9, which is based on the equivalent circuit of Fig. 8B, and is similar to the Heyland diagram, but slightly more accurate. By rotating Fig. 9 a quarter turn it will be readily recognized as an induction motor diagram.

Although any induction motor diagram can be drawn by following the transmission network mode of attack that has been outlined, such a procedure is not advisable where the usual Heyland diagram based on blocked rotor and no load tests will do. For this usual case, the classical procedure is so satisfactory and so well standardized that there is no incentive to replace it by something different, even if equally good.

The transmission network method of approach does, however, have a considerable field of usefulness in induction motor problems. For example, it gives a straightforward way of obtaining the operating circle when equivalent motor circuits other than that of Fig. 8A are used. Again, the usual construction for obtaining slip on the Heyland diagram is not accurate when the effective rotor resistance depends upon the slip frequency. This variation can be correctly taken into account in the network constant method of attack. The procedure is to assume a slip, and then draw a load conductance circle for a load resistance computed from the rotor resistance at the slip in question. The intersection with the operating circle gives the operating point for the slip in question.

An important use of the transmission network method of viewing the induction motor is in the analysis of problems where electromotive forces are introduced into the rotor circuit by commutator machines. The performance of induction motors equipped in this way can ordinarily be represented by some sort of a circle diagram, the exact nature of which depends upon the characteristics of the electromotive force generated by the commutator motor.[3]

An example that illustrates the power of the network constant method of attack is the case of induction motor in which a series commutator motor driven at constant speed is inserted in the rotor circuit. Such a machine, commonly called a phase advancer, is at its terminals equivalent to an impedance that is fixed both in magnitude and phase angle by the machine construction, and is independent of frequency. To incorporate in the circle diagram the effect of a phase advancer equivalent to a vector impedance $Z$ one computes the network constants of the motor circuit assuming the rotor resistance is zero. Using these constants a circle is drawn corresponding to a load power factor represented by the phase angle of the impedance $R_r + Z$, where $R_r$ is the rotor resistance. This circle is the operating circle of the motor when equipped with a phase advancer of the type mentioned. Slip, shaft power of the induction and commutator motors, etc., can be represented on the diagram by methods that are readily devised. An adequate discussion of this and similar cases would require a separate paper, however, and it is merely intended at this time to point out the possibilities of the transmission network method of attacking induction motor problems, particularly those out of the ordinary.

Induction generator action is represented by the negative power portion of the motor diagram so that the discussion that has been entered into applies to the induction generator with obvious modifications.

## Representation of Machine Characteristics on a Power Coordinate System

In representing the relation between two variables it is customary to use a coordinate system in which one of these variables is plotted as a function of the other. Thus in a synchronous motor, one might plot efficiency as a function of shaft load, there being one such curve for each value of field current. Where a very comprehensive picture of machine performance is desired, however, it is preferable to use a power—reactive power coordinate system and to superimpose the desired loci upon this as has been done to a limited extent in Figs. 2, 4, 5, and 7. Lines representing such loci may be either circular or non-circular, depending upon the circumstances, but no matter how much saturation, etc., is present it is always possible to show correctly the complete performance of the apparatus on a single diagram.

The use of a power coordinate system to show characteristics has the advantage of permitting a ready visualization of the entire behavior under all conditions. From such a diagram it is possible to determine quantitatively the operating characteristics of a piece of equipment for a given set of conditions by inspection. Thus in the case of a synchronous motor which is to carry a certain load at a certain power factor, the point on the coordinate system that corresponds to this condition can be readily found from the power factor and load power loci using Fig. 4. The input power, field current, total power lost, efficiency, etc., are then given by the various loci lines passing through the operating point, using diagrams such as Figs. 4 and 5.

## Conclusion

The principles presented in this paper have been put to laboratory test[4] as far as the university facilities allow and satisfactory agreement of theoretical and experimental results was found in all cases.

3. For example, see John I. Hull, *Theory of Speed and Power Factor Control of Large Induction Motors by Neutralized Polyphase A-C. Commutator Machines*, A. I. E. E. Trans., Vol. 39, 1920, p. 1135.

4. The results are to be found in the following Stanford University theses: T. L. Lenzen and K. A. Rogers, *Application of the Transmission Line Circle Diagram to Transformers and Alternators;* C. L. Freedman, *Application of the Transmission Line Circle Diagram to the Induction Motor.*

The circle diagram of a transmission network, developed to solve transmission line problems, seems to be the fundamental circle diagram, applying to many varieties of electrical circuits and machinery. Its use in connection with transformers and synchronous motors, generators, and condensers leads to circle diagrams fully as useful as the classical induction motor diagram.

The authors wish to express their appreciation for the assistance rendered by Mr. Monges of the General Electric Company in supplying data on commercial equipment.

## Appendix I

### Determination of Network Constants by Measurement

*Direct Measurement of A.* From Equation (1) it is seen that with the receiver open:

$$A = E_s/E_r \tag{8}$$

The vector ratio $E_s/E_r$ can be measured in both magnitude and phase by the three-voltmeter method, or by successive applications of the three-voltmeter method. The phase can also be measured by a wattmeter in which the current in each of the coils is proportional to one of the two voltages.

*Direct Measurement of B.* From Equation (1) it is seen that with the receiver terminals short circuited:

$$B = E_s/I_r \tag{9}$$

The phase of $B$ can be determined by the use of a wattmeter in which $E_s$ is applied to the voltage coil and $I_r$ flows through the current coil.

*Measurement of C.* From Equation (1) it is seen that when the receiver terminals are open circuited:

$$C = I_s/E_r \tag{10}$$

This vector ratio can be readily obtained by the use of ammeter, voltmeter, and wattmeter.

*Measurement of D.* With power supplied at the receiver terminals, and with the sending end terminal open, Equation (2) shows:

$$D = E_r/E_s \tag{11}$$

*Measurement of Constants When Both Ends of Network are not Available at One Point.* An example of this is a transmission line. Since there are three independent network constants any three independent measurements are sufficient. The measurements most easily made are:

(1) Sending end impedance $Z_1$ with receiver open.
(2) Sending end impedance $Z_2$ with receiver shorted.
(3) Impedance $Z_3$ at receiver with sending end open.
(4) Impedance $Z_4$ at receiver with sending end shorted.

According to Equations (1) and (2) these impedances are related to the network constants as follows:

$$\begin{aligned} Z_1 &= A/C \\ Z_2 &= B/D \\ Z_3 &= D/C \\ Z_4 &= B/A \end{aligned} \tag{12}$$

The simultaneous solution of any three of these four equations together with the relation $A\,D = 1 + B\,C$ will enable the four network constants to be computed. The four equations of (12) cannot be simultaneously solved themselves to give the four network constants because only three of these constants are independent.

## Appendix II

### Approximate Method of Computing Loss Radii

Reference to a previous article[2] shows that loss circle radii are given by an equation of the form

$$\text{Radius} = m\sqrt{L - L_0}$$

where $m$ and $L_0$ are constants that can be computed from the network constants and the terminal voltage. In these computations, however, $L_0$ is difficult to determine accurately as it is the small difference of two nearly equal quantities.

In the case of equipment such as the transformer, alternator, etc., where the minimum possible loss with the fixed terminal voltage is for all practical purposes the no-load loss, it is permissible to substitute the no-load losses for the quantity $L_0$. This is because the loss $L_0$ is the minimum possible loss with the fixed terminal voltage being used. With this simplification the loss radii may be easily computed with satisfactory accuracy.

# Effect of Electric Shock

W. B. KOUWENHOVEN* and ORTHELLO R. LANGWORTHY†
Member, A. I. E. E. Non-Member

*Synopsis.—This paper describes an investigation of the effects of electric shock on the central nervous system. A total of 288 rats was employed in the investigation. These were shocked at 110, 220, 500, and 1000 volts on both alternating and continuous current circuits for varying lengths of time. In each series the duration of the shock was increased until it was found impossible to resuscitate the rats. When possible the rats were resuscitated by means of artificial respiration, and kept alive for about a week. Then they were killed by an overdose of ether and an autopsy was immediately made.*

*The rats reacted in entirely different manner on the two types of circuit. At the lower voltages the alternating current was deadlier than the continuous, but at the high voltage the opposite was found to be the case.*

*In many instances the rats were paralyzed by the application of the current and in the majority of these animals gross hemorrhages were found in the spinal cord at autopsy. All of the deaths that occurred as a result of the shock were caused by respiratory failure, which could usually be traced to an injury of the central nervous system. In some cases the electric current produced peculiar effects upon the rats.*

* * * * *

## General

THE first death from contact with an electric circuit occurred in France in 1879. As the use of electricity has become prevalent the number of deaths has also increased; at present the death rate from electricity in the United States is 0.9 per 100,000, in Switzerland 0.7 per 100,000, and in England and Wales 0.07 per 100,000. There has been less development of the electric industry in England and Wales and this no doubt accounts for their lower death rate. The number of deaths from electricity in the United States has kept pace with the growth in population but is not increasing as fast as the use of electricity is being extended. Approximately 50 per cent of the accidents in this country are fatal. The injuries occur with greatest frequency between 9 and 10 in the morning and 2 and 3 in the afternoon. Recently there seems to be a definite increase in the number of deaths caused by contact with low-voltage circuits such as are used in residences.

In the case of an electric accident there are five factors that are of importance for investigation, namely:

1. The voltage of the circuit.
2. The amount of current that flows through the body.
3. The duration of the contact.
4. The type of circuit, direct or alternating, and the frequency.
5. The points on the body where contact is made with the circuit.

## Voltage

It is a well recognized fact that high voltages are dangerous. Low voltages are also dangerous and especially so when the victim makes good contact. There is an authentic case in Italy of a man who was electrocuted on a 46-volt circuit, one in Vienna on 60 volts, and one in England on 65 volts. All of these accidents took place on alternating systems. Deaths on 110-volt a-c. circuits are becoming quite common as already mentioned. It has not been possible to find any record of a fatal accident on a 110-volt continuous current system. Approximately one-third of the fatal accidents reported, occur on low-voltage a-c. circuits.

On high-voltage circuits the victim is often thrown away from the conductors due to the severe contraction of the muscles. On low voltage it is often impossible to let go.

## Current

The current that will flow in any given instance depends not only upon the voltage of the circuit, but also upon the resistance offered by the body. The determination of the resistance of the body is a very complex problem. There is a voltage drop at the contacts in addition to the resistance drop in the body itself. Dry skin on the palm of the hand has a resistance which varies from 40,000 ohms to 100,000 ohms per sq. cm. Blood is a good conductor and the subcutaneous tissue being rich in blood vessels is therefore a good conductor. The resistance of muscle is of the order of 1500 ohms per cu. cm., the brain 2000 ohms, the liver 900 ohms, and that of bone 900,000 ohms. It is evident that the major part of the resistance that the body offers to the flow of electric current lies in the contacts with the skin. When the skin is thoroughly wet its resistance falls to about 1000 ohms. When the contacts are excellent, as at Sing Sing, the resistance offered by the victim falls to nearly 200 ohms.

The sensation produced by an alternating current of 18 to 20 milliamperes is painful and currents of 100 milliamperes are dangerous and may cause death. It is therefore quite evident that 110-volt circuits are dangerous if the skin of the victim is wet.

The resistance of the body decreases if contact is made with an electric circuit for any length of time. In the experiments on animals it was found that the current increased 5 to 10 per cent if the animal was allowed to remain in the circuit for any length of time.

*Associate Professor of Electrical Engineering, The Johns Hopkins University, Baltimore, Md.

†Associate in Neurology, The Johns Hopkins University, Baltimore, Md.



29-161

There was also a rise in temperature as determined by rectal thermometer.

### Duration of Contact

The possibility of successful resuscitation decreases rapidly as the time of contact with the circuit increases. The higher the voltage of the circuit, the shorter the time that a man can remain in contact with it and still be resuscitated.

### Type of Circuit

Low-voltage a-c. systems of commercial frequency are more dangerous than continuous current circuits of the same voltage. A continuous current produces electrolysis of the body fluids and some strong contractions of the muscles. Alternating current, on the other hand, produces no electrolysis but a very severe contraction of the muscles.

### Position of the Electrodes

If the contact of the body with the circuit occurs at points so located that the current does not pass through any vital organ no permanent damage as a rule will result.

### Effects of Electric Shock

Jex-Blake[2] in his Gulstonian Lectures discussed at some length the injuries produced by electricity and more recently Jaffe[1] has published a review of this whole subject. Only a few of the effects of electric shock will be discussed here and the reader is referred to the original articles for a more complete study of the subject and for other references.

One of the most common effects of the passage of an electric current through the body is a burning of the skin. The skin receives a negative of the conductor with which it makes contact. Severe electric burns usually are slow in healing and leave a thin pinkish scar.

The passage of the current through the body produces a severe continuous contraction of the muscles or tetanus as it is called. The walls of the blood vessels through which the current has passed are brittle and friable and this accounts for the severe hemorrhages that are often found following electrical accidents. The blood contains an increased number of white corpuscles after the passage of an electric current.

When a low-tension current passes through the heart of animals uncoordinated contractions of the separate muscle fibers of the ventricles of the heart take place. This is called fibrillation and it is produced by the direct action of the current on the muscle fibers of the heart. It is not believed that the heart of man or of the larger animals ever recovers spontaneously from fibrillation. Perhaps a counter shock will combat the fibrillation, but there are few data available on this subject. When a high-tension current is applied the heart stops immediately, on breaking the circuit it starts to beat rapidly and strongly and the blood pressure rises. Injury to the heart is believed therefore to be more common at low voltage and this is perhaps one of the reasons that more people are resuscitated after contacts with high-voltage circuits than with low-voltage circuits.

Exposure to circuits of 550 volts and higher gives a number of indications that the central nervous system is involved. These are the arrest of respiration, irregular respiration, clonic spasms, loss of sensation, loss of reflexes, and great prostration which may pass into a deep coma. Jaeger[3] states that an electric shock is similar to a concussion of the brain.

The possible causes of death are:

1. Prolonged tetanus of the muscles during passage of the current, producing exceedingly high temperatures or death from asphyxia.
2. Heart failure usually associated with ventricular fibrillation.
3. Respiratory failure through nervous inhibition or actual damage to nervous system; and
4. Burns or other complications.

Death usually centers around the paralysis of the heart or of the respiratory centers.

### Experimental Study

The purpose of this investigation was to determine the effect of an electric shock upon the central nervous system, to study the behavior of shocked animals, to ascertain if possible the cause of deaths due to respiratory failure, and to find how many cases of delayed deaths are the result of demonstrable lesions in the central nervous system.

In studying the effects of electric shock two methods are available, the study of accidents or animal experimentation. The study of accidental deaths is difficult because of lack of accurate knowledge of all the factors involved, and the long delay before performing autopsies.

The sensibility to an electric current varies greatly with different animals. Frogs and turtles are the most resistant, rats and rabbits come next in the scale, and dogs and horses are very easily killed. Rats were chosen for this investigation because they are easy to transport and inexpensive. The heart of a rat recovers spontaneously from fibrillation and in the present tests there were no deaths from either prolonged tetanus of the muscles or heart failure.

The effect on rats of alternating and continuous currents at potentials of 110, 220, 500, and 1000 volts for varying lengths of time was studied. The authors felt that the changes in the nerve cells could be seen especially clearly if the animal was resuscitated after the shock and allowed to live several days. This procedure was carried out, the rat was then killed and the central nervous system examined at once. Attention was confined mainly to a study of the effects produced by the electric current on the spinal cord and brain.

These experiments were made at constant supply voltage, which was maintained except in the preliminary tests as mentioned below. Constant voltages were

1. For numbered references see Bibliography.

chosen rather than constant currents because they correspond to standard practise. In the case of an accidental death on a circuit the voltage applied to the victim is usually known quite accurately, but there are few or no data as to the amount of current that passed through his body.

It must be remembered that the results obtained from a study of one experimental animal cannot be directly applied to a consideration of other animals or of man. It is expected that the pathological changes in the central nervous system, the study of which formed the main object of this investigation, will be found similar in all mammals.

## Current Supply

The 110- and 220-volt alternating and continuous current supplies were taken directly from the Electrical Engineering Laboratory circuits. The 500- and 1000-volt a-c. voltages were furnished by a 1 to 10 step-up transformer, in which primary voltage was furnished by a separate alternator whose voltage controlled by means of a field regulation. The 500- and 1000-volt continuous current voltages were furnished by a separately excited 800-volt continuous current generator. A switch was placed in the high-tension circuit in which the rat was connected, and this switch was used to close the circuit. The frequency of the alternating current was 60 cycles.

In the first test at 500 and 1000 volts alternating current the primary voltage feeding the step-up transformer was furnished from the laboratory circuit and controlled by a potentiometer type of rheostat. The amount of current taken by the animals was larger than anticipated and there resulted a considerable fall in voltage due to the drop in the rheostat. Measurements showed that in the case of the 500-volt preliminary tests, the voltage felt to approximately 100 volts and in the preliminary 1000-volt series to 220 volts. The actual values varied with the size of the animals. This method of connection was abandoned and the primary voltage controlled by means of the alternator field as described above. Nevertheless the results of the observations made on the circuit in which the voltage fell upon closing the switch to about 20 per cent of its initial value are very interesting, because they show that the initial shock plays a large part in the injury to the animal.

The current flowing through the rat was measured by means of the proper range and type of ammeter.

## Technique

While the animal was being given ether the voltage was adjusted to the desired value for the test. As soon as the rat was anesthetized the electrodes were attached after wetting the skin with a saturated salt solution. One electrode, two voltmeter clips filed smooth, was fastened to the base of the tail, and the other electrode placed on the skull. The electrode, used on the skull, was especially made for the work and was held in place by springs that pressed against the lower jaw and did not in any way obstruct the breathing. The electrode proper was 1.2 cm. in diameter and was insulated from the springs so that all of the current passed through the top of the head.

In the majority of tests the electrodes were applied on the head and tail of the rats as described above. Another group of observations was made with one electrode on the head and the other on one of the fore legs and also with one electrode on one fore leg and the other on the opposite hind leg. The results obtained were similar and apparently entirely independent of the electrode positions.

After the electrodes were in position the animal was closely watched until it showed signs of initial recovery from the ether; then the high-tension switch was closed for the proper length of time. Immediately following the opening of the circuit the electrodes were removed from the animal and artificial respiration was applied. If possible the rat was resuscitated and allowed to live for three or four days. It was then killed and an autopsy performed at once.

In addition to the findings at autopsy the authors have made sections of the central nervous systems of the animals. The preparation and study of the sections requires considerable time and a further report will embody these findings. It is hoped that these microscopic data will furnish considerable information concerning the cause of the abnormalities seen in the rats after the shock.

The resuscitation method used was as similar as possible to the Schaefer prone-pressure method used for man. Every effort was made to save the rat and often artificial respiration was continued for 10 or 15 minutes. In the case of those animals which died under shock, and which could not be induced to breathe, autopsies were performed at once.

The circuit was held closed for varying lengths of time, the shortest interval, called instantaneous time, being just sufficient to close and open the switch. The duration of the shock was measured by means of a stop watch. In making the tests at any given voltage a shock of short duration was used for the first experiments and gradually increased until it was no longer possible to resuscitate the animal.

## Observations

The experiments described in this paper are 286 in number and include groups of rats shocked on alternating and continuous circuits at different potentials. The results of these observations may be grouped and examined in a number of different ways. After studying them from several different points of view it was decided best to describe the results obtained with alternating and continuous circuits using in each case four potentials of 110, 220, 500, and 1000 volts. With each potential and circuit, rather characteristic results of the shock were obtained. The time that the current was

allowed to flow through the body was varied in the different experiments in each series. In general the time was longest with the lower voltages. The different experiments will first be described in groups or series on the basis of the potential and the type of circuit, and later these series will be compared.

The results are given in the form of tables and the data on the rats shocked at a given voltage for a certain interval of time are arranged in the order of the currents that flowed through the animal.

*110 Volts Alternating Series.* Eleven rats were shocked at this voltage; the time of contact varied from 10 to 30 seconds. The results are given in Table I. The average resistance was 3091 ohms. Of the eleven rats of this series, seven, 64 per cent recovered; three, 27 per cent died, and one, 9 per cent, was paralyzed. When the paralyzed rat was examined blood was found in the urine and a large hemorrhage in the spinal cord. Hemorrhages of this type in the spinal cord were found often as a result of the shock.

As may be seen from Table I, artificial respiration was used on all but one of the rats. Their recovery was slow and they lay quiet from a few minutes to half an hour following the shock. They were inactive for the first 24 hours and did not eat or drink; after that period they became apparently normal.

One of the rats that recovered, No. 8, died three hours later, and upon autopsy was found to have a large hemorrhage in the spinal cord. One of the three rats that died at once was found to have a hemorrhage in the cord, but the other two showed no gross abnormalities.

Of the six rats that recovered and continued to live, until killed, five were found to be normal and one showed a hemorrhage in the brain.

Three of the rats, Nos. 9, 10, and 11, that were in the circuit for some time breathed spontaneously while the circuit was closed. They all stopped breathing when the circuit was opened; two were saved by artificial respiration, and the third never breathed again although the heart was strong.

Two of the rats that recovered had spasms of the muscles and in two cases bleeding from the nose was evident, caused by the rupture of the small blood vessels.

In summary, 45 per cent of the rats died or were permanently injured as a result of the shock on a 110-volt alternating circuit.

*220 Volts Alternating Series.* Twenty-nine rats were shocked at this voltage; the time of contact varied from 5 to 35 seconds. The results are given in Table II. The average resistance was found to be 1890 ohms, and the currents varied from 80 to 200 milliamperes. Of the 29 tested, eight, 28 per cent, recovered; eleven, 34 per cent, died; and ten, 38 per cent, were paralyzed. The ten that were paralyzed became incontinent (could not control the bladder). All showed blood in the urine, and all showed typical hemorrhages in the spinal cord.

It was necessary to use artificial respiration on all but two of the rats. Their recovery was slow and their breathing was shallow, labored, and irregular.

Seven, of the eleven that died, started to breathe with artificial respiration, but the breathing was not maintained and they died despite efforts to save them. One of the four that never started to breathe, rat No. 29, was kept in the circuit for 35 seconds and during that time the current increased from an initial value of 80 milliamperes to 166 milliamperes, and its rectal temperature rose from 36.5 deg. cent. to 38 deg. cent. In the case of all of the rats that were held in the circuit for several seconds there was an increase in current with time.

Of the eleven rats that died, three showed a developing hemorrhage in the spinal cord and one a hemorrhage in the brain. The others were normal as far as could be detected at autopsy. One of the eight that recovered showed a slight hemorrhage in the cord.

A study of Table II shows several instances marked "No specimen." This indicates that either the rat managed to free himself of a little aluminum tag carrying his identification number or that no autopsy was performed directly after death.

The chances of injury or death from contact with an electric circuit decreases with the length of time of the contact. This is clearly brought out by the data in Table II; one-half of the eleven rats tested at contact durations of five to eight seconds recovered, but only 13 per cent of the rats shocked for ten seconds recovered.

An interesting point is brought out by the results of

TABLE I
110-VOLT A-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | | Sex | Wt. gr. |
|---|---|---|---|---|---|---|---|---|
| | | | | | Brain | Cord | | |
| 1 | 10 | .... | Yes | Recovered | Normal | Normal | .... | .... |
| 2 | 10 | 26.5 | Yes | Died | Normal | Normal | .... | .... |
| 3 | 10 | 38 | Yes | Paralyzed | Normal | Yes | .... | .... |
| 4 | 10 | 40 | Yes | Died | Normal | Normal | .... | .... |
| 5 | 14 | 25 | Yes | Recovered | Yes | Normal | .... | .... |
| 6 | 14 | 33.5 | No | Recovered | Normal | Normal | .... | .... |
| 7 | 18 | 47 | Yes | Recovered | Normal | Normal | .... | .... |
| 8 | 22 | 47.5 | Yes | Recovered | Normal | Yes | .... | .... |
| 9 | 26 | 40 | Yes | Recovered | Normal | Normal | .... | Large |
| 10 | 30 | 30 | Yes | Died | Normal | Yes | .... | Very large |
| 11 | 30 | 47 | Yes | Recovered | Normal | Normal | .... | .... |

TABLE II

220 VOLT A-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | | Sex | Wt. |
|---|---|---|---|---|---|---|---|---|
| | | | | | Brain | Cord | | |
| 1 | 5 | .. | No | Recovered | Normal | Normal | F | 240 |
| 2 | 5 | 100 | Yes | Paralyzed | No specimen | | M | 160 |
| 3 | 5 | 110 | No | Paralyzed | Normal | Yes | .. | .. |
| 4 | 5 | 135 | Yes | Recovered | Normal | Normal | M | 150 |
| 5 | 6 | 110 | Yes | Paralyzed | Normal | Yes | M | 120 |
| 6 | 8 | 105 | Yes | Died | Normal | Normal | M | 140 |
| 7 | 8 | 110 | Yes | Recovered | No specimen | | M | 160 |
| 8 | 8 | 120 | Yes | Recovered | Normal | Normal | M | 150 |
| 9 | 8 | 120 | Yes | Paralyzed | No specimen | | F | 140 |
| 10 | 8 | 140 | Yes | Recovered | Normal | Yes | F | 110 |
| 11 | 8 | 140 | Yes | Paralyzed | Normal | Yes | F | 200 |
| 12 | 10 | 80 | Yes | Died | Normal | Yes | .. | .. |
| 13 | 10 | 80 | Yes | Died | Normal | Normal | .. | .. |
| 14 | 10 | 90 | Yes | Paralyzed | Normal | Yes | M | 210 |
| 15 | 10 | 100 | Yes | Paralyzed | No specimen | | M | 100 |
| 16 | 10 | 120 | Yes | Died | Yes | Normal | .. | 190 |
| 17 | 10 | 125 | Yes | Paralyzed | Normal | Yes | M | 160 |
| 18 | 10 | 130 | Yes | Paralyzed | No specimen | | M | 210 |
| 19 | 10 | 140 | Yes | Recovered | Normal | Normal | M | 170 |
| 20 | 12 | 100 | Yes | Died | Normal | Normal | M | 140 |
| 21 | 12 | 120 | Yes | Died | Normal | Normal | M | 180 |
| 22 | 12 | 160 | Yes | Paralyzed | Normal | Yes | M | 260 |
| 23 | 14 | 100 | Yes | Died | Normal | Normal | F | 180 |
| 24 | 14 | 150 | Yes | Recovered | Normal | Normal | M | 270 |
| 25 | 14 | 150 | Yes | Died | Normal | Normal | M | 230 |
| 26 | 14 | 150 | Yes | Died | Normal | Yes | F | 200 |
| 27 | 14 | 170 | Yes | Recovered | Normal | Normal | M | 250 |
| 28 | 14 | 200 | Yes | Died | Normal | Normal | F | 180 |
| 29 | 35 | 80 | Yes | Died | Normal | Yes | .. | .. |

a 14-second shock; the two rats that recovered from this shock were both very large. It was found that the small rats succumb much more easily to electric shock than the larger animals. It is believed that this is due to the lower current density in the vital organs of the larger animals.

No differences were found between the death rates of the two sexes. Pregnant females, however, are very easily killed by contact of short duration.

Twenty-two of the rats used in this series bled from the nose or eyes. One peculiar phenomenon, for which no explanation is known, is that in case of bleeding from the eyes the right eye bled more often than the left. In the case of one of the males there was an ejaculation.

The percentage of rats that were permanently injured or died on the 220-volt circuit was 72. This greater percentage of injuries in combination with the short time of application indicates clearly that 220 volts is much more deadly to rats than 110 volts.

*500-Volt A-C. Series.* Twenty-six rats were shocked at this voltage; the time of contact was varied from 1 to 4 seconds. The detailed results are given in Table III. Of the 26 tests, ten, 38 per cent recovered; three, 12 per cent died, and thirteen, 50 per cent were paralyzed. All of the paralyzed rats, except one, showed the typical hemorrhage in the spinal cord. The average ohmic resistance of the rats was 1425 ohms, and the current varied from 240 to 490 milliamperes.

An inspection of Table III will show that a number of rats on this circuit recovered spontaneously after the circuit was opened. As the time of the contact was increased, artificial respiration became necessary. The contraction of the muscles upon the closing of the circuit was very great, the legs were stiffly extended, and the contraction persisted for several seconds after opening the circuit. There were clonic movements and tremors following the opening of the circuit. Eighteen of the animals bled from the nose or eyes following the shock.

Not a single animal survived a four-second application without permanent injury. In the paralyzed rats that were examined the typical hemorrhage in the spinal cord was found in all except rat 24. In one, of the three that died, the surface of the cortex was found to be seared, in another there was a hemorrhage in the brain. One was apparently normal.

There was some burning at the points where the electrodes were fastened to the animal in four of the rats. Bleeding from eyes or nose or both was observed in 18 cases, and in three of the rats there was a discharge of bloody fluid from the mouth. Ejaculation was noticed in the case of four of the six males that were shocked for periods of 3 and 4 seconds. In one of the ten rats that recovered there was a slight hemorrhage in the brain; the others appeared normal.

This series also clearly demonstrated that there is no difference between the susceptibility of the sexes to electric shock. It is evident that an application of 500 volts is much more injurious than the lower voltages; with a maximum time of application of four seconds, 62 per cent of the animals were paralyzed or died.

*1000 Volts Alternating Series.* Twenty-eight rats were subjected to a potential of 1000 volts for periods varying from one to four seconds. The results are given in Table IV. The average resistance was found

TABLE III
500 VOLTS A-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | | Sex | Wt. gr. | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Brain | Cord | | | |
| 1 | 1 | .... | Yes | Recovered | Normal | Normal | F | 280 | |
| 2 | 1 | 300 | No | Recovered | Normal | Normal | M | 180 | |
| 3 | 1 | 305 | No | Recovered | Normal | Normal | M | 230 | |
| 4 | 1 | 340 | Yes | Recovered | Normal | Normal | M | 180 | |
| 5 | 1 | 380 | No | Paralyzed | No specimen | | M | 140 | |
| 6 | 1 | 395 | Yes | Paralyzed | No specimen | | F | 170 | |
| 7 | 2 | 240 | Yes | Recovered | Yes | Normal | .. | .. | |
| 8 | 2 | 250 | No | Recovered | No specimen | | M | 220 | |
| 9 | 2 | 350 | Yes | Paralyzed | No specimen | | F | 170 | |
| 10 | 2 | 360 | No | Recovered | Normal | Normal | F | 210 | |
| 11 | 2 | 380 | No | Paralyzed | Normal | Yes | F | 180 | |
| 12 | 2 | 385 | No | Recovered | Normal | Normal | F | 180 | |
| 13 | 2 | 400 | Yes | Paralyzed | No specimen | | F | 100 | |
| 14 | 3 | 280 | Yes | Died | Normal | Yes | .. | .. | |
| 15 | 3 | 360 | Yes | Recovered | Normal | Normal | F | 200 | |
| 16 | 3 | 380 | Yes | Died | Normal | Normal | M | 150 | |
| 17 | 3 | 400 | Yes | Paralyzed | No specimen | | M | 210 | |
| 18 | 3 | 400 | Yes | Paralyzed | No specimen | | M | 260 | |
| 19 | 3 | 430 | Yes | Recovered | Normal | Normal | F | 210 | |
| 20 | 3 | 430 | Yes | Paralyzed | Normal | Yes | F | 280 | |
| 21 | 3 | 490 | Yes | Paralyzed | No specimen | | M | 250 | |
| 22 | 4 | 280 | Yes | Paralyzed | Normal | Yes | F | 180 | |
| 23 | 4 | 340 | Yes | Paralyzed | Normal | .... | M | 210 | |
| 24 | 4 | 350 | Yes | Died | .... | Normal | F | 350 | Cortex burned |
| 25 | 4 | 400 | Yes | Paralyzed | Normal | Yes | F | 200 | |
| 26 | 4 | 430 | Yes | Paralyzed | No specimen | | M | 220 | |

to be 1140 ohms, and the current varied from 700 to 1200 milliamperes. Of those tested, eight, 29 per cent recovered; nine, 32 per cent, died, and eleven, 39 per cent, were paralyzed. The ten that were paralyzed all became incontinent, blood was found in the urine, and all except one showed the typical spinal hemorrhage.

It was necessary to use artificial respiration on nearly every rat and in many cases considerable effort for a prolonged period was required to save the animals. In some cases, breathing was started by means of artificial respiration, only to stop again. Then artificial respiration had to be applied anew. In a few cases it was necessary to watch the animals for half an hour or more. Some died despite every effort. In those that lived the breathing was shallow, irregular, and labored.

The contraction of the muscles was very great and it persisted for several seconds after the circuit was opened. Clonic movements and tremors also followed the opening of the circuit. Many of the rats exhibited spas-

TABLE IV
1000-VOLT A-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | | Sex | Wt. gr. | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Brain | Cord | | | |
| 1 | 1 | .... | Yes | Died | Yes | Normal | F | 90 | |
| 2 | 1 | .... | Yes | Paralyzed | Normal | Yes | M | 160 | Cortex burned |
| 3 | 1 | 680 | Yes | Paralyzed | No specimen | | M | 140 | |
| 4 | 1 | 700 | Yes | Paralyzed | Normal | Normal | M | 170 | |
| 5 | 1 | 720 | No | Recovered | Normal | Normal | M | 160 | |
| 6 | 1 | 800 | No | Paralyzed | Normal | Yes | M | 160 | |
| 7 | 1 | 1000 | Yes | Recovered | Normal | Normal | F | 110 | |
| 8 | 2 | .... | No | Paralyzed | Normal | Yes | .. | .. | |
| 9 | 2 | .... | Yes | Paralyzed | Normal | Yes | F | 230 | |
| 10 | 2 | 650 | Yes | Paralyzed | Normal | Yes | .. | .. | |
| 11 | 2 | 800 | Yes | Recovered | No specimen | | F | 190 | |
| 12 | 2 | 830 | No | Paralyzed | Normal | Yes | F | 230 | Skull injured |
| 13 | 2 | 900 | Yes | Recovered | .... | Normal | F | 240 | Abscess brain |
| 14 | 2 | 950 | Yes | Died | .... | Normal | M | 200 | Cortex burned |
| 15 | 2 | 980 | Yes | Paralyzed | Normal | Yes | F | 270 | |
| 16 | 2 | 1000 | Yes | Died | .... | Normal | F | 180 | Cortex burned |
| 17 | 2 | 1000 | Yes | Recovered | .... | Normal | F | 210 | Cortex burned |
| 18 | 3 | 770 | Yes | Died | Normal | Yes | .. | .. | |
| 19 | 3 | 800 | Yes | Died | Normal | Normal | .. | .. | |
| 20 | 3 | 820 | Yes | Recovered | No specimen | | M | 290 | |
| 21 | 3 | 840 | Yes | Died | Normal | Yes | F | 280 | |
| 22 | 3 | 850 | Yes | Paralyzed | Normal | Yes | F | 290 | |
| 23 | 3 | 890 | Yes | Died | .... | Normal | F | 230 | Cortex burned |
| 24 | 3 | 980 | Yes | Recovered | Normal | Yes | M | 390 | Skull injured |
| 25 | 3 | 1060 | Yes | Paralyzed | Normal | Yes | M | 320 | |
| 26 | 3 | 1200 | Yes | Died | .... | Normal | F | .. | Cortex burned |
| 27 | 3 | 1250 | Yes | Recovered | Normal | Yes | M | 380 | |
| 28 | 4 | 1200 | Yes | Died | Normal | Normal | M | 350 | |

modic contractions of the muscles of mastication. Twelve bled from the nose or eyes or both.

Of the nine rats that died, seven showed injuries to the spinal cord or brain, and two were apparently normal. It was possible to start respirations in several of these animals, but breathing could not be maintained. In all nine cases the heart beat strongly after the shock.

There was severe burning at the electrode contact and several of the rats that recovered subsequently showed severe injuries from this cause.

A study of Table IV will show that many of the rats used in this series were of large size. This to some extent accounts for the fact that there was not a greater mortality. The results show that 71 per cent died or were paralyzed. The large size of the rats also accounts for the low average resistance, and large values of current found for this series.

*500 Volts Alternating Not Maintained Series.* Sixteen rats were shocked for periods varying from instantaneous contact to 14 seconds. The voltage fell to approximately 100 volts upon closing the switch. An oscillogram of the voltage in the high-tension circuit showed that it fell to its final low value in less than one-fourth a cycle. The final maintained current varied from 20 to 30 milliamperes. Of the 16 experimental animals, eleven, 69 per cent, recovered and five, 31 per cent, were paralyzed. Autopsy showed that four of the paralyzed rats had the typical hemorrhage of the spinal cord and one was apparently normal.

The contraction of the muscles was great and clonic movements followed the opening of the circuit. Artificial respiration was applied to four and in almost every case the breathing was shallow and irregular.

Of the eleven that recovered, no autopsy was performed on one rat; one showed a developing hemorrhage in the brain and cord, and the other nine were apparently normal.

It is interesting to note that, although the voltage was not maintained, a number of rats was paralyzed after contact with this circuit. This contact, however, did not produce as severe injuries as the 500-volt a-c. maintained voltage circuit.

*1000 Volts-Alternating Not Maintained Series.* Fifty-two rats were shocked in this series; the time was varied from instantaneous contact to six seconds. After closing the circuit the voltage fell to approximately 220 volts in less than a quarter of a cycle as shown by an oscillogram. The final maintained current varied from 98 to 155 milliamperes. Of the number tested, twelve, 23 per cent, recovered; twenty-four, 46 per cent, died, and sixteen, 31 per cent, were paralyzed. Thirteen of the sixteen paralyzed rats showed gross hemorrhages in the spinal cords, one showed a hemorrhage in the brain, and on the other two no autopsies were performed.

It was necessary to use artificial respiration on 31 per cent of the rats in this series, but it was not necessary to continue it as long as in the experiments where the voltage had been maintained at 1000 volts. Breathing, however, was shallow, irregular, and labored for a considerable time following the shock.

The contraction of the muscles was severe and clonic movements followed the opening of the circuit; three rats bled from the nose following the shock.

Of the twelve that recovered eleven were normal, and one showed signs of a hemorrhage in the cord.

The results of this series show that 77 per cent of the rats were either permanently injured or killed by contact with this circuit where the voltage was at its full value for only a very short time. This points to the conclusion that the hemorrhages in the spinal cord are largely the result of the first contact with the circuit. This contact was very nearly as injurious to the rats as the 1000-volt alternating circuit where the voltage was maintained.

*110-Volt Continuous Series.* Thirty-three rats were subjected to this voltage; the duration of the shock varied from 5 to 60 seconds. The results are given in Table V. The average resistance equaled 2685 ohms and the current varied from 28 to 53 milliamperes. Of the number observed twenty-eight, 85 per cent, recovered, four, 12 per cent, died, and one, 3 per cent, was paralyzed. The paralyzed rat showed the typical hemorrhage in the spinal cord which was so commonly found in rats shocked on a-c. circuits.

During the passage of the current the contraction of the muscles was not as great as on an a-c. circuit of the same voltage. During long time applications the current increased as it did in the alternating cases. There were clonic contractions of the muscles during the passage of the current. No artificial respiration was needed in the case of those rats which were held in circuit less than 20 seconds; they started to breathe spontaneously. If the rat was held in the circuit for more than 20 seconds it began to breathe while the current was still flowing. When the circuit was opened breathing stopped and it was usually necessary to apply artificial respiration to start the animal breathing again. The rats recovered promptly and were active sooner than those which had been given a shock with 110-volt alternating current. There was no evidence of bleeding in this series.

One of the four rats that succumbed to the shock was found to have a hemorrhage in the brain; the other three showed no abnormalities at autopsy. In two of the rats that recovered, hemorrhages were found; the others examined were normal. The heart beat well following the shock in all cases.

Only 15 per cent of the rats tested on a 110-volt continuous circuit were injured or died, although the duration of the shock was considerably longer than in the 110-volt alternating series.

*220 Volts Continuous Series.* Nineteen rats were shocked at 220 volts continuous potential; the duration of the shock varied from 5 to 30 seconds. The detailed

results are given in Table VI. The average resistance equaled 1635 ohms and the current varied from 100 to 200 milliamperes. Of the rats tested at this voltage ten, 53 per cent, recovered, eight, 42 per cent, died; and one, 5 per cent, was paralyzed. No sign of any gross abnormality could be detected on examination after death in the paralyzed rat.

In this group it was again noted that the muscle contraction was less than on an alternating circuit; the animals were more relaxed after the shock. Clonic movements were present in all of these rats both during and immediately following the shock. It was necessary to use artificial respiration on all but five of the rats in this series, and none of them breathed while in the circuit. No bleeding was noticed in this series.

TABLE V
110-VOLT D-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | | Sex |
|---|---|---|---|---|---|---|---|
| | | | | | Brain | Cord | |
| 1 | 5 | .. | No | Paralyzed | Normal | Yes | .. |
| 2 | 5 | 28 | No | Recovered | No specimen | | .. |
| 3 | 5 | 38 | No | Recovered | No specimen | | .. |
| 4 | 10 | 35 | No | Recovered | No specimen | | .. |
| 5 | 10 | 40 | No | Recovered | Normal | Normal | .. |
| 6 | 10 | 40 | No | Recovered | Normal | Normal | .. |
| 7 | 10 | 44 | No | Recovered | Normal | Normal | .. |
| 8 | 14 | 39 | No | Recovered | No specimen | | .. |
| 9 | 14 | 46 | No | Recovered | No specimen | | .. |
| 10 | 15 | 40 | No | Recovered | Normal | Yes | .. |
| 11 | 20 | 42 | No | Recovered | Normal | Normal | .. |
| 12 | 20 | 44 | Yes | Died | Normal | Normal | .. |
| 13 | 22 | 42 | Yes | Recovered | Normal | Nomral | .. |
| 14 | 22 | 53 | Yes | Recovered | Normal | Normal | .. |
| 15 | 25 | 30 | No | Recovered | Normal | Normal | .. |
| 16 | 26 | 41 | No | Recovered | No specimen | | F |
| 17 | 28 | 40 | No | Recovered | Normal | Normal | .. |
| 18 | 30 | 36 | No | Recovered | Yes | Normal | F |
| 19 | 30 | 48 | Yes | Recovered | No specimen | | M |
| 20 | 30 | 50 | Yes | Recovered | Normal | Normal | .. |
| 21 | 35 | 35 | No | Revoereed | Normal | Normal | M |
| 22 | 35 | 47 | Yes | Recovered | Normal | Normal | F |
| 23 | 35 | 50 | Yes | Recovered | No specimen | | M |
| 24 | 40 | 32 | No | Recovered | No specimen | | M |
| 25 | 40 | 41 | Yes | Recovered | Normal | Normal | M |
| 26 | 45 | 40 | No | Died | Yes | Normal | M |
| 27 | 45 | 43 | No | Recovered | Normal | Normal | M |
| 28 | 50 | 36 | No | Recovered | Normal | Normal | M |
| 29 | 50 | 34 | No | Recovered | Normal | Normal | M |
| 30 | 50 | 36 | No | Died | Normal | Normal | M |
| 31 | 50 | 47 | No | Recovered | Normal | Normal | M |
| 32 | 60 | 37 | Yes | Recovered | Normal | Normal | .. |
| 33 | 60 | 47 | Yes | Died | Normal | Normal | M |

TABLE VI
220-VOLT D-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | |
|---|---|---|---|---|---|---|
| | | | | | Brain | Cord |
| 1 | 5 | 100 | No | Recovered | Normal | Normal |
| 2 | 5 | 145 | Yes | Recovered | Normal | Normal |
| 3 | 5 | 170 | No | Recovered | Normal | Normal |
| 4 | 10 | 145 | Yes | Recovered | Normal | Normal |
| 5 | 10 | 195 | Yes | Paralyzed | Normal | Normal |
| 6 | 10 | 200 | Yes | Recovered | Normal | Normal |
| 7 | 15 | 135 | No | Recovered | Normal | Normal |
| 8 | 15 | 135 | Yes | Died | Normal | Normal |
| 9 | 15 | 140 | Yes | Died | Yes | Normal |
| 10 | 15 | 155 | Yes | Recovered | Normal | Normal |
| 11 | 15 | 155 | Yes | Died | No specimen | |
| 12 | 15 | 175 | Yes | Died | Normal | Normal |
| 13 | 15 | 250 | Yes | Died | No specimen | |
| 14 | 20 | 120 | Yes | Died | Normal | Normal |
| 15 | 20 | 200 | Yes | Recovered | Normal | Normal |
| 16 | 25 | 115 | No | Recovered | Normal | Normal |
| 17 | 30 | 100 | No | Recovered | Normal | Normal |
| 18 | 30 | 150 | Yes | Died | No specimen | |
| 19 | 30 | 155 | Yes | Died | Normal | Normal |

Of the eight rats that died, one was found to have a hemorrhage in the brain; the others that were examined were normal. None of the rats that recovered showed abnormalities in either the spinal cord or brain. In this series 47 per cent of the rats died or were injured.

*500-Volt Continuous Series.* Thirty-seven rats were shocked at this voltage; the duration of the shock varied from 1 to 4 seconds. The results in detail are given in Table VII. The average resistance was 1385 ohms; the current varied from 280 to 640 milliamperes. Eighteen, 49 per cent, of the thirty-seven recovered; seventeen, 46 per cent, died; and two, 5 per cent, were paralyzed. No trace of hemorrhage in the nervous system could be found in the two paralyzed rats at autopsy.

The contraction of the body musculature was not as severe as on an alternating circuit. Clonic movements were noticed both while the current was flowing and after the circuit was opened. Artificial respiration was needed in all except four cases, and the heart beat well in all of the rats for four or five minutes after the shock. Five of these rats had convulsions following the shock and showed increased and abnormal responses to all stimuli. This was the only series in which these convulsions were observed. Ten of the animals bled from the nose, eyes, or mouth, and it will be noted that this is the first appearance in the continuous current series of this phenomenon which was so common in the alternating groups.

No apparent injury to the nervous system on gross examination could be detected in any of the eighteen rats that died. Only two of the rats in this series showed hemorrhages in the brain, and these two rats recovered from the shock. All of the recovered rats were normal; their breathing, however, was labored and fast.

This series brings out clearly the effect of the size of the animal upon the experimental results. Eleven rats, three months old, were given a two-second shock and seven of them died. Of four larger rats under the same duration of shock two died, and two recovered. The results of three-second application, as may be seen from Table VII, also confirms this conclusion as to the effect of size of the animal upon the results.

TABLE VII

500 VOLTS D-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | | Sex | Wt. |
|---|---|---|---|---|---|---|---|---|
| | | | | | Brain | Cord | | |
| 1 | 1 | 280 | No | Recovered | Yes | Normal | F | Small |
| 2 | 1 | 300 | No | Recovered | Normal | Normal | M | Small |
| 3 | 1 | 300 | Yes | Recovered | Normal | Normal | F | Small |
| 4 | 1 | 300 | Yes | Recovered | Normal | Normal | F | Small |
| 5 | 1 | 300 | Yes | Died | Normal | Normal | F | Small |
| 6 | 1 | 320 | No | Recovered | Normal | Normal | F | Small |
| 7 | 1 | 370 | Yes | Recovered | Normal | Normal | M | Small |
| 8 | 1 | 390 | Yes | Recovered | Normal | Normal | F | Small |
| 9 | 2 | 270 | Yes | Recovered | Normal | Normal | F | 110 |
| 10 | 2 | 280 | Yes | Recovered | Yes | Normal | F | Small |
| 11 | 2 | 310 | Yes | Died | Normal | Normal | F | Small |
| 12 | 2 | 320 | Yes | Recovered | Normal | Normal | F | 140 |
| 13 | 2 | 320 | Yes | Died | Normal | Normal | M | Small |
| 14 | 2 | 340 | Yes | Died | Normal | Normal | M | Small |
| 15 | 2 | 350 | No | Recovered | Normal | Normal | M | Small |
| 16 | 2 | 370 | Yes | Recovered | Normal | Normal | F | 110 |
| 17 | 2 | 370 | Yes | Recovered | Normal | Normal | F | 120 |
| 18 | 2 | 380 | Yes | Died | Normal | Normal | M | Small |
| 19 | 2 | 390 | Yes | Recovered | Normal | Normal | F | Small |
| 20 | 2 | 400 | Yes | Recovered | Normal | Normal | M | Small |
| 21 | 2 | 410 | Yes | Died | No specimen | | M | Small |
| 22 | 2 | 420 | Yes | Died | Normal | Normal | M | Small |
| 23 | 2 | 420 | Yes | Died | Normal | Normal | M | Small |
| 24 | 3 | 300 | Yes | Died | Normal | Normal | F | Small |
| 25 | 3 | 330 | Yes | Died | Normal | Normal | .. | Small |
| 26 | 3 | 340 | Yes | Died | Normal | Normal | F | Small |
| 27 | 3 | 360 | Yes | Died | Normal | Normal | F | Small |
| 28 | 3 | 360 | Yes | Paralyzed | Normal | Normal | F | Small |
| 29 | 3 | 380 | Yes | Died | Normal | Normal | F | Small |
| 30 | 3 | 400 | Yes | Died | Normal | Normal | M | 120 |
| 31 | 3 | 410 | Yes | Recovered | Normal | Normal | F | 160 |
| 32 | 3 | 430 | Yes | Died | Normal | Normal | F | 230 |
| 33 | 3 | 500 | Yes | Recovered | Normal | Normal | M | 130 |
| 34 | 4 | 440 | Yes | Died | Normal | Normal | F | 260 |
| 35 | 4 | 550 | Yes | Recovered | Normal | Normal | F | 280 |
| 36 | 4 | 610 | Yes | Died | Normal | Normal | M | 390 |
| 37 | 4 | 640 | Yes | Paralyzed | Normal | Normal | M | 280 |

There was some burning at the electrodes caused by the current density, but there was no indication of any actual burning of the cerebral cortex.

A study of Table VII shows that 51 per cent of the rats died or were paralyzed as the result of contact with the 500-volt continuous current circuit, but the cause of death can not be ascribed to gross damage to the nervous system. It is hoped that the sections which are being prepared may give some information concerning the cause of death.

*1000-Volt D-C. Series.* Thirty-three rats were tested at this voltage; the duration of the shock varied from instantaneous contact to four seconds. No rats,

irrespective of size, survived a contact of one second or longer with this circuit. Of the thirty-three shocked nine, 27 per cent, recovered; twenty, 61 per cent, died; and four, 12 per cent, were paralyzed. In this series the central nervous system of the paralyzed rats was found to be grossly normal at autopsy. The average resistance was 1365 ohms.

These rats showed the clonic movements of the legs which appear to be so characteristic of continuous current shocks. The contraction of the muscles was somewhat greater than with the 500 volts continuous current, but not nearly as great as with the alternating currents.

Breathing was shallow and irregular and those rats that recovered were very disturbed. Artificial respiration was used in every case but one. Although the heart beat strongly it was seldom possible to initiate breathing despite the greatest efforts. The chests of the animals were collapsed following the shock, and no air would enter the lungs. Four of the animals bled from the nose, eyes, or mouth, following the shock. The two paralyzed rats became incontinent after 24 hours although no blood was found in the urine.

No signs of gross injury to the nervous system could be detected in any of the rats that were used in this series and although there was considerable burning at the electrodes no damage to the surface of the brain was found. The cause of death may later be demonstrated by means of the sections being prepared for microscopic study. This series is characterized by a high percentage of fatalities and the most prominent feature noted was persistent priarpism (permanent erection) in the males.

TABLE VIII
1000-VOLT D-C. SERIES

| Rat No. | Duration of shock—sec. | Current milliamperes | Artificial respiration | Result | Gross hemorrhage | | Sex | Wt. gr. |
|---|---|---|---|---|---|---|---|---|
| | | | | | Brain | Cord | | |
| 1 | Inst. | .. | Yes | Recovered | Normal | Normal | F | Small |
| 2 | Inst. | .. | Yes | Paralyzed | Normal | Normal | M | Small |
| 3 | Inst. | .. | Yes | Died | Normal | Normal | M | Small |
| 4 | Inst. | .. | Yes | Died | Normal | Normal | M | Small |
| 5 | Inst. | .. | Yes | Recovered | Normal | Normal | M | Small |
| 6 | Inst. | .. | Yes | Died | Normal | Normal | M | Small |
| 7 | Inst. | .. | Yes | Recovered | Normal | Normal | F | Small |
| 8 | Inst. | .. | No | Recovered | Normal | Normal | .. | Small |
| 9 | Inst. | .. | Yes | Recovered | Normal | Normal | .. | Small |
| 10 | 0.5 | .. | Yes | Paralyzed | Normal | Normal | M | Small |
| 11 | 0.5 | .. | Yes | Paralyzed | Normal | Normal | M | Small |
| 12 | 0.5 | .. | Yes | Died | Normal | Normal | M | Small |
| 13 | 0.5 | .. | Yes | Recovered | Normal | Normal | M | Small |
| 14 | 0.5 | .. | Yes | Died | Normal | Normal | M | Small |
| 15 | 0.5 | .. | Yes | Died | Normal | Normal | M | Small |
| 16 | 0.5 | .. | Yes | Died | Normal | Normal | F | Small |
| 17 | 0.5 | .. | Yes | Recovered | .. | .. | M | Small |
| 18 | 0.5 | .. | Yes | Died | Normal | Normal | M | 250 |
| 19 | 0.5 | .. | Yes | Recovered | Normal | Normal | F | 290 |
| 20 | 0.5 | .. | Yes | Died | Normal | Normal | F | 240 |
| 21 | 0.6 | .. | Yes | Paralyzed | Normal | Normal | M | Small |
| 22 | 0.6 | .. | Yes | Recovered | Normal | Normal | F | 200 |
| 23 | 1 | 600 | Yes | Died | Normal | Normal | M | Small |
| 24 | 1 | 640 | Yes | Died | Normal | Normal | M | Small |
| 25 | 1 | 710 | Yes | Died | Normal | Normal | M | Small |
| 26 | 1 | 730 | Yes | Died | Normal | Normal | .. | Small |
| 27 | 1 | 740 | Yes | Died | Normal | Normal | M | Small |
| 28 | 1 | 750 | Yes | Died | Normal | Normal | .. | Small |
| 29 | 1 | .. | Yes | Died | Normal | Normal | M | 380 |
| 30 | 1 | 1000 | Yes | Died | Normal | Normal | M | 390 |
| 31 | 1 | 1100 | Yes | Died | Normal | Normal | M | 320 |
| 32 | 2 | 730 | Yes | Died | Normal | Normal | M | Small |
| 33 | 4 | 750 | Yes | Died | Normal | Normal | M | Small |

## Comparison of the Alternating and Continuous Series

Exact comparison between the results of shocks with alternating and continuous currents is impossible because the duration of the contact was not the same; the size of the animals differed with corresponding differences in current, and the number of animals varied in the two series. There is also the factor of the relative strength and health of the rats at the time of experimentation, which it is impossible to ascertain.

On a-c. circuits there was a continuous severe tetanic contraction of the muscles which usually persisted for a few seconds after opening the circuit. The chest of the animal was greatly expanded, and the shock was usually followed by clonic movements of the legs. A large number of rats was subsequently found to be paralyzed in the hind legs and in these a hemorrhage was present in the spinal cord. Bleeding from the eyes or nose occurred in many of the animals.

On continuous current circuit the contraction of the muscles was not as severe as on the alternating circuit, and clonic movements were usually present while the current was flowing. Relatively few of the animals were paralyzed and only one of these showed the characteristic hemorrhage in the cord, so common in the

alternating series. Few gross injuries could be detected in the central nervous system. Bleeding from the nose was only observed at the higher voltages.

After contact with the a-c. circuits the hair of the rats was ruffled and stood out from the body. The fur on the rats shocked on continuous current circuits, on the other hand, lay smooth and unruffled. When rupture of the blood vessels in the eye occurred the pupil was in every case found to be greatly constricted.

*110-Volt Alternating and Continuous Series.* After contact with the alternating current at 110 volts, 64 per cent of the rats recovered and 36 per cent died or were permanently injured, in contrast to 85 per cent that recovered and 14 per cent dead or injured after contact with the continuous voltage circuit. The duration of the shock was greater on the continuous than on the alternating circuit. From this it must be concluded that alternating circuits of 110 volts are more dangerous to rats than continuous circuits of the same voltage.

*220-Volt Alternating and Direct Series.* Here again the shocks were longer with the continuous than with the alternating potentials, provided rat No. 29, which received a 35-second shock (Table II) is eliminated. Seventy-two per cent of the animals died or were injured with the a-c. circuit as compared to 47 per cent with the continuous circuit. The conclusion is that the continuous 220-volt circuit is less dangerous than the 220-volt alternating circuit; however, the difference is not as great as in the 110-volt series.

*500-Volt Alternating and Continuous Series.* In these two series the duration of the shock was the same. Of the alternating series 38 per cent recovered, 12 per cent died, and 50 per cent were paralyzed. In the alternating series a large number was paralyzed and few died, while in the continuous current series the reverse is the case. If dead and paralyzed rats are grouped together, the total for the alternating group is 62 per cent in contrast with 51 per cent for the continuous potential group. Both circuits may be considered as being equally dangerous to rats.

*1000-Volt Alternating and Continuous Series.* No rats survived a continuous potential of 1000 volts for more than one second while with the circuits of the same alternating voltage several rats were resuscitated after a shock lasting three seconds. The percentage of dead and permanently injured at this voltage was 73 per cent in the continuous group and 71 per cent in the alternating. A 1000-volt continuous current circuit is therefore much more dangerous to rats than an alternating circuit of the same voltage.

This series was characterized by ejaculation of the males on the alternating circuit and persistent priarpism on the continuous circuit. In these series there were also severe injuries at the site of the electrodes.

*Artificial Respiration.* Several methods of artificial respiration were tried, as it was difficult to find an ideal procedure. It was not possible to insert a tracheal tube to fill the rats' lungs with air; with a larger animal such a procedure would be ideal.

One of the methods tried consisted of a respiration bottle in which it was possible to alternately raise or lower the pressure by means of a pump. The rat's body was placed inside of the bottle with the head outside. A rubber diaphram fitted snugly about the neck. This method was not satisfactory and was abandoned.

The most successful method for rats was to place the animal on its back and alternately compress and release its chest, at the same time holding the tongue out of the mouth. In some cases it was found advantageous to stroke the throat to remove any mucus that obstructed the passage of air.

Adequate artificial respiration is of prime importance. Urquhart[4] believed that with proper artificial respiration all of the animals could be saved in which the current passed through the head only, provided no actual burning of the nervous system or brain occurred. On this basis he proposed his theory of a temporary block in the respiratory center without permanent damage.

In the present experiments the brain was actually burned in only a few cases and all of the rats' hearts beat strongly following the shock. If Urquhart's theory is correct it should have been possible to resuscitate nearly every rat provided the artificial respiration was adequate. As shown by the results, many rats were subsequently found to have large hemorrhages in various parts of the central nervous system, particularly in the spinal cord. At least five rats died within less than four hours after the shock as the result of hemorrhages in the fourth ventricle of the brain pressing on the respiratory center. In the present experiments a large number of rats never breathed after the injury and died at once. At autopsy developing hemorrhages in the central nervous system were found in many. It is the opinion of the authors that few if any of these rats could have been saved by any means of artificial respiration. Sections of the central nervous system of all these rats are being prepared and it is hoped that in these cases the cause of death may be demonstrated.

In general, artificial respiration was more successful with rats shocked by the high voltage a-c. circuits than with those shocked by the corresponding continuous current circuits. In the case of the rats shocked by alternating current the chest was expanded and by manipulation air could be drawn into the lungs and breathing initiated. On the continuous current circuits, on the other hand, the chest was usually completely collapsed following the shock and no air could be forced into the lungs.

In the rats that recovered, some breathed fast and shallowly, and in others the breathing was slow and labored. In many cases it was irregular and a series of five or ten quick breaths would be followed by a slight pause. Often these respiratory difficulties continued for several days until the rats were killed. These abnormalities indicate injury to the respiratory system.

None of the rats died due to primary cardiac injury; deaths were invariably due to respiratory failure.

It is important that artificial respiration be started immediately following the shock, as the slightest delay increases the probability of death.

### Activity of the Rats Following the Shock

Few of the rats were active immediately following a shock at any voltage. When breathing began they usually lay quietly from five to ten minutes to half an hour. When they attempted to walk they were considered as recovered. Rats that later appeared normal were quiet for the first twenty-four hours and refused food and water. The paralyzed rats never became active, never ate, and could only be kept alive three or four days.

### Resistance

The resistance of the animals was found to decrease with the increase in the weight of the rats. This is

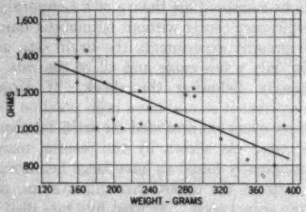


Fig. 1—Variation of Resistance with Size of Animals for the 1000-Volt A-C. Series

clearly indicated by the curve in Fig. 1, where the resistance in ohms is plotted against the weight in grams for the twenty-eight rats tested at an alternating potential of 1000 volts. Similar curves were found for the other series.

These experiments give the average values of the resistance of the rats as follows:

| | Resistance ohms | |
|---|---|---|
| Voltage | A. C. | D. C. |
| 110 | 3090 | 2685 |
| 220 | 1890 | 1635 |
| 500 | 1425 | 1385 |
| 1000 | 1140 | 1365 |

There is a large variation in resistance between the different series and part of this at least is caused by variation in the weight of the animal. For example, the rats tested with a 1000-volt alternating current were large compared to the majority of the rats tested with the same continuous potential.

As stated before the total resistance offered by an animal to the flow of current is made up of two parts, one the contact resistance and the other the ohmic resistance of the body. It is clear from a study of the resistance results in the case of rats that the contact resistance drop is of the form of a voltage drop which is practically independent of the current. The authors have calculated the value of this contact resistance voltage drop on the basis that the current through the animal equals the applied voltage minus the contact voltage divided by the resistance. On the basis of an average ohmic resistance of about 1200 ohms per animal the contact voltage drop equals 70 volts.

The current increased on long time applications and in some cases where the time was very long it nearly doubled in value. In most cases, however, the increase amounted to about 10 per cent.

### Current

The current that passes through the animal is of great importance in determining the injury that will result from the shock, but it is not the only factor. Other clearly evident factors are the voltage of the circuit and the duration of the shock.

In these tests no correlation was found between the current under a given set of conditions and the resulting injury. As already pointed out, the current that flows depends to a considerable extent upon the size of the animal.

The ideal condition would be to know not only the actual amount of current that passed through the organ to be studied when the electrodes are applied to the body, but also the current density in that organ.

### Voltage

Many data have been presented concerning the effect of the voltage and it is clear that the injuries increase as the potential is raised. It is very interesting to note again the fact that the initial shock is of importance. The 500- and 1000-volt a-c. tests, where the voltage was not maintained but fell rapidly to approximately 100 and 220 volts respectively, produced injuries much greater than the alternating 110- and 220-volt circuit experiments. In fact the injuries compare very well with those produced on the respective constant high-voltage circuits. It is therefore clear that the initial shock is of great importance in determining the injury to the animal. In this regard it would be interesting to know if there would be any difference in the injury produced by closing the a-c. circuit at different points of the voltage wave.

### Hemorrhages

Hemorrhages were observed following the shock in different portions of the body. In large numbers of the rats, particularly with those shocked on a-c. circuits, a small amount of blood emerged from the nose. This was thought to have been produced by a rupture of small blood vessels in the mucus membrane. Often blood was found in one or both eyes due to the rupture of vessels in the conjunctiva.

When artificial respiration was begun a rush of blood and frothy liquid came from the mouth of a number of rats. It was possible that hemorrhages had occurred in

the lungs of these animals. The methods of artificial respiration were, however, somewhat strenuous for such small animals.

The hemorrhages in the ventricles of the brain were caused by the rupture of the delicate blood vessels (choroid plexus) in the brain. Several of the rats died a few hours after apparent recovery, from large collections of blood in the cerebral ventricles.

The hemorrhages in the spinal cord were very typical for all cases and were caused by the rupture of a small artery in the posterior septum of the spinal cord at about the middle of the back (lower thoracic region). The blood escaped among the fiber tracts of the cord, and the hemorrhage often extended for a considerable distance up and down the cord. If the hemorrhage remained small and localized, little abnormality was produced in the behavior of the rats.

These hemorrhages were much more common as a result of shock with alternating than continuous currents. The time element seemed of little importance since they were as often found with short as with long exposure to the current. They were also common in the two series where the voltage was not maintained and the duration of the high-voltage shock was less than one hundredth of a second.

Urquhart[4] has shown that there is a rise of blood pressure to twice normal value immediately following a shock and he believes that this is responsible for hemorrhages. This theory would account for all the hemorrhages found in this investigation with the possible exception of those in the spinal cord.

Practically all of the spinal cord hemorrhages were caused by the rupture of small arteries in the spinal cord at the point of greatest curvature of the spine. The uniformity of the process is difficult to explain on the basis of a rise in blood pressure throughout the body. The duration of the shock had little to do with these hemorrhages. It may be that the sudden strong pull exerted by muscles when the a-c. circuit was closed, applied enough force upon the spine and subsequently upon the cord to mechanically break the artery at this point. The spinal cord, however, lies so free in the vertebral canal that it is difficult to imagine that any sudden pull on the spine, no matter how violent, could injure the blood vessels in the cord. The authors have advanced their theory as a possible explanation of the spinal hemorrhages, but they have no proof that this is actually the case.

## Paralysis

It was clearly demonstrated that the hind legs and the posterior portion of the body were paralyzed in a large number of rats after contact with the circuit. Paralysis was more common with those rats shocked with alternating than continuous currents.

Paralysis of the hind legs of rats shocked with continuous current, even though marked directly after the injury, had a tendency to decrease rapidly or even disappear entirely. Even in those rats in which the condition persisted and incontinence developed, no gross signs of hemorrhage were found in the spinal cord at autopsy. The paralysis observed after injury with continuous currents must be ascribed to other causes than hemorrhage. The characteristic injuries produced by continuous currents were convulsions, temporary paralysis, and priarpism. All these may be attributed to irritation of the central nervous system.

In the case of paralysis following shock with alternating circuits it was possible to gage in a rough way the extent of the hemorrhage. When the rats had recovered from the period of complete inactivity following the shock, and attempted to walk, they dragged their hind legs. If no active response to pinching the extremities was obtained during the first few hours following the shock it was concluded that the hemorrhage was severe, involving the lower portion of the spinal cord and completely interrupting the nerve tracts.

The subsequent behavior of this group of paralyzed rats was characteristic. After twenty-four hours, the great majority of the rats became incontinent and large quantities of blood were found in the urine. None of the animals could be induced to eat or drink, and they showed no activity. They would lie quietly in any position in which they were placed for hours at a time. None of them could be kept alive for more than three or four days.

At one time it was thought that the position of the electrodes on the tail might be responsible for the hemorrhages in the cord. As already stated, application of the electrodes to the head and one fore leg, or to one fore leg and the opposite hind leg produced the same effect. It must therefore be concluded that the paralysis of the hind legs was due to hemorrhage in the rats shocked by alternating current. Although beginning hemorrhages in the cord were found in a number of rats that died as an immediate result of the shock, it is doubtful if the spinal cord injury was responsible for the death. The paralyzed rats had no hope of permanent recovery.

## Summary

The following conclusions are drawn from this investigation.

1. The 110- and 220-volt a-c. circuits are more dangerous to rats than the corresponding continuous current circuits.

2. The 1000-volt continuous current circuit is more dangerous to rats than the a-c. circuit of the same voltage.

3. A large rat can withstand a greater shock than a small rat and still survive.

4. There is no difference between the sexes in their susceptibility to electric shock.

5. The longer the contact with a circuit the greater the chances of death.

6. The danger increases as the voltage is raised.

7. The contraction of the body musculature is greater on an alternating than on a continuous circuit.

8. The a-c. experiments are characterized in many cases by paralysis of the hind legs caused by large hemorrhages in the spinal cord.

9. Paralysis depends more upon the initial shock than upon the duration of the shock.

10. The death of the rats was due in every case to respiratory failure.

11. The three different positions of the electrodes investigated produced similar abnormalities.

12. A severe electric shock probably produces changes in the nervous system that are incompatible with life.

13. The death of rats that lived for only a few hours following the shock was found to be caused by hemorrhages produced in the brain by the current.

14. The injuries are not directly proportional to the amount of current that passes through its body. Not only must the initial voltage be taken into account, but also the duration of the contact and the size of the animal.

It must be kept in mind that these results can not be applied directly to man or to other animals.

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5

# The Metal-Clad Switchgear at State Line Station

BY A. M. ROSSMAN*

Fellow, A. I. E. E.

*Synopsis.—This paper describes a 22-kv. metal-clad outdoor type of switchgear. The design is a new departure from customary engineering practise in that all live parts are immersed in oil and enclosed in metal housings with each phase in its own independent compartment.*

*The switchgear insures maximum safety to the operating and maintenance personnel and reduces construction costs for power station switching.*

*The design is well adapted to mass production which should lead toward standardization resulting in a material savings in cost of manufacturing.*

* * * * *

THE State Line Power Station is located on the shore of Lake Michigan just east of, and adjacent to the boundary line between the States of Illinois and Indiana. This boundary line is also the eastern boundary line of the City of Chicago. The station is strategically located to supply electrical energy to the Chicago district, particularly to the industrial section that extends from the center of Chicago to east of Gary. The present plans for the ultimate station call for a generating capacity of 1,400,000 kw.

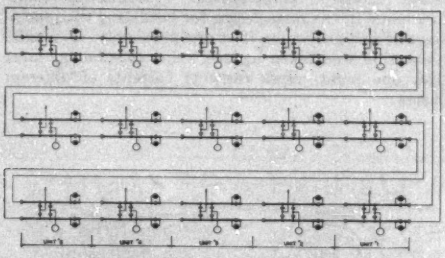

FIG. 1—DIAGRAMMATIC SCHEME OF CONNECTIONS SHOWING MAIN BUS BARS, REACTORS, AND FEEDERS

Reactance of each generator 15 per cent bus reactors 9.2 per cent based on maximum generator rating of 89,411 kw.

The three generators of each unit are connected 120 deg. apart on the ring bus. There is one bus section per generator and the different bus sections are tied together through bus reactors

When a generator is disconnected from the bus bars its corresponding bus reactor is automatically short-circuited so that only one bus reactor is in the circuit between any two adjacent connected generators

The initial installation is a three-machine unit rated 208,000 kw. at 0.85 power factor. It is made up of a high-pressure turbine with generator rated 76,000 kw. at 0.85 power factor or 89,500 kv-a., and two low-pressure turbines with generators each rated 62,000 kw. at 0.85 power factor or 73,000 kv-a., and two, 4000 kw. at 0.7 power factor auxiliary generators, one direct-connected to each low-pressure turbine. In order to keep currents within reasonable limits, the generators were wound for 22,000 volts. At this voltage, the large generator has a rated current of 2350 amperes.

The initial electrical design problem was the development of a system of connections that would handle the ultimate output of the station without excessive concentration of energy under short-circuit conditions and which would also give such a balance of current flow in the bus bars that there would be no undue disturbance of current flow when a machine is connected to or disconnected from the bus bars. The diagram finally adopted is shown in Fig. 1. The diagram is shown in a somewhat different form in Fig. 2. It utilizes a duplicate closed ring bus to which the three generators of a unit are connected 120 deg. apart. Adjacent generators are separated by bus reactors. The short-circuit kv-a. computed for five units (1,000,000 kw. at 0.85 power factor) are shown by the curves of Fig. 3. Attention is called to the fact that with this system of connections there is little increase in short circuit kv-a. after the second unit is installed. The oil circuit breakers have

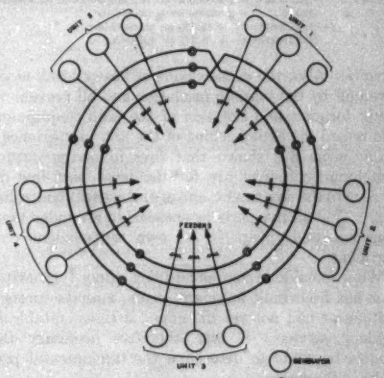


FIG. 2—RING BUS DIAGRAM SHOWING ONLY ONE BUS

a rated interrupting capacity of 2,000,000 kv-a. By spacing the three generators 120 deg. apart around the ring bus instead of connecting them to adjacent sections, the second objective—a better balance of bus bar currents—is achieved.

The next major problem was to design a suitable bus

*Electrical Engineer, Sargent & Lundy, Chicago, Ill.

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and switching structure. The conditions that were considered fundamental in this structure were:

1. That the oil circuit breakers be located out of doors.

Fires involving indoor switching equipment frequently fill the switchhouse with conducting gases which threaten and frequently cause secondary short

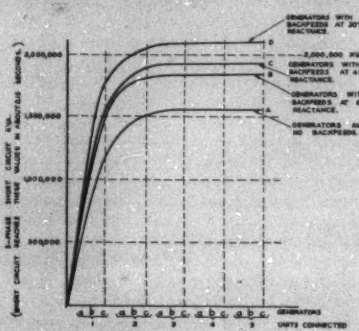


FIG. 3—SHORT-CIRCUITING VALUES FOR STATE LINE STATION

1—Gen. $a$ = 72,900 kv-a.
Gen. $b$ = 89,400 kv-a.
Gen. $c$ = 72,900 kv-a.
Total for 1 unit 235,200 kv-a.
2—Backfeeds on each unit
Gen. $a$ & $c$ = 1-20,000 kv-a. & 1-60,000 kv-a. backfeeds
Gen. $b$ = 2-60,000 kv-a. backfeeds
3—Gen. reactance = 15.5% on all machines
Bus reactance = 9.2% on 90,000 kv-a.

circuits. Also, the dense clouds of heavy black smoke given off by the burning insulation and oil prevent the ready location and isolation of the faulty equipment, and retard the extinguishing of the fire. Experience of many years has shown that fires involving outdoor switching equipment are for the most part less disastrous to the equipment, and are more easily controlled.

2. That all live parts be enclosed in grounded metal housings, each phase in its own independent compartment.

While metal-clad compound-filled indoor type switchgear has been built for many years, manufacturers of switchgear had not yet developed designs suitable for outdoor service. It was therefore necessary that studies be made to determine the fundamental principles of the design.

First began an investigation of metals to determine which ones had characteristics which made them suitable for enclosures for the large conductors. During this investigation there were gathered together from manufacturers on both sides of the Atlantic a varied collection of plates and tubes of non-magnetic metals. These included manganese steel alloys, nickel chromium steel alloys, copper, and copper alloys. The tubes were of ⅛-in. metal approximately 7 in. in diameter. In order to make the different materials comparable on test, the plates were formed from ⅛-in. material to the same diameter as the tubes, and then welded.

Through the courtesy of the Public Service Company of Northern Illinois, which placed at our service the laboratory and personnel of its testing department, a series of thermal tests was run on these tubes. The most important test was one made by looping a conductor through all of the tubes in series and then passing through the conductor 60-cycle currents up to 4000 amperes. This test revealed almost no difference in the temperature rises of the different tubes. This result was contrary to our expectation that eddy currents would cause greater losses and consequently higher temperatures in some of the pipes. It was then decided to use copper, because copper is close grained, is cheaper than the other metals, is easily worked in a well-established industry, and successfully withstands wide changes in climatic and atmospheric conditions.

It was also shown by test that the metal pipes would, if grounded at both ends, set up sheath currents that caused excessive temperatures. Provision was therefore made in the final design for insulating the pipe at one end and grounding it at one place only. A similar precaution was taken against tying together at more than one point, pipes carrying currents of different phases.

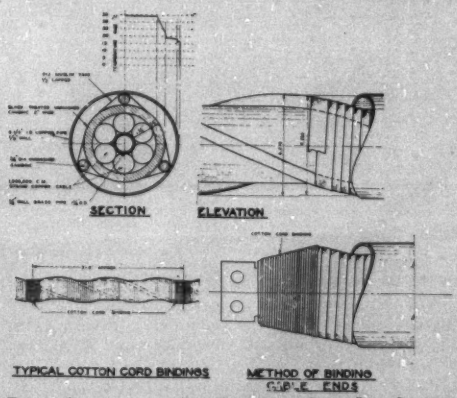


FIG. 4—CONDUCTOR AND PIPE ENCLOSURE, STATE LINE STATION

The next problem was to develop a small diameter conductor of large ampere carrying capacity with small skin effect. The General Electric Company kindly provided shop and laboratory facilities and the cooperation of their engineers to build and test various types of transposed bar and stranded cable conductors. From these tests a satisfactory design was evolved. This consists of six 1,000,000-cir. mil stranded conductors laid around a hollow center core. Each strand is independently insulated. It was found by measure-

ment that the a-c. 60-cycle resistance of this conductor was approximately 125 per cent of the d-c. resistance. (In a sample of the same size with bare strands this ratio was 168 per cent.)

Fig. 4 shows a cross-section of the conductor and pipe in the completed assembly. Above this section is

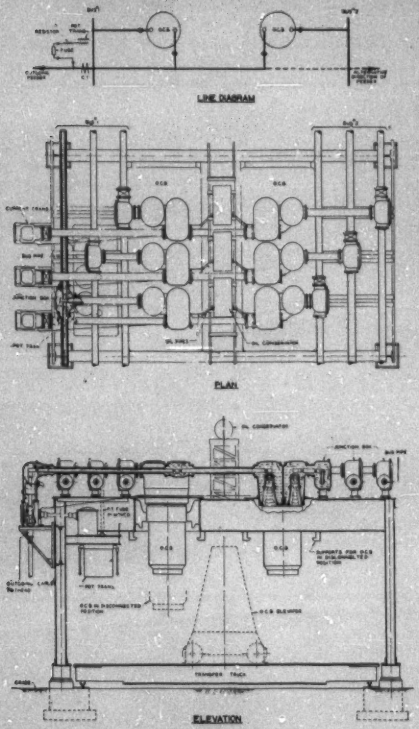


Fig. 5—Metal-Clad Switch Structure—Unit No. 1, State Line Station

shown the temperature distribution from conductor through the various media to the outside air with 2500 amperes at 60 cycles flowing in the conductor. The temperature rise of the conductor is about 30 deg. cent. While the performance of this conductor was satisfactory, it is now being superseded by one less costly to manufacture.

Other details that involved much study, search for materials, and testing, were the junction boxes, expansion fittings for both pipes and conductors, conductor terminals, devices for centering the conductors in the tubes, oil diaphrams, and insulating joints to prevent the flow of circulating currents in the metal enclosures. A description of the various schemes considered, designs worked out, and models made and tested would unduly extend the length of this paper.

A typical circuit bay as built and installed at State Line Station is shown in plan and sectional elevation in Fig. 5. All live parts are covered with a solid insulation. The space between the insulation and the metal enclosure is then filled with mineral oil. This gives an insulation designed to withstand a test of 85 kv. for one minute between the live parts and their metal enclosures. Oil-tight barriers subdivide the oil reservoirs into nine compartments per bay. Oil is piped to these compartments from elevated conservators.

Current transformers are bolted solidly to the conductors and are immersed in the oil which surrounds the conductors.

Circuit breakers and potential transformers are detachable. They are raised and lowered by a portable motor operated elevator. This arrangement permits the elimination of disconnecting switches and very greatly simplifies the interlocking.

A plan of the complete switching structure of 23 bays with the transformers adjacent thereto is shown on Fig. 6. A typical cross-sectional elevation is shown on Fig. 7. Connections between switching structures and

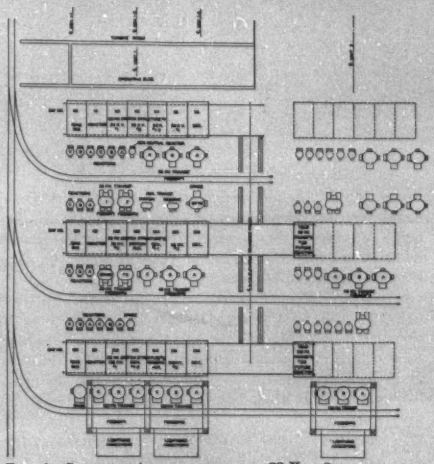

Fig. 6—General Arrangement of 22-Kv. Switchyard—State Line Station

power equipment are made with single-conductor, lead-covered cables through oil-tight cable end bells. The cables are supplied with oil by special independent expansion type oil reservoirs. The end-bells are provided with insulating joints to prevent the flow of circulating currents in the cable sheaths and to prevent the shunting of fault currents to ground through the cable sheaths.

Inasmuch as all live parts are surrounded by metal

enclosures which are in turn mounted on a metal supporting framework, it was only necessary to insulate the supporting framework from ground to make it capable of utilization as a ground fault bus. This was done by inserting insulating blocks in the steel supporting columns and then grounding the upper structure through current transformers. Any fault current must then pass through the current transformers to reach ground. Their secondaries are connected to relays which when they trip cause all the circuit breakers in that section to trip out and thereby isolate the section.

As no live parts are exposed, it is possible for an inexperienced person to climb all over the switching structure without danger of electrocution.

The structure at State Line Station was first energized at 22 kv. on November 20, 1928. It has been delivering energy in commercial service since April 8, 1929.

The State Line equipment was shipped piece by piece, and much of the erection was carried on through the winter months. This method of erection, especially under cold weather conditions, was found to be slower and more costly than had been expected. To improve these conditions, a subsequent study has been directed

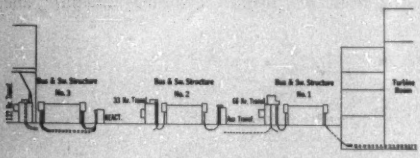


Fig. 7—Sectional Elevation—22-Kv. Switchyard—State Line Station

toward modifying the design so that more of the parts could be assembled in the factory and fewer in the field. This study developed the more compact arrangement of parts shown in Fig. 8. Here, except for the normally detachable parts such as oil circuit breakers, potential transformers, and a few minor parts, all of the housings and all the current carrying parts of each circuit are assembled at the factory into three groups. In the field, these three group assemblies are elevated into position, one by one, by the oil circuit breaker elevator and are then bolted together. The new arrangement is but two-thirds as wide as the original arrangement. Twenty-five bays of this later design are now being built for the Powerton Power Station of the Super Power Company of Illinois located near Peoria, Illinois and it will be used on future extensions at State Line Station.

The main objects of the metal clad design were to provide a structure that would:

1. Insure maximum safety to the operating and maintenance personnel.

2. Provide a thoroughly reliable switching equipment by reducing to a minimum the chance of a phase-to-phase short circuit, and

3. Reduce costs (a) by eliminating the switch house building; (b) by providing a switching arrangement that would lead toward standardization and would be susceptible of mass production as a complete factory-built unit. This will naturally tend to cut factory costs and to eliminate a great deal of field construction which is often done under adverse conditions.

It is felt that these objectives have been achieved.

In the development of this new type of bus and switching structure, advice was sought from and was freely given by many engineers and manufacturers,

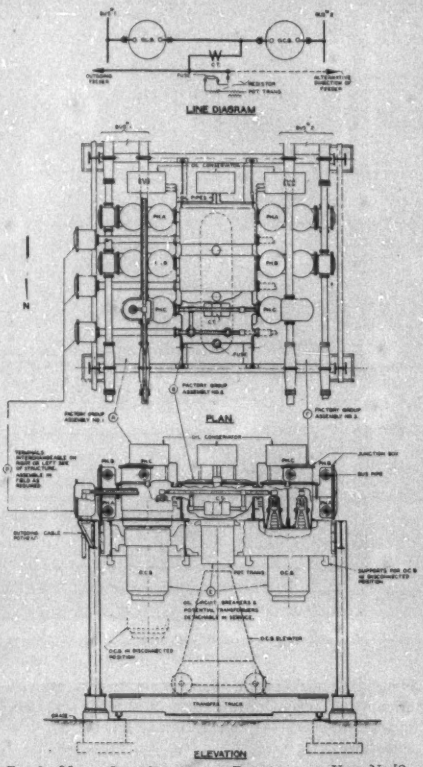


Fig. 8—Metal-Clad Switchgear Proposed for Unit No. 2—State Line Station

both in this country and abroad. Special acknowledgment is due the General Electric Company for the interest it has shown in this new design and for the careful attention it has given to the manufacture of the State Line equipment to insure the success of this new and somewhat radical departure from customary engineering practise.

## Discussion

**G. G. Cree:** After many years of successful use of metal-clad switchgear in other lands, its adaptation to meet the demands of American practise on such a large scale deserves careful attention.

Sufficient operating experience has already been obtained at Wheaton and State Line to warrant the further adoption of this type of heavy duty switching equipment.

While reliability and safety to operating and maintenance staffs have been the main factors leading to the use of metal-clad gear, it is also true that for certain conditions it may be attractive on purely economic grounds.

In heavy duty switching stations the total cost per switch position is composed of two elements, one a fixed charge unaffected by the kw. load on each circuit, and the other a variable proportional to that load.

In comparing metal-clad gear with the two alternatives usually considered, namely, isolated phase indoor construction and adjacent phase outdoor construction, we find that the fixed charge per circuit is a much more important factor in the cost of metal-clad equipment than in the case of the more conventional alternatives.

As a result, stations such as State Line and Powerton, from which the entire output is stepped up and transmitted to a distance, with the circuit loading reaching as high as 100,000 kw., might well adopt metal-clad designs for purely economic reasons.

On the other hand, a typical station located within the concentrated load area and fulfilling the dual functions of generation and distribution through a multiplicity of feeders, of say 6000 to 10,000 kw., would normally have to rely on preference on the basis of safety, reliability, and ease of installation.

The present trend is so clearly in the direction of placing large generating stations remote from the load center that rapid extension of the use of metal-clad switchgear of this type may be expected as its advantages become more apparent.

An extension of the generator bus at Cahokia was carried out in metal-clad gear, and due to special conditions is believed to show a saving in cost.

It is to be hoped that there may be a tendency toward uniformity in user's specifications so that the standardization and mass production to which Mr. Rossman refers may be a reality.

**H. J. H. Huber:** Mr. Rossman omitted one factor that I think is quite important. In working out the design for this metal-clad gear, many kinds of circuits were studied and the simplest circuit that would do the job was the one that was adopted. Mr. Rossman's object, and also the object of the manufacturing companies' engineers, was to get away from the present day custom-made switch house construction. At the present time there is a tendency to design each station differently, and when an addition is made to a station, it generally is different. This keeps the manufacturers continually making new designs.

It was our object, and also the object of the consulting engineers, to develop metal-clad switchgear which would be simple and which could be built over and over again. There will be improvements, of course. The improvements will be in the details. The general scheme is what should be standardized, so manufacturers can get quantity production. Engineering, pattern, and tool expense will be reduced. This will be of great help to the purchaser and manufacturer, as it will reduce cost.

Mr. Rossman mentioned this in his paper, but did not bring out this point in his presentation.

**Philip Sporn:** I know personally that there have been many problems of design and construction that required a great deal of engineering ingenuity to work out. I think Mr. Rossman and his design associates are to be congratulated on the successful working out of some of these. There is one question, however, that hasn't been brought out very forcefully, and that is the economics of the design. As Mr. Cree has pointed out, the design is fundamentally one that involves heavier fixed charges than any design heretofore developed.

The question that the designer of central stations today has to face, and that he will have to face more and more as the years go on, is the question of cutting down his expenses. It isn't a question any more of getting something better that he has had heretofore, unless he can do it at less expense. While the design described offers possibilities of greater safety perhaps, it is doubtful whether it can be justified in the average system. The safety features of outdoor structures which have been developed in their many forms today are at a point where continuity of service can almost be forgotten. Where a large quantity of power can be concentrated on a single feeder, without doubt the design discussed can be justified.

It was very interesting to find in the paper that Mr. Rossman decided to go to the outdoor design on the general principle of safety; in other words, that the outdoor design is safer than the indoor design. I know of at least one large system where that same problem was studied and a conclusion exactly the reverse was reached, namely, that the indoor design was fundamentally safer than the outdoor, and the indoor design is a course being followed.

In connection with the switching layout, in which each line is given its own transformer bank, I should very much like to hear from Mr. Rossman, or from any of the Commonwealth Edison people, whether studies have been made to determine the effect on system stability of that type of construction. It seems to me that while it may work out all right at a certain point on the system, in general however, the breaking up of the system with the additional impedances in each line may result in many operating conditions that will be less stable with that set-up than with the standard bus arrangement.

Another disadvantage of this arrangement is that it makes it impossible to supply the entire load of a district normally fed, say, by two lines through one line, a situation that might readily arise during sleet or other emergency conditions. Of course it can be done if the transformer banks are made 100 per cent larger than the normal rating. But again you are confronted with a situation of greater cost, which is the reverse of what most people are trying to accomplish today.

**E. C. Williams:** The company which I represent has been experimenting since 1926 with the metal-clad type of switchgear referred to in Mr. Rossman's paper. There is no statement of performance included in the paper, and I therefore wish to offer what our company has experienced. We have a total of 18 such installations either in service or on order. The voltages range from 2300 volts to 33,000 volts. We have on order one 132,000-volt equipment using this system with slight modifications.

To date there have been no electrical failures chargeable to the metal-clad principle. In the original oil-filled installation which was operated at 33,000 volts, outdoor, three cases of porcelain failure have occurred, apparently due to incorrect mechanical design, which difficulty is rapidly being corrected. On this same installation the question of oil retention was a serious problem, but on later installations this is being taken care of successfully by the selection of proper materials.

On the matter of cost, it appears rather early to judge, and there seems to be an unwarranted premature prejudice being worked up against this switchgear on this score. When all of the various factors which enter into switchgear *total costs*, such as equipment cost, installation labor, salvage value, maintenance charges, probable life, etc., are considered, the cost of this type of switchgear does not appear to be higher than that of the ordinary type. Also it cannot be doubted that this equipment is much safer than the open type equipment, and the value of this feature is sometimes beyond measure.

Also it is reasonable that we can expect lower equipment costs ultimately through this principle, as under this arrangement the manufacturer can supply a complete switching machine which will no doubt lead to simplified standardized arrangements,

and the resultant lower costs which follow factory assembly on a mass production basis.

This equipment seems to offer a means of reducing the cost of one of the most expensive parts of our plant equipment, and the operating companies should therefore cooperate patiently with the manufacturers in working out this problem.

**W. H. Colburn:** No matter how much one favors a particular type of equipment from personal, theoretical, or academic considerations, economic considerations have greater weight and, in the end, will be found to govern. Hence experiment is the only admittable excuse for installing one type of equipment in preference to another to perform an identical function, unless it can be shown that earnings or savings, or both, will be increased thereby. Obviously the use of metal-clad switchgear cannot provide greater earnings except as it can provide distinct improvement in service continuity. This can but rarely be the case when compared with well thought out, conventional designs. Therefore, we must look to economies for major justification of the use of metal-clad equipment. Unfortunately, Mr. Rossman has omitted discussion of the economic phase of this subject.

Recently I examined the economic feasibility of using metal-clad outdoor equipment in a 25,000-volt substation. The conclusions reached were that, with present manufacturing costs of metal-clad gear, the station diagram as well as the phase isolation requirements of the conventional design may be a controlling factor. For instance, admitting all safety and economy advantages claimed for metal-clad equipment, and placing as much financial value as possible upon them, it was impossible to justify its use except as an experiment, for any case but a large switching center requiring a double bus with conventional thorough phase isolation. This case showed, however, a saving of approximately 10 per cent of the cost of conventional equipment to be expected by using outdoor metal-clad gear.

From this study I am led to believe that anyone who will investigate will agree that this switchgear has such advantages that it will come into wider and wider use. When this becomes the case we may expect that manufacturing costs will be somewhat further reduced, and that this equipment will come into competition economically even more with conventional equipment of various diagrams, thereby making possible still further economy. It seems evident that at present no major switching undertaking in the voltage ranges for which this equipment is suitable should overlook consideration of the use of this type of gear.

**M. M. Samuels:** (communicated after adjournment) For a number of years I have been trying to digest the metal-clad idea, to weigh all the arguments for and against it. I must admit that I liked it and still like it, and I should be delighted to find some good sound economic reasons for it. To my own displeasure I have so far failed to find sufficiently convincing reasons for the adoption of the scheme, and I will attempt to summarize the various arguments which have been brought out against it in the hope that they will all be disproved.

1. Boiled down to its basic principle it is comparable with a low-tension cable bus in a conduit, with a condulet or junction box at each joint, and compound or oil added as an additional precaution. This is one of the oldest methods of making a bus, and has all the drawbacks which induced engineers in the past to get away from it. I can even go a step further and recall that a few years ago on the occasion of removing an old rope-drive railway generator I found a piece of ancient cable which was made up of a brass pipe filled with compound and a conductor in the center.

2. The old question, which has been repeated over and over again, is still unanswered: What if something happens to the bus? It would not be easy to locate the fault and quite an elaborate process is required to repair it. The only answer I have heard so far is that nothing ever happens to it, an answer which I must consider as foolish, because there is nothing built by human hands or by nature itself to which nothing ever happens.

3. It is claimed that it is safer, that one can walk around or sit on top of it. As for myself, I have no desire to walk around or sit on top of switchgear,—the sidewalk and a chair serve my purpose much better. But when a statement is made that something is safer, one is justified in asking for accident statistics, to substantiate the statement. If there are such statistics they have escaped my notice, and I should like to be enlightened.

4. It is claimed to represent a great economy in space. Perhaps so. But so far I can see only an economy in height. I never could find any economy in floor space; I always could find another type of switchgear either indoors or outdoors which did not require any more floor space or ground space, and in most cases required even less. Height is not so important as ground space, especially outdoors.

5. When one breaker per circuit is used without by-passes, transfers, or other devices, or when there is sufficient money available as in the case of State Line, to use two breakers per circuit, the design is comparatively simple, especially when such excellent, ingenious designing is done as was done at State Line. But when money for two breakers is not available—and in most cases it is not—and when selectors, by-passes, or transfers are required, the thing becomes so complicated with oil or compound filled switchgear as to be practically impossible.

6. There is nothing more standardized than switchgear, and yet manufacturers advise that there is very seldom any call for even such a simple standard article as a standard switchboard panel. The electrical industry is developing very rapidly, and changes are called for at all times. Nothing installed in a power house can remain very long without requiring changes,—changes in capacity, changes in diagram, changes in relay systems and the corresponding additional or changed instrument transformers. Compound filled or oil filled switchgear, to say the least, make it very difficult to make such changes.

7. I have not as yet seen a full hearted statement any place that it represents an actual saving in money, so I am assuming that it does not. If it does I should like to see some figures, submitted in such detail that they can be readily analyzed and criticized.

8. One of the main advantages of this, as well as of the truck type switchgear, seems to be the elimination of the disconnecting switch, not so much for the reason that it is always only a necessary evil, but more for the reason that there is not a decent gang-operated disconnecting switch on the market. However, what will be done when disconnecting switches become an economic necessity as mentioned under 6? Why not concentrate and design a good disconnecting switch?

In conclusion I want to repeat that I am not raising all these questions because I don't like this type of switchgear. I do like it, and I was particularly impressed with the fine designing skill shown at State Line. But I should like to see some good sound economic reasons for this liking. So far, in my humble opinion, such good, sound economic reasons have not been presented. I should be delighted to find that they exist and that I have overlooked them.

**J. W. Bennett:** (communicated after adjournment) Mr. Rossman's paper describes a very interesting departure from the conventional in the design of power station switchgear. The equipment described possesses undoubted advantages from the point of view of safety and continuity of service, both of which are of great importance in the design of switchgear for any station. Use of this equipment, in its present state of development, seems to me to be somewhat limited by plant location and economic considerations. With increased use, some modifications in design, and consequent reduction of cost, this type of equipment should come into more general use. In its development the operating engineers should work closely with the engineers of the

manufacturing companies to the end that a standardized design may be developed as soon as possible.

The arrangement of equipment described indicates possibilities for extensive development along this line and Mr. Rossman and his associates are to be congratulated upon their pioneer work in this field.

**A. M. Rossman:** Mr. Sporn raised the question of the reliability of outdoor *versus* indoor switching equipment. The point I stressed in my paper was that in case of a fault on outdoor equipment it does less damage to adjacent equipment and it can usually be cleaned up more quickly and easily than a corresponding indoor failure. You who are familiar with failures, especially in metropolitan systems, know what happens when an oil circuit breaker goes bad in a closed room. I don't need to elaborate on that. In my own experience I know of no such disastrous results from the failure of an outdoor circuit breaker.

Three speakers have discussed the economics of the metal-clad design. I might say with respect to the State Line equipment, that we got proposals on indoor isolated phase, on indoor grouped phase, and on metal-clad equipments, and we made very careful cost estimates of all three schemes. The outdoor metal-clad showed an appreciable saving over the other two. I want to say also that the actual installation cost was very close to the estimated cost. We also made studies based on using outdoor open type equipment, but found the layouts too dangerous for a station of the size of State Line with the amount of power it will handle. We abandoned them on that account.

Mr. Williams discussed the matter of costs. I am sorry he didn't feel free to give some actual figures with reference to costs of the 33,000-volt substations which his company has installed. I have seen some of these figures and was quite amazed that the saving in installation costs went so far toward offsetting the higher prices of the metal-clad equipment.

Mr. Colburn referred to estimates made by him of the cost of 25,000-volt substations and Mr. Huber has pointed out one way in which these costs can be kept down.

Operators' engineers have been prone to ask for almost anything they wanted in the way of electrical equipment because they usually design the structures in which these equipments are mounted and the equipment must fit the structures. Metal-clad equipment should be viewed from a different angle. In our work we have tried to keep the design just as simple and just as close to the elements as possible, with the idea that such a design is susceptible of standardization. If you are interested in this type of equipment, please do not ask the manufacturer for too much in the way of built-in testing facilities, or grounding facilities, or other special features that are peculiar to the practise of your company, but are not generally used by other companies. Put the special features into external devices that can be plugged into the standard switching structure.

I hope that the design will soon crystallize into a form that will be acceptable to so large a group that it may be standardized and put into mass production, thus hastening the day when this type of equipment can be purchased at much lower prices than are possible today. As an example of low prices due to standardized design, I cite the Ford automobile.

# Development of the New Autovalve Arrester

BY J. SLEPIAN,* R. TANBERG,* and C. E. KRAUSE*
Fellow, A. I. E. E. Associate, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—This paper describes the development of a new autovalve lightning arrester operating on the principle of discharge in restricted passages.*

*A brief résumé is given of the improvements in performance and size desired in lightning arresters. Reference is made to laboratory tests on insulation protected with arresters to determine the limits of discharge voltage required for good local protection. Oscillograms show that the new autovalve arresters meet these requirements. Successful operating experience with these arresters is stated to give final verification of the results obtained in the laboratory investigations.*

*The steps in the development of materials are described and the materials finally chosen and the design of arresters are considered.*

*The performance is discussed and illustrated by oscillograms covering a wide range of currents, both with and without power voltage applied.*

*The size of the new arresters is about one-half that of the present commercial autovalve arresters. One of the probable benefits resulting from this reduction in size is the possibility of making practicable the protection of high-voltage lines against lightning flashover.*

* * * * *

1. *NEED of Further Improvements in Arresters.* The composite experience of designers, manufacturers, and users of protective equipment has indicated that the proper use of modern valve type arresters permits a radical reduction in the damage of apparatus by lightning. Lightning arrester engineers have realized, however, that the present available arresters have limitations in performance and in their application because of their size.[1] Experience indicates that available arresters may be expected to reduce the lightning damage to an unprotected system to about one-tenth or perhaps one-twentieth, but this is the limit of the arresters now generally available.

In recent years the fact that instruments like the klydonograph and cathode ray oscillograph have been available has given a great impetus to investigations of lightning phenomena in general, including the characteristics of arrester types. A large amount of information has been collected and this helped to form better opinions of the requirements which lightning arresters should meet. The work done with these new tools has made possible the development of a new valve arrester which not only offers better electrical protection but also is reduced in size, thus opening up new possibilities of application including high-voltage line protection.

The characteristics of this new arrester can be illustrated best by referring to Fig. 1, which shows its maximum discharge voltage and the sharply defined cut-off which indicates true valve action. The ratio of the maximum discharge voltage of the arrester to the cut-off voltage, which is approximately equal to the crest value of normal line voltage for which the arrester may be used, is about 2.5. The present commercial autovalve arresters of line and station types have, for the same current, voltage ratios which are greater, as may be seen by referring to the oscillograms shown in Fig. 2.

Extended tests in the laboratory on insulation protected with arresters have indicated that there is probably no deterioration of insulation with arresters having ratios not exceeding about 2.5.[2] Later experience with these new autovalve arresters having a ratio of about 2.5, in the field operating under all kinds of service conditions, has thoroughly corroborated the results of laboratory tests. It appears that it may eventually be feasible, with this new form of valve

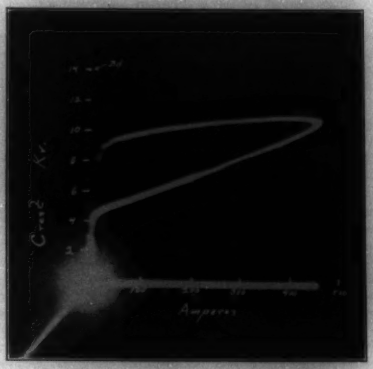

FIG. 1—VOLT-AMPERE CHARACTERISTIC OF A NEW AUTOVALVE ARRESTER COMPLETE WITH SERIES GAP

The arrester is rated at 3000 volts r. m. s. or 4200 crest

arrester, to reduce the protective ratio to less than 2½. Since lower ratios than 2½ are not necessary for the adequate protection of apparatus, arresters of these reduced ratios will be applied on the basis of their crest discharge voltage rather than their cut-off voltage. The cut-off voltage then will be considerably in excess of the maximum rated circuit voltage of the system to

*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. "Arrester Aims and Prospects," by A. L. Atherton, *Electrical Wld.*, April 13, 1929.

2. "The Ideal Lightning Arrester," by A. L. Atherton, *Electric Jl.*, August 1929.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*



30-47

which the arrester is connected, thereby providing a greater factor of safety against arrester failures caused by high dynamic voltage and increasing the reliability of the circuits without sacrificing protection.

*2. Principle of Operation of New Arrester.* In a preceding paper by the authors[3] it was shown that the properties of discharges confined to narrow passages are such that good electrical valve characteristics may be obtained by the use of a block of slightly conducting

FIG. 2—VOLT-AMPERE CHARACTERISTICS OF COMMERCIAL AUTOVALVE ARRESTERS WITHOUT SERIES GAPS

The arresters are rated at 3000 volts r. m. s. or 4200 crest. The oscillograms to the left are of line type arresters with and without mica washers. Those to the right are of station type arresters

porous material. This is the principle of the new autovalve arrester. Like the old autovalve, it depends for its valve characteristics on special forms of discharges in gases in which the voltage for maintaining the discharge is kept from falling much below the voltage for initiating the discharge.

*3. Development of New Arrester.* The principle of operation referred to above and described in the authors' previous paper, broadly defines the mechanical and electrical properties of the materials to be used in the structure of the valve element. In the development of the arrester it was necessary, however, to determine the range of materials which is suitable, the permissible range of fineness of these materials, the cross-section and length of the element, and to make a careful study of the effects of variation in the methods of manufacture. The materials selected as the component parts of the porous element are fabricated into cylindrical blocks of the desired cross-section and convenient length. Each one of these then provides a unit with valve characteristics. At the present time the blocks are made in units rated at 3000 volts maximum, one inch long and two inches in diameter, this cross-section providing sufficient discharge capacities for line type arresters.

The blocks contain insulating and conducting materials. A great deal of attention was devoted to the problem of binding these materials with organic and ceramic bonds. In many cases it was found that the organic bonds did not offer the stability and permanence and presumably mechanical strength, which were obtained with the use of ceramic bonds. The latter made it possible to make structures having a greater uniformity of pore sizes and thus reduced the chance of large holes forming through the material which might impair the cut-off action.

In the course of the experimental work, numerous materials were tried and several thousand arrester elements of various types manufactured, these generally consisting of a specially prepared clay which is carefully ground to obtain the proper fineness, with a small amount of conducting material added to initiate the discharges in the pores provided by the granular insulating material. The range of conducting materials which may be used is large. For example, good results were obtained by the authors with metals such as brass, aluminum, iron, nickel, and copper; with ferro-alloys such as ferro-silicon, ferro-tungsten, and ferro-manganese; with refractories such as graphite and carborundum; with minerals such as rutile, coal, coke, and many other materials. The proper amount of new kinds of conducting material to try out in these blocks was arrived at from a general study of the volume of conducting material required.

The two kinds of material, namely, conducting and insulating, are thoroughly mixed together and pressed into blocks having the proper porosity. If the material is coarse, the cut-off gradient will be quite low, while if it is very fine, the gradient will be high. Studies of this nature revealed that the desirable structure to use in lightning arresters was not the finest which was tried, having a high cut-off gradient. These extremely fine

FIG. 3—NEW AUTOVALVE ARRESTER ELEMENT

Rated at 3000 volts, after it has been copper sprayed and insulated

materials as a rule are not as permanent, although it is possible to construct workable arresters with voltage ratios as low as 1.4. Permanent structures, somewhat coarser and thicker for a given voltage rating, gave ratios around 2.5. This latter type of block was chosen as the desirable one to use in arrester designs at the present time since its ratio falls within the limits of adequate protection and its size is small.

The preferred shape of element is a cylindrical block, since elements of this kind are simple to manufacture and can be assembled conveniently in porcelain casings

3. *The Theory of a New Valve Type Arrester*, by J. Slepian, R. Tanberg, and C. E. Krause, A. I. E. E. Quarterly TRANS., Vol. 49, January 1930.

of designs which are comparatively easy to make. The thickness of these blocks is proportional to the voltage for which they are intended to be used and their cross-section may be made to suit the discharge current requirements.

The blocks or arrester elements are sprayed with copper on the parallel faces by the Schoop spray process to insure a good electrical contact, leaving a small unsprayed rim near the edges to eliminate the possibility of particles of copper getting on the other surfaces. The

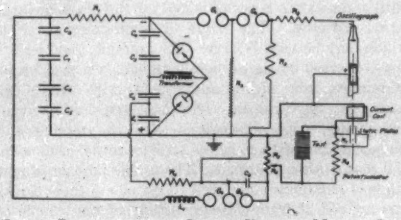


Fig. 4—Diagram of the Circuit Used in Making Volt-Ampere Oscillograms of Arresters

cylindrical surface of the blocks is then insulated with a coat of cement to prevent any chance of flashover due to surface creepage and the blocks are then ready to be used for assembly in arresters. See Fig. 3.

Completely assembled arresters are built up by stacking the blocks one above the other in a porcelain casing, the number depending upon the voltage rating of the arrester. A spark-gap is placed in series with the assembled element.

4. *Electrical Characteristics of New Arrester.* Volt-ampere characteristic curves have been made on many of the 3000-volt arrester elements to determine the maximum discharge and cut-off voltages and their ratios with various discharge currents ranging from 12 amperes to about 1100 amperes. These tests were made by means of a DuFour type cathode ray oscillograph used in conjunction with the unique circuit devised by Harrington[4] for simultaneously tripping off the impulse circuit, which is the source of test voltage, and the cathode ray oscillograph used for measuring arrester performance. Refer to Fig. 4. The results of these tests can be explained best by referring to the oscillograms shown in Fig. 5. It will be noted that for current densities of the order of about 4 amperes per square inch the voltage ratio is about 1.8, while for the higher current densities of the order expected from lightning discharges, it is about 2.5. The low-current oscillogram is interesting in that it shows the nature of the cut-off at extremely low current densities. The oscillogram showing only the first part of a high-current characteristic was produced by allowing the cathode beam to go off the film and is included to give a magnified picture of the cut-off at the higher current densities.

The practical arrester as applied to circuits is so designed that the cut-off voltage is close to the crest of the arrester's voltage rating in order that only a small current is permitted to flow through the arrester following the passage of a lightning discharge. This small leakage current is interrupted by the series gap. If the cut-off voltage is much less than the rated voltage of the arrester, considerable line current will follow the lightning discharge, the amount depending upon the magnitude of the cut-off voltage. Thus, by maintaining a high cut-off without altering the crest of about 2.5 times the system voltage the arresters may be made safer against dynamic over-voltage. It is also desirable to keep the cut-off voltage as high as possible so that the volt-ampere loop will be narrow and more energy extracted from the surge as its voltage is decaying.

The sharp cut-off action of the new arresters discussed and illustrated above by oscillograms covering a wide range of currents indicates that arresters of this type should not allow a large power current to follow a lightning discharge when they are connected to a source of power voltage as they normally would be in practise.

Fig. 5—Volt—Ampere Characteristics of 3000-Volt Arrester Elements with Various Values of Surge Current

| Oscillogram | Voltage ratio | Maximum current density |
|---|---|---|
| C-303-AA | 1.8 | 4 amperes per sq. in. |
| C-303-AC | 2.5 | 140 " " " " |
| C-303-AE | 2.6 | 320 " " " " |
| C-303-AH | 2.6 | 350 " " " " |

In order that this may be checked, oscillograms were taken with arresters connected to a source of power of large capacity and whose voltage is equal to that of the maximum ratings of the arresters being tested. An oscillogram obtained in this manner on a 15-kv. arrester is shown in Fig. 6. It will readily be seen that the current which follows the discharge, indicated by the small break in the zero current line, amounts to only a little over an ampere and lasts for a fraction of a half-cycle of the 60-cycle voltage. Currents of this order of

4. "Technique of the DuFour Cathode Ray Oscillograph," by G. F. Harrington and A. M. Opsahl, *Electric J.L.*, August 1927.

magnitude and duration are not sufficient to interfere with the operation of the arrester.

*5. Size of New Arrester.* The new autovalve arrester elements are of such small size that a block one inch thick is good for a maximum rating of 3000 volts r. m. s. This has made it possible to reduce the size

FIG. 6—OSCILLOGRAM SHOWING POWER FOLLOW ON A 15-KV. NEW AUTOVALVE ARRESTER

Note that the power follow current is only a little over one ampere. This oscillogram should be compared with the volt—ampere curve shown in Fig. 1

of arresters, particularly those of high voltage, partly because of the small size of the porcelain casings which are required and partly because of the reduction in size, and in some cases the elimination, of the supporting structures. This reduction in size of high-voltage arresters has made it possible to install arresters in

FIG. 7—COMPARATIVE SIZE OF 3000-VOLT ARRESTER ELEMENTS OF THE NEW AND OLD AUTOVALVE TYPES

Note that the new type is only one-half as large

existing substations where space limitations do not permit the application of the arresters now in general use. These new autovalve arresters are light in weight, require little space for their installation, are simple to install, and the expense of transportation is considerably reduced.

The small size of the new arrester is indicated in Figs. 8, 9, and 10, which show the new arrester compared to a present standard autovalve of the same voltage rating.

The reduction in size and weight makes it possible to suspend arresters of this type from the station structure, or even from the transmission line towers, thereby entirely eliminating the requirements for arrester space

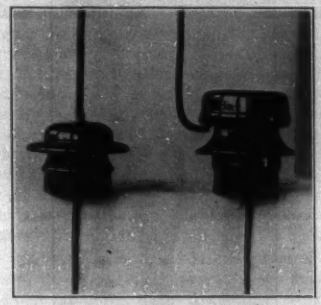

FIG. 8—COMPARATIVE SIZE OF 3000-VOLT NEW AND OLD LINE TYPE AUTOVALVE ARRESTERS

It will be noted that the new arrester is smaller

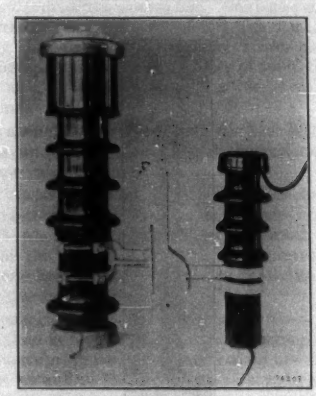

FIG. 9—COMPARATIVE SIZE OF 25-KV. NEW AND OLD LINE TYPE AUTOVALVE ARRESTERS

The arrester on the right is the new type.

in a station. This possibility is of particular importance in the field of line protection for high-voltage systems. It has been realized for some time that distributed lightning protection, that is, the placing of arresters at intervals along a transmission line, will not only decrease the lightning hazard to station apparatus but will also greatly reduce the likelihood of insulator

flashovers on the line, the degree of reduction effected being a function of the density of the distributed arresters. Heretofore such distributed protection has not been considered economically practicable because of the size and weight of the present available arresters. The new valve arresters described in this paper bring

Fig. 10—Comparative Size of 73-Kv. New and Old Station Type Autovalve Arresters

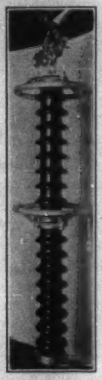

Fig. 11—New Autovalve Line Type Arrester Used for 110-Kv. Grounded Neutral Service

this method of protection within the realm of practical use. High-voltage line type arresters of the new construction are little different in size from the strings of insulators generally used. Incorporating arrester elements in insulator strings may be a development of the future.

It may now be economically feasible to increase the reliability of existing lines which suffer from outages caused by lightning flashover by the installation of arrester protection. The effect of an efficient line arrester on construction of new lines may be considerable. Such an arrester, besides reducing the likelihood

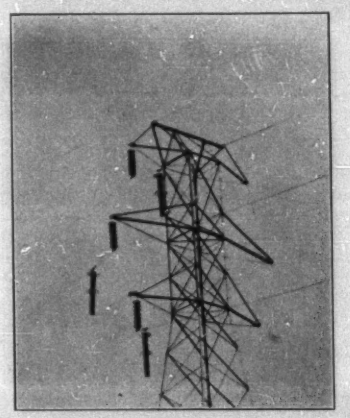

Fig. 12—A 100-Kv. Transmission Line Protected with New Auto-Valve Arresters

The small size of the new arrester has made high-voltage line protection practicable for the first time

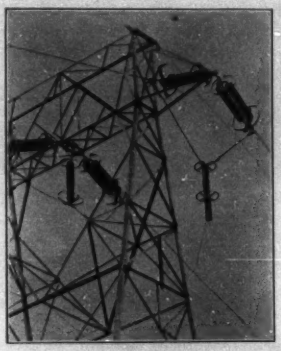

Fig. 13—One of the New Arresters Suspended from One Phase of a 110-Kv. Transmission Line

The installation in this case was made at a substation to serve both for line and station protection

of lightning outages, permits a reduction in the lengths of the insulator strings now used to increase the reliability of a line. This decrease in insulators in itself involves but a small saving, but the resultant decrease in crossarm spacing and tower height reduces the cost of

construction considerably. With impulse voltage data available on insulating structures and arrester performance, and with field data on the character of lightning disturbances being accumulated by means of cathode ray oscillographs, it appears that in a short time it may be practicable so to rationalize the insulation and protection of a system that lightning outages will be reduced to the optimum economical minimum.

A number of installations of high-voltage line type arresters has been in service during the past season, chiefly for the purpose of determining the degree of benefit actually obtained in reducing line flashovers, and to secure operating data on the desirable spacing of arresters for this purpose. Figures 11, 12, 13, and 14 show the type of arrester used and its method of mounting.

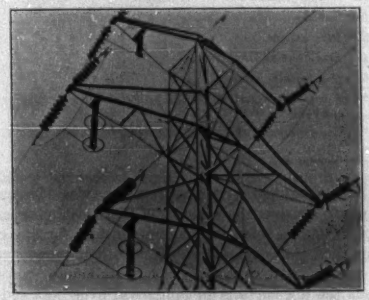

Fig. 14—A Close-Up View of a 66-Kv. Arrester Installation

Note that the arrester protecting the top phase has an open gap while those on the other phases are equipped with enclosed gaps

*6. Arrester Installations and Experience.* Exhaustive laboratory tests on the new valve arrester at the factory had thoroughly proved its remarkable performance. However, since laboratory experience must finally be substantiated by successful results in service, it was thought desirable to place a number of these arresters in service in the field as a final verification of their performance. Tests of this type offer the only opportunity to gain operating experience with arresters connected to complicated networks providing a multiplicity of circuit conditions which can only be reproduced in part in the laboratory.

Such a procedure is always advisable before any new piece of electrical apparatus is produced in large quantities, since it gives the manufacturer an opportunity to correct minor defects or make additional improvements in the final design while the field tests are progressing on a comparatively small scale.

Numerous arresters were installed in all sections of the country, both on grounded and ungrounded electrical systems of various voltages, in order that the maximum number of operating conditions would be secured, due partly to differences in the behavior of electrical systems themselves and partly because of atmospheric variations such as differences in altitude and the amount and kind of impurities contained in the air. The first of these arresters were installed on a 2300-volt system about August 1, 1928. Other installations with higher voltage arresters rapidly followed; these included station type arresters of 73-kv. rating, until by the end of 1928 over 1200 arresters had been placed in the field. Additional installations were made during 1929 and by the end of the lightning season, over 1500 additional arresters had been placed in service, including high-voltage line type arresters and station arresters of 132-kv. rating. The arresters installed to date include all voltages from 3 kv. to 132 kv. and thus represent a wide range of operating conditions. These field tests will be continued.

Thus far, with over 2500 arrester years of service experience, the operating record has been remarkably good. There have been a few disputable cases of small low-voltage transformer failures. A few arresters of the lower voltage classes have been damaged because of mechanical defects which only service experience will reveal and provide the remedy for. One high-voltage line type arrester out of a total of 200 was damaged, apparently due to a close-by direct stroke because a klydonograph connected to another phase of the same circuit at the same location was destroyed at the same time.

Such a service record, it is felt, has been encouraging and has undoubtedly established the performance of these new valve type arresters.

*7. Conclusion.* This development has made possible arresters of reduced size. At the same time it has brought about performance improvements. As a result of the size and performance improvements, it makes practical for the first time the protection of high-voltage transmission lines.

In conclusion, the authors wish to thank Messrs. A. L. Atherton and E. Beck for the strong support they have given during the development of the new autovalve arrester, as well as for their valuable suggestions in the preparation of this paper. Others whom the authors wish to thank for the aid they have given in suggestions or in making tests include principally Messrs. A. M. Opsahl, H. M. Kraner, M. E. Gainder, R. A. Wycoff, and L. R. Smith.

## Discussion

For discussion of this paper see page 417.

# Thyrite

## A New Material for Lightning Arresters

K. B. Mc EACHRON[1]

Member, A. I. E. E.

***Synopsis.***—*A new material has been developed which is peculiarly adapted for use in lightning arresters. It is physically similar to dry process porcelain and it can be made in any shape that can be successfully moulded. The manufacturing processes have been perfected so that the electrical and mechanical characteristics can be duplicated or varied as desired within practical limits.*

*This material, which is called thyrite, does not follow Ohm's law, for each time the voltage is doubled the current increases 12.6 times. The ratio of change of current to change in voltage is constant over ranges of current of 10,000,000 to one. This means the resistance decreases as the current and voltage increase. The resistance at any particular value of voltage or current is fixed by the physical dimensions of the piece. It is slightly lowered at high temperatures but returns to normal when cooled. The resistance does not depend upon the rapidity of current or voltage change and it is unaffected by long service. Because of these definite characteristics of thyrite the action of lightning arresters can be accurately calculated for the first time.*

*Thyrite is now being used experimentally in three types of lightning arresters. The station type is made in 11.5-kv. sections, each one containing its own gap unit so that no series arrester gap is required. These gap units have the desirable property of sparking over at practically the same voltage irrespective of wave front. The 11.5-kv. sections are assembled in the field in the same manner as pedestal insulators.*

*The distribution arresters are smaller than those of the station type and have but one-fourth of the impulse current carrying capacity. For discharge currents up to 1000 amperes neither of the arresters will allow more than 2.8 times the arrester rating in crest volts to appear across it.*

*The third type of arrester is incorporated directly in the transmission line suspension insulators and is designed to absorb a considerable portion of abnormal surge energy, as well as to protect the insulators from flashover.*

*This new line of lightning arresters has the following advantages:*

1. *Ample protection for all insulation.*
2. *Conservative factor of safety from failure.*
3. *Permanence.*
4. *Small size and weight.*
5. *Low installation cost.*
6. *Invariable characteristics and predictability of results for any given condition.*
7. *Characteristics which can be measured by the user.*

A LIGHTNING arrester to be successful today must be able to protect apparatus from the harmful effects of lightning and must prevent or suppress the flow of system follow current after the discharge has passed through the arrester. After functioning, the arrester should be in condition to immediately repeat its operation without alteration of these two essential properties.

### The Ideal Arrester

It is usually of value to set up an ideal in order that one's approach may be orderly and consistent. The ideal arrester may be defined as one which passes zero current as the applied potential is increased until the critical discharge voltage, set by the designer, is reached, when current begins to flow in whatever amount is needed to hold the potential across the arrester constant at the initial discharge value. The current ceases when the applied potential drops below the critical value for the arrester. The critical voltage for such an arrester should be unaffected by the rate of voltage application, in other words it should have no time lag. The volt-ampere characteristic of such an arrester is shown in Fig. 1A. Fig. 1B shows voltage waves of various steepness, held down to the same critical voltage at the arrester. With such an arrester the effects of wave front, duration of the wave (lightning), and maximum current are removed from the discussion.

Since we are striving to approach the ideal it is worth while to consider the meaning of these ideal characteristics. If the potential remains constant for any current then the resistance varies from infinite resistance at zero current to zero resistance at infinite current. Thus the $R\,I$ curve is an equilateral hyperbola and its equation is $R\,I = C$ where $C$ is numerically equal to the critical voltage. This curve is shown in Fig. 1C.

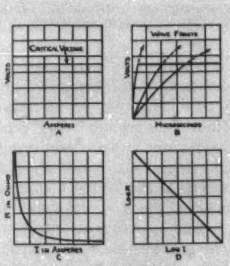


Fig. 1—Ideal Lightning Arrester Characteristics

If log $R$ is plotted against log $I$, as in Fig. 1D, then the curve is a straight line having a slope of 45 deg. This slope is important for in the general equation which is $R\,I^a = C$ the exponent $a$ is the slope of the $R\,I$ curve when plotted on log-log paper. Thus for the ideal case, the slope is one (tan 45 deg. = 1) and the equation is $R\,I^1 = C$. When $I$ = one ampere then $R = C$, no

1. Research Engineer, General Electric Co., Pittsfield, Mass.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

matter what the exponent may be. Thus when $a$ and $C$ are known the characteristic is immediately known, for $C$ determines the position of the curve and $a$ determines its slope.

### Lightning Arrester Material—Thyrite

In the search for a suitable arrester material the first requisite is that it shall have a slope similar to that of Fig. 1D, although it may not be possible to reach the ideal and get a slope of one. If possible, the characteristic should not be affected by the rate of voltage application or the rate of current rise through the material. Its characteristic should not be affected by whether the current is increasing or decreasing. Other desirable characteristics are: reproducibility, permanence, ability to return to its original characteristics if overheated, and other properties of a similar nature.

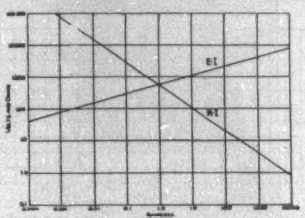


Fig. 2—Characteristic $E$-$I$ and $R$-$I$ Curves

For a thyrite disk 6 in. in diameter and ¼ in. thick

A search for such a material having the properties described was begun in 1923 and this paper is the first public announcement of the results of that work. A material has been developed having mechanical properties somewhat similar to those of dry process porcelain, but possessing the remarkable property of being substantially an insulator at one potential and a good conductor at certain higher potentials. This material called thyrite[2] represents a new class of conductor which covers the middle ground between the insulator and the conductor.

No attempt will be made here to describe the manufacture of thyrite, except to state that its successful production involves the very accurate control of a large number of variables. This has been accomplished so that it now appears that thyrite can be manufactured within sufficiently close limits for successful operation. At the present time thyrite for arrester use is manufactured in the form of disks, six inches in diameter by three-quarters of an inch thick and also three inches in diameter by one inch thick. It probably can be made, however, in any form which can be moulded.

In Fig. 2 are plotted the $E$ $I$ and $R$ $I$ characteristics for a six-inch thyrite disk for which $a = 0.72$ and $C = 580$ respectively. When considering the application of thyrite it should be noted that the constant varies directly as the thickness of the piece but not inversely with the area as does the ordinary resistance. For instance, with an exponent of one, the constant for the piece depends on the length but is independent of the area. To make this clear, we may consider the effect of doubling the area, remembering that the constant is defined as the resistance at one ampere, which, with an exponent of one, is inversely proportional to the current. By doubling the area, the current in the original area is reduced to one-half, but the resistance of each half is thereby doubled and so the total resistance remains unchanged. It should be noted that these relationships are dependent upon the definition of the "constant" as the resistance at one ampere. As the exponent approaches zero as a limit these relationships approach those of the ordinary resistor.

It is interesting to note the wide range over which the change of resistance with current takes place, the available data showing that the law holds over current ratios of 10,000,000 to one. Each time the voltage is doubled the current increases 12.6 times for thyrite with an exponent of 0.72, thus if the potential increases 16 times the current increases 25,000 times.

### Time Lag

Although thyrite may possess time lag, yet up to the present time the tests made have not disclosed its existence. One of the best illustrations of this characteristic is shown in Fig. 3, which shows test results taken on 90 disks connected in series. The characteristic of each disk was first determined with direct current using a potentiometer up to 0.1 ampere. The exponent for the entire stack was found to be 0.7 and the constant 500 per disk. The whole stack was next tested with alternating current with sufficient potential so that a crest current of nearly four amperes flowed through the stack. Oscillograms were taken and the instantaneous resistance calculated and the results are plotted as in Fig. 3. The stack of disks was then tested with a million-volt impulse generator, the current being determined by the voltage drop across a series water tube. The voltages were determined by sphere-gap

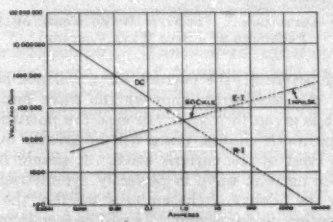


Fig. 3—Tests on Ninety 6 by ¼-In. Thyrite Disks

With a-c., d-c. and impulse

2. Thyrite—meaning gate or opening.

measurement. These results are also given in Fig. 3 and fall on the same straight line as the data taken with alternating current and direct current. That the results fall so nicely on the same characteristic with such widely varying wave front shows clearly that no measurable time lag exists. That there should be no time lag seems reasonable for the material always acts as a resistance, and its operation does not depend on any arcs or sparks or the breakdown of any dielectric.

A large amount of other data has been taken since that shown in Fig. 3, in which the cathode ray oscillograph has drawn the volt-ampere curve. These data have always fallen on the same straight line as the characteristics obtained on the same piece with direct current, so that today the men working in the laboratory with this material under transient conditions, trust its faithful performance of its characteristic as much as they would the performance of a piece of nichrome wire or other similar resistor.

### Operation on Alternating Current

Since the current varies as the $\frac{1}{1-a}$ power of the voltage, with an exponent 0.72 the current will vary as the 3.57 power of the voltage. With a sine wave of

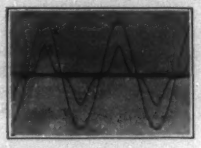

Fig. 4—Oscillogram Showing Wave Form of Current Produced by a Sine Wave Voltage

applied potential, the current wave will not be a sine wave. An oscillogram showing the wave form of the current is given in Fig. 4. In case the potential wave contains tooth ripples, these will be greatly magnified on the crest of the current wave. It should be noted that the current wave is perfectly symmetrical, illustrating the fidelity of the material whether the current is increasing or decreasing. As will be seen later, this is just as true for an impulse lasting but a few millionths of a second.

Because the current wave is not a sine wave, it is desirable always to speak of both the voltage and current in terms of actual instantaneous values and not effective values. Thus, with the ordinary resistor, one may find the corresponding current from either the effective or the crest voltage, but with thyrite, if the potential is given in effective volts it must always be changed to crest volts and the crest current found. If energy loss in the piece with an applied sine wave voltage is desired, the product of the crest voltage and the crest current is to be multiplied by a factor taken from Fig. 5 for the particular exponent possessed by the piece.

### Effect of Change in Temperature

The effect of increase in temperature is to lower the resistance of the material, especially at the weaker current values. The results of a series of tests to determine the effect of temperature are given in Fig. 6. When cold, the original values reappear. These data indicate that for the usual temperature changes in an arrester under operating conditions, the effect on the resistance will be small.

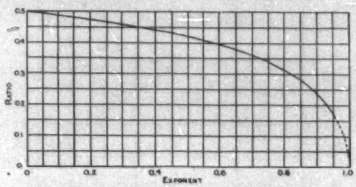


Fig. 5—Ratio of Average Power Expended in Thyrite to the Maximum Instantaneous Power

With a sine wave of voltage applied

### Permanence and Life

Several samples of the first thyrite made have been on life test for more than five years, and tests at frequent intervals have shown the characteristics to be practically unchanged. The samples were connected to an 1100-volt, 60-cycle source, the current through the pieces being sufficient to raise their temperature to about five degrees above the room temperature. Other

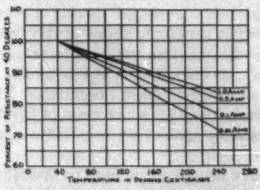


Fig. 6—Effect of Temperature Change on Resistance of Thyrite with Various Currents

tests have been made in which the sample was exposed to the weather for a year with various degrees of protection from the weather and no deterioration has been detected either by inspection or electrical tests. Still other samples have been tested with both impulse and alternating current applied and no changes in the material were noted, even after several hundred impulses were applied.

### Summary—Thyrite

It seems then that a material having the proper characteristics for lightning arresters has been found.

It has the desirable hyperbolic characteristics, not to a degree indicated in the ideal arrester where the exponent is one, but sufficiently so that it may be used successfully. It has no measurable time lag and is durable. Its characteristics are permanent and not affected by use.

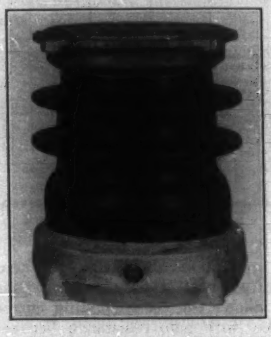

Fig. 7—11.5-Kv. Thyrite Lightning Arrester Unit

## The Arrester

In designing lightning arresters for all voltage ratings, it is worth while to build them in the form of standard units which will all be alike, various numbers being used to correspond to the different ratings. This will greatly

Fig. 8—69-Kv. Thyrite Lightning Arrester

simplify manufacturing and stocking the arresters. For certain conditions, it may be necessary to supply smaller or part units, and this applies particularly to the lower voltages. The standard unit is rated 11.5 kv. grounded neutral. Thus for a system rated 115 kv. with a solidly grounded neutral ten units would be used. The arrester does not employ a separate series gap, each unit being complete within itself and containing its own gap structure. Fig. 7 shows a single unit and Fig. 8 six in series, such as would be used on 69-kv. grounded neutral. No steel work is required for the 69-kv. arrester. The units should be mounted on a concrete foundation to keep clear from weeds, snow, etc.

## Performance Characteristics

For the first time in the history of lightning protection, it becomes possible to calculate arrester performance accurately. The volt curve ampere for the 11.5 kv. unit is given in Fig. 9 and is the curve for eleven, six-inch disks in series, making a total height of 8¼ inches. In this design the disks are coated with copper on both sides by the schoop process and stacked up inside the porcelain container. It is necessary to use a series gap arrangement which is housed in each 11.5-kv. container.

The reason for the series gap will be apparent from an examination of the characteristic curve. The normal voltage to ground is 9.4 kv. crest, which would cause a steady current of four amperes crest to flow through the

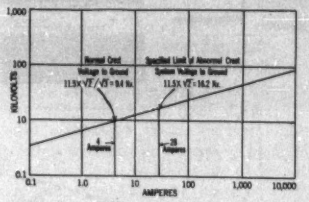


Fig. 9—Characteristic of 11.5-Kv. Grounded Neutral Thyrite Lightning Arrester

arrester continuously. If an over-voltage is applied as may occur in the case of dropping a load and overspeeding generators, a potential as high as 16.2 kv. may be applied between line and ground. With this potential a current of 28 amperes would flow and thus for safe operation it is necessary that the gap be capable of stopping the flow of current after one-half cycle, even if the impressed potential is 16.2 kv. and the current 28 amperes. A single arrester gap is unable to break an arc of this magnitude and it is therefore necessary to break the single gap up into a series of small gaps, which possess the property of quenching an arc if the voltage distribution across the gaps is such that the potential per gap is kept small. Because of the necessity of introducing several small gaps in series two opposing conditions develop. With a 60-cycle voltage applied, the distribution of potential between the gaps must be kept uniform, otherwise spitting would occur, which not only would set up radio interference, but would make impossible the operation of the arrester with several units in series, with several gaps in each unit. At the same time unless some means could be found to upset

the uniform distribution under impulse conditions, the arrester breakdown would be too high for satisfactory protection. Fortunately this problem has been solved so that a uniform distribution is obtained with the application of system potential, but the distribution becomes non-uniform when a steep wave front of potential is applied. Thus the impulse ratio is kept close to one, as for example, the breakdown of the series gap at system frequency is about 35 kv. crest, while with the application of an impulse requiring one microsecond to reach breakdown it is about 45 kv. crest. Thus for currents up to 1000 amperes the arrester unit holds the voltage to a value not in excess of 2.8 times its rating.

From the curve (Fig. 9) it may be seen that 45 kv. corresponds to a current of about 1000 amperes, so that for discharges involving currents smaller than 1000 amperes the gap breakdown represents the limiting potential, while for currents in excess of 1000 amperes

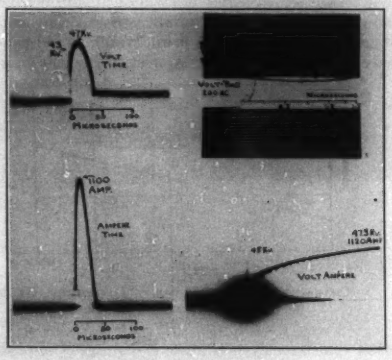


Fig. 10—Protective Characteristics of 11.5-Kv. Thyrite Lightning Arrester

the $I\,R$ drop represents the maximum applied to nearby insulation in parallel with the arrester. Cathode ray oscillograms taken on a complete 11.5-kv. unit are given in Fig. 10. It should be noted that in this illustration the volt-ampere curve shows no loop, the increasing and decreasing characteristics following the same curve. The close agreement between this volt ampere curve and the curve of Fig. 9, illustrates how accurately the arrester characteristics can be determined.

When applying arresters to particular circuit conditions it is very desirable to be able to determine the performance characteristics under those conditions. In Fig. 11 are shown the characteristic curves for arresters whose ratings extend from 46 to 230 kv. grounded neutral. Plotted on the same sheet are curves which the author calls impulse regulation curves for the transmission line. The arrester is considered for the given case to be at the end of a transmission line whose surge impedance is 500 ohms. For each arrester rating an impulse regulation curve is taken, corresponding to the flashover value of the insulation used on that line. If for 230 kv. fourteen insulator disks were used, and for 138 kv. ten disks were used, the flashover voltages cor-

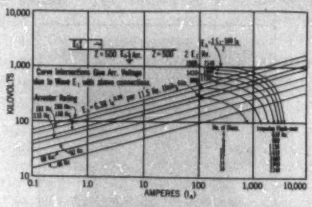


Fig. 11—Grounded Neutral Thyrite Arrester Characteristics with Traveling Waves

(Arrester at end of line)

responding are 1900 kv. and 1410 kv. The curved lines represent the potential across a resistor at the end of the line which allows the corresponding current to flow. For instance, with zero resistance between line and ground a complete current reflection will take place and for the 230-kv. case the current to ground would be 3800 amperes. The value of voltage where the arrester volt-ampere curve crosses the impulse regulation curve for the corresponding number of insulators used, represents the maximum voltage allowed by the arrester. Thus for the 230-kv. arrester, the maximum potential is one million volts. For any impulse less than this the arrester potential will be less.

Fig. 12 is plotted for conditions similar to those represented in Fig. 11, except that the arrester is connected to a bus with two incoming lines so arranged as to deliver simultaneous impulses to the arrester. Such a situation is often found in practise where double circuit

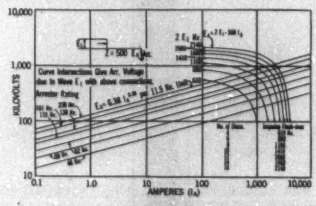


Fig. 12—Grounded Neutral Thyrite Arrester Characteristics with Traveling Waves

(Arrester connected to receive two simultaneous impulses)

lines are connected to the same bus. Thus for fourteen disks of insulation, a 230-kv. arrester will hold the potential to 1200 kv., which is 200 kv. more than if an arrester is used on each circuit. The arrester current with the arrester on the bus is about 2800 amperes compared with 1800 amperes when two arresters are used. It must be remembered that this condition only applies

when the circuits are such that impulses can arrive from each circuit at the arrester at the same time. Thus for the first time it is possible to evaluate accurately the advantage of the use of one arrester on the bus compared to one arrester for each circuit. If more than two circuits can deliver impulses to the same bus at the same time, additional curves must be drawn for that condition.

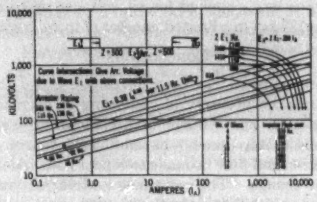


Fig. 13—Grounded Neutral Thyrite Arrester Characteristics with Traveling Waves

Arrester connected to receive impulse in one direction, with outgoing circuit in another direction

If, on the other hand, the circuits are so arranged that impulses travel to the arrester from one direction with outgoing circuits in another direction, the arrester's potential will be correspondingly reduced. Such a condition is illustrated in Fig. 13, where the arrester is considered as being on a bus with one incoming and one outgoing line in perhaps opposite directions. Using the same examples as before of a 230-kv. arrester with fourteen disks of insulation, the arrester potential is 800 kv. with a current of 650 amperes flowing through the arrester.

By similar methods the arrester potential can be calculated for almost any assumed circuit condition so that arrester protection performance can be predicted accurately.

The condition of direct stroke, if occurring within one span length of the arrester but with an insulator string in between, has been assumed to be equivalent to that of a traveling wave having a potential equal to the insulator flashover, such as might result from an induced potential of twice the insulator flashover. On the assumed 230-kv. circuit, this potential is nearly 4,000,000 volts, which is much in excess of any potential yet indicated by the surge investigations on such a line. Curves similar to those of Fig. 11 show that under such an extreme condition the arrester potential would be 1300 kv. which is still safe for the modern transformer. It seems certain that such potentials could occur only in connection with direct strokes very close to the point of connection of the arrester to the transmission line and could not represent a possible induced condition with present insulation levels.

## The Arrester Unit

The arrester unit for 11.5-kv. grounded neutral service as designed at present is 14½ in. high and 12 in. in diameter. It weighs about 100 pounds. The unit is sealed, as no venting is necessary with this new arrester. If it is desired to check the arrester's characteristic this can be done by the use of the ordinary oscillograph. If arrangements are made to measure voltage and current by the use of the oscillograph, a few cycles of 60-cycle current can be made to pass through the arrester and from the oscillogram showing voltage and current the arrester characteristic can be determined accurately. Such a test cannot be prolonged as the arrester would become hot and the series gaps would be burned.

## Distribution Arrester

In the distribution arrester thyrite disks one inch thick and three inches in diameter are used. The 3-kv. arrester requires two disks in series. It has a volt-ampere characteristic designed to be similar to the station type arrester for the same rating. Thus at 1000 amperes the arrester potential is 2.8 times the arrester rating. Since the distribution arrester is provided with but one-fourth of the area of the station type, it has but one-fourth of the current carrying capacity. A cathode ray oscillogram giving the volt ampere characteristic for the 3-kv. arrester is shown in Fig. 14 and like Fig. 10 it shows how accurately the volt-ampere curve checks the calculated curve pro-rated from Fig. 11.

## Transmission Line Type Arrester

Probably the least reliable part of electric transmission is the transmission line itself during lightning storms. No transmission line has yet been built which is proof against lightning flashovers. The number of flashovers has been reduced by the use of ground wires and extra insulation, but they have not yet been eliminated. From the standpoint of interruption to service two methods of attack are available, one to render the flashover innocuous by the use of such devices as the fused grading ring or the Peterson coil, and the other to prevent the flashover by whatever means possible.

The better method is to prevent the flashover and if possible at the same time absorb a considerable portion

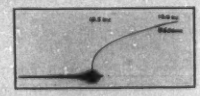

Fig. 14—Volt-Ampere Characteristic of 3000-Volt Thyrite Lightning Arrester

Gap sparks in one microsecond

of the energy of the charged capacity of the line by the use of some device, such as a lightning arrester.

The idea of using arresters along a line is not new but suitable arresters have not been available either from the standpoint of size or cost.

The new arrester material will, it is believed, offer a means of protecting insulator strings on towers at a cost which is reasonable and it should greatly increase the reliability of transmission lines.

The problem is more definite than that of protecting station insulation, since the arrester is placed very close to the insulator string and both have the same ground.

An arrester using thyrite disks for the protection of transmission line insulators is shown in Fig. 15. The arrester shown is rated 69 kv. and uses 72 disks three inches in diameter and one inch thick, so that the protective characteristic would correspond to a station type rated 108-kv. According to Fig. 11, with a current of 2000 amperes flowing, the arrester potential is about 500 kv., while the flashover for four insulators is 610 kv., or for six insulators is 890 kv.

It is probable that experience will show that the number of disks can be reduced, which will improve the protection afforded and also reduce the cost of the arrester.

With such application of arresters it is not necessary that the arrester have large discharge capacity, as several would operate in parallel. Whether or not such protection would eliminate flashovers due to direct strokes is not known. It is the intention to try out arresters of this character on at least two transmission lines this summer.

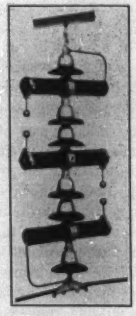

Fig. 15—69-Kv. Transmission Line Lightning Arrester

## Failure Tests

Many careful tests have been conducted on low-voltage units of all three types in the factory, in which were supplied both 60-cycle power and impulses timed to strike at the most dangerous point on the wave.

In May 1929, a 66-kv. thyrite arrester was tested on a 66-kv. transmission line with the line energized at normal potential, the impulse being supplied with a million volt portable generator. During the test the six units were reduced to four, which withstood many impulses with no signs of distress. As far as the author is aware this is the first time that a high-voltage arrester has been tested in this manner.

Later, in September 1929, a similar test was carried out on a 132-kv. transmission line with over 100,000 kv-a. available, again using a million volt impulse generator. In this case the number of units was reduced to seven, the line to ground potential being 77 kv., and again the arrester showed no signs of any weakness, and an examination of the gaps in each unit after tests showed practically no effect of the discharges.

Because of the complete tests made, both from the protective standpoint and the failure standpoint, the arrester is being applied for all voltages up to and including 132 kv. in a limited number of installations.

## Conclusions

A new material has been developed called thryrite, which has the property of increasing or decreasing its resistance as the voltage is decreased or increased. This relationship does not depend on the rate of voltage application and may be made to repeat itself indefinitely without change. The resistance and current relationships follow a definite law which can be expressed in the form of a simple hyperbolic equation. The characteristics of the material are defined by the exponent and constant taken from this hyperbolic equation. The change in resistance is such that the current increases 12.6 times each time the applied voltage is doubled.

Thyrite can be manufactured successfully from the standpoint of duplication with proper control of materials and processes. It can be produced in any shape which can be successfully moulded. The effect of increased temperature is to slightly decrease its resistance for any given voltage.

This material is well adapted for use in a protective device; lightning arresters in three different forms are now being tested in service.

The station arrester is made in 11.5-kv. sections which are assembled in the field in a manner similar to pedestal insulators. These units are self-contained and do not require a series gap. An arrester for grounded neutral 69-kv. service is approximately 87 in. high. For currents up to 1000 amperes the potential across the arrester will not exceed 2.8 times the arrester rating in crest volts.

The protective characteristics of the distribution arrester are similar to those of the station type arrester, although its impulse current capacity is but one-quarter of that of the station type.

The great advantages of the new arresters lie in their permanence, small size, low installation cost, small weight, and the predictability of the results to be expected for any given condition.

A new type arrester for protection of the transmission line against flashover is being developed, which is incorporated in the insulator string. This arrester is designed not only to prevent the flashover of the insulator string, but also to absorb a considerable portion of the energy of the discharge. Laboratory experience with the cathode ray oscillograph gives definite knowledge of the protective characteristics which can be calculated for any given circuit condition, while tests

in the field on high-voltage transmission lines with portable impulse generators have successfully demonstrated the ability of the arrester to prevent the continuous flow of power current following the impulse.

The ability of an arrester to successfully withstand all of the exigencies of operation without failure cannot be completely determined in the laboratory. For this reason it is necessary for the arrester to pass through a certain period of trial in the field, which will help determine whether or not the factor of safety employed is proper. For several months arresters have been in service on lines up to 66 kv., and 110 and 132 kv. installations are soon to be made.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Messrs. J. R. T. Craine, L. H. Whitney, and A. C. Campbell for their assistance in the development of thyrite. Their help has been invaluable. Messrs. E. M. Duvoisin, E. G. Newton, and L. W. Evans have all had a large share in the development of the arrester, while to Mr. T. Brownlee the author is indebted for assistance in the preparation of the paper.

## Discussion

### DEVELOPMENT OF THE NEW AUTOVALVE ARRESTER

(J. SLEPIAN, TANBERG, AND KRAUSE)

### THYRITE, A NEW MATERIAL FOR LIGHTNING ARRESTERS

(K. B. McEACHRON)

NEW YORK, JANUARY 27, 1930

**Edward Beck:** The two papers on lightning arresters, that by Mr. McEachron and that by Messrs. Slepian, Tanberg, and Krause, indicate an important fact, namely that the two manufacturers of high-voltage lightning arresters are on common ground in several respects. For instance, Mr. McEachron states that he believes a voltage ratio of 2.8 to be a good one which agrees with the ratios of 2.5 mentioned by A. L. Atherton and others. The paper entitled *Thyrite* also stresses the importance of energy absorption in a lightning arrester, particularly in those for protection of line insulators against flashover, indicating that it is preferable to maintain a definite voltage across the lightning arrester terminals during discharge in order to secure energy absorption rather than to reduce the voltage of the arrester to zero. This desirability of energy absorption in the lightning arrester is apparently generally agreed upon.

The paper on thyrite indicates that there has been a most interesting development in resistance materials. Of course it has been known for some time that certain resistance materials, such as those containing large amounts of carborundum, have a characteristic which droops as the applied voltages increase. This particular characteristic is a drawback when the material is to be used as a pure resistor but is very desirable when it is to be used in a lightning arrester. Mr. McEachron has been able to improve considerably on this drooping characteristic over those generally known in the past. It is disappointing that he has not given more information on the structure of his material other than that it resembled dry process porcelain. In this connection it would be interesting to know whether the author has cathode ray oscillograph tests on a very poor quality of dry process porcelains and how these compare with the characteristics of thyrite. In the progress of the research activity leading to the development of the confined discharge arrester described by Slepian, Tanberg, and Krause, tests were made on material such as building brick which disclosed a valve action, which although poor for lightning arrester purposes was nevertheless quite pronounced, and similar test data on dry process porcelains would be of interest. In the early work done during the search for the most suitable porous material for the new autovalve arrester described by Slepian, Tanberg, and Krause, it was found that the type of characteristics secured with a ceramic block is largely governed by the material used and can be controlled by the conducting particles used in the block.

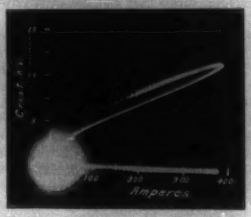


FIG. 1

With a large percentage of conducting particles the block has the characteristics of a resistance which varies with the current as shown in Fig. 1, herewith, while with a very small percentage of conducting particles the characteristics take the shape of Fig. 3 with a high ratio of maximum voltage to cut-off. By using the proper percentage of conducting particles, which lies between those with which characteristics in Figs. 1 and 3 are secured, a valve characteristic is obtained as in Fig. 2, with a sharp cut-off at a definite value of voltage. This is the type of characteristic possessed by the standard autovalve arrester and the one retained in the new autovalve arrester described by Slepian, Tanberg, and Krause. The voltage ratio of the block shown in Fig. 2, that is the ratio of the maximum voltage which exists during the discharge to the cut-off or the voltage at which discharge ceases, is 11 to 5 or 2.2. From these data it might be predicted that a slight change in the composition of thyrite would also produce

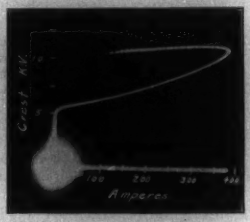


FIG. 2

the effect illustrated in Figs. 1, 2, and 3, including a valve characteristic, and it would be a matter of considerable scientific interest to know whether Mr. McEachron has such test data and if it is in agreement with ours.

The variation in resistance of thyrite with changing voltage as described in the thyrite paper does not depend on sparks or arcs in the material. Evidently it is also not a temperature effect. The process by which the resistance varies must be a very interesting one and the writer hopes that in the near future the principle by which this comes about will be published. I should

like to ask whether impregnating this material with an insulating liquid exerts any effect on its characteristics.

In the March 1929 issue of the *A. E. G.*, Mitteilungen, a periodical published by the Allgemeine Elektrizitats Gesellschaft of Germany, there appears an article by Mayr describing a new lightning arrester which employs a resistance material called Ocelit by the *A. E. G.* In this article some oscillograms are shown of its performance which resemble those shown for thyrite. I should like to ask how these two arresters compare in performance.

Mr. McEachron states that the use of thyrite has made it possible for the first time to calculate the action of a lightning arrester and some curves are presented in his paper showing the performance of his arrester under various circuit conditions. I am inclined to disagree with the statement that this is possible for the first time. The requisite for calculations of this sort are a definite arrester characteristic and permanence. In the case of the autovalve arrester, both the old and the new, particularly the station type, the characteristics have been disclosed by the cathode ray oscillograph and the value to which these arresters limit the lightning flashes is definitely known. Moreover as these arresters are of the valve type, the voltages which exist across their terminals during discharge are practically

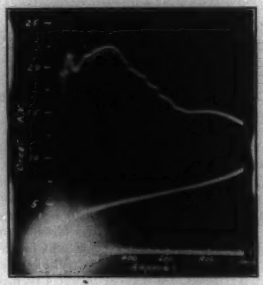

Fig. 3

constant, independent of the type of wave applied or of the discharge current within very wide limits. Hence the conditions at the arrester terminals are already established and calculations can be made of the arrester effect not only at the arrester location but also at a distance. With data available on the general nature of the surges to be expected in practise, these calculations are quite simple since the arrester voltage is fixed and numerous computations of this kind have been made by us in the applications which have been made of distributed arresters along high-voltage transmission lines, and in the application of high-voltage station arresters such as the 220-kv. autovalves installed several years ago.

**A. M. Opsahl:** On page 415 Mr. McEachron speaks of line type arresters. He gives the impulse flashover of four suspension insulators, 10-in. disks, 5¾-in. spacing, as being 610 kv. InFig. 2 of the paper by Mr. Torok, *Surge Characteristics of Insulators and Gaps*, the impulse flashover characteristic of four units, the ordinate being crest kilovolts, and the abcissa being microseconds. In getting this curve, the voltage rises rather abruptly to a quite constant value above the crest 60-cycle flashover of the insulators. After a certain time lag, the insulator flashes over. The time is measured from the point at which the surge rises above the crest 60-cycle flashover voltage. The point taken by Mr. McEachron as the flashover of four units (610 kv.) is a voltage at which the time lag of flashover is in the order of one microsecond.

The duration of lightning surges that appear on lines is in the order of 30 microseconds or possibly greater, in which case the voltage across the arrester, as shown in Fig. 4, would rise above the 60-cycle flashover of the insulators to a maximum of 500 kv. at the current assumed by Mr. McEachron. As can be seen, the voltage across the arrester is above the impulse flashover of the four units for a considerable length of time and will not protect the four unit string.

In the case of the six units, the 60-cycle flashover is 540 kv. or 40 kv. above that of the arrester under the conditions given, in

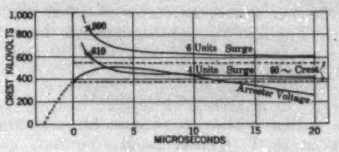


Fig. 4

which case the insulator would be safe. It would not be safe on four units even though adjacent arresters on the line might come into play. The time required for the traveling waves to traverse the distance to the adjacent line arresters and return would be too great to affect the voltage at the first arrester in time to prevent flashover with such a low margin as obtains in this case.

For line type protection it is as yet rather hard to say just what range of surge currents will have to be taken care of by the arresters. If one assumes the direct stroke theory, that is, that the surges are due to direct strokes or side strokes into the line, the current may reach high values. Perhaps some of them cannot be taken care of by any means we have.

If the voltage across the arrester instead of rising with increasing current as in Fig. 5, curve *A*, were to stay more nearly constant with wide variations in current as in curve *B*, it would not make so much difference how high a surge is applied. The voltage rise across the arrester would still be below the flashover voltage of the insulator.

In case arresters are spaced at certain intervals along the line and a surge voltage appears across the insulators between, the protection afforded by the arresters involves other considerations where the arrester requirements are more rigid than in the above case.

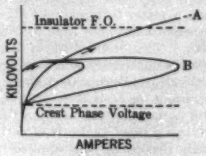


Fig. 5

**Philip Sporn:** Referring to Mr. McEachron's paper, no experimental data have been obtained to date in the course of any of the lightning investigations that have been going on for the past three or four years, to justify the lightning arrester economically. There have been, nevertheless, many users of equipment who have, in spite of these results, consistently continued to use the lightning arrester. We have been one of this group. It is to be hoped that with this further development of the lightning arrester, experimental work will be continued in the field, that will show definitely whether the arrester does or does not justify itself.

In the same connection, the development of the data on thyrite may be of particular benefit, since for the first time it enables the design engineer to calculate the lightning voltages that he may get after the arrester gets through with the job. The constancy of characteristics of the thyrite arrester makes this possible. When we first went into the question of rationalization of insulation about three years ago, we tried to get some data as to what might be expected on the performance of arresters under certain conditions, with various numbers of cells, and so forth. The best we could get was an answer that was good to about plus or minus 50 per cent. It is obvious that for intelligent design greater accuracy than that is needed.

The marked step in development of the lightning arrester brought out by Mr. McEachron ought to make the problem of design and the problem of rationalization of insulation much easier than it has been heretofore.

**J. H. Cox:** Mr. McEachron has presented some rather interesting calculations on the performance characteristics of lightning arresters and the solutions developed are valuable in that they illustrate a method of attack. However, I disagree with the quantitative values assumed in so far as they are indicative of the adequacy of a lightning arrester.

In Mr. McEachron's calculations he has chosen as the maximum surge to be handled by the lightning arrester one which is not above the flashover voltage of the line insulation. This states in effect that the maximum surge against which lightning arresters need protect apparatus is one limited to the flashover voltage of the line, and further that the arrester itself must be protected behind the line insulator string. Obviously, this is not the most severe condition as a surge can always start at the location of the arrester, even in a station. Even in the case of an induced surge, which, theoretically at least, can have a voltage above the flashover of the insulator string, the arrester may have to conduct a greater current than that assumed in Mr. McEachron's calculations in order to keep the voltage to a safe value.

This is particularly true in the application of lightning arresters for line type protection where their sole function is to keep the insulator from flashing. Furthermore, it is not reasonable at the present time to relieve the arrester from responsibility against direct strokes in general, since as far as the present knowledge is concerned it is possible that the majority of the surges giving trouble are caused by direct strokes and until more definite knowledge is obtained the direct stroke must be taken into account. Present knowledge indicates that a large portion of these are entirely within control. On page 415 Mr. McEachron deals with the direct stroke but in so doing he limits the voltage which he considers to four million volts. At the present time no such definite limit can be specified. It is true that higher voltages than this have not as yet been measured but all these measurements have been on lines with limited insulation and therefore it is probable that the surges were limited by line flashover. Therefore, we know very little about the maximum voltage a lightning surge might attain if generated on a line with sufficient insulation. In the future when this limit has been determined we may be able to designate a maximum current which an arrester may be called upon to handle and at that time definite calculations will be possible, but at the present time without these necessary fundamental data it is not possible to specify the maximum current which an arrester may be called upon to handle, and therefore it is not possible to make calculations of performance which mean much.

In any case an arrester which has a flat characteristic, that is one whose voltage does not rise with increase in current, is the most nearly ideal, as also mentioned by Mr. McEachron, and therefore, that arrester which most nearly approaches this characteristic comes closest to being completely adequate. It is possible that an arrester with a sloping characteristic might still be adequate if the voltage does not reach dangerous values when carrying the maximum currents required. However, as indicated above, at the present time these maximum values are not known and, therefore, such an arrester must be considered unsafe. Furthermore, the only part of the volt-ampere characteristic which is really important is the upper line, that is the manner in which the maximum voltage is reached and the manner in which the current returns to zero is of no importance so long as the ratio of the maximum voltage reached to the minimum voltage cut-off is satisfactory. This, according to the test data available at the present time, should be of the order of 2.5.

**K. B. McEachron:** In the development of thyrite, as might be suspected, a large number of different mixtures of various materials was studied. In all of this work the goal has been to secure a pure resistance whose performance characteristics did not depend on the breakdown of any gas and therefore the volt ampere curve for such a material would be devoid of any loop. The presence of a loop in a characteristic curve indicates that the conduction has changed as the result of the flow of current for a period of time. Such a material does not have a permanent resistance ampere characteristic during discharge. Thyrite is a material whose resistance for a given current value is invariable and whose characteristics do not alter between successive shots. Mr. Beck has asked for a comparison between thyrite and porous materials, from the standpoint of performance. The two materials do not act in the same manner at all, since the performance of the porous block is dependent on material having pores which contain gas, whereas thyrite does not depend on the presence of pores and will have exactly the same characteristic if immersed in oil that it has when immersed in air.

As may be noted from the curves given in the paper for the thyrite unit, its performance does not depend on the nature of the applied voltage, for direct current, 60 cycle, or high-voltage transients have the same current flow for the same applied voltage. The characteristic curve holds for currents as small as one milliampere through the 6-in. diameter disk.

Referring to Mr. Beck's question with regard to the material described by Dr. Meyer, called "ocelit," I may say that we have studied this material and although similar to thyrite, it does not possess the desired characteristics to the same degree as does thyrite. In other words, the exponent of thyrite which is now being manufactured is considerably in excess of that of any ocelit material which we have tested. Mr. Beck has taken exception to my statement that for the first time it is possible to calculate arrester performance. I agree with Mr. Beck that any arrester's performance can be calculated, providing all of its conditions of operation are known. Since the characteristics of thyrite are fixed and permanent and as it does not have two values of resistance for the same value of current, it is possible to draw curves such as those given in the paper knowing that the test will agree with the calculated results without reference to rate of voltage rise, rate of current rise, or duration of the lightning impulse. With an arrester volt ampere characteristic having a loop, in order to be able to make such calculations it is necessary to know the effect of a change of rate of voltage rise or current rise and also to know the effect on the volt ampere curve of the duration of an impulse. To my knowledge, such characteristics have not been shown on any of the arresters now manufactured which have loops in their volt ampere curves. This does not mean that such arresters are not good protectors, but it does mean that calculations involving such an arrester can only be made with confidence when the rate of rise and duration of the impulse is the same as that of the laboratory test for the cathode ray oscillograms shown.

Concerning Mr. Opsahl's question with regard to the protection of four disks, the arrester design in the paper is based on the use of six disks, which it will protect satisfactorily. It is the intention to apply transmission arresters in groups so that one arrester may always be aided by a nearby arrester in carrying the current of the discharge. For induced discharges it is only necessary

that each arrester discharge the line for a distance of half a span length on either side of an individual arrester. Since the arrester itself supports the transmission line it is only necessary that it protect its own insulation. Mr. Cox and Mr. Opsahl have both raised a question concerning the performance of this arrester on a direct stroke. I do not believe that either of the transmission type arresters discussed today, will give certain protection in case a direct stroke comes on the transmission line at the point where the arrester is connected. In order to secure an arrester whose application is economically feasible its discharge capacity is limited and dependence is placed on arresters on adjacent towers to help any individual arrester in case of severe discharges. I do not expect that the transmission type arrester will protect against direct strokes. In this connection it is interesting to turn to (p. 409) of the paper by Messrs. Slepian, Tanberg, and Krause, and find the following statement: "One high-voltage line type arrester out of a total of 200 was damaged, apparently due to a close-by direct stroke, because a klydonograph connected to another phase of the same circuit at the same location was destroyed at the same time," which indicates that the authors do not expect a line type arrester to withstand the effects of a direct stroke.

Mr. Sporn's comments referring to the advantages accruing from being able to calculate arrester performance is interesting and indicates that a real necessity has existed in the past for being able to put the performance of lightning arresters on a more definite basis.

Mr. Cox seems to believe that a lightning arrester should be able to discharge direct strokes without difficulty. I agree with him that this is a desirable ideal to work for, but when our station type arresters, having a much larger discharge area than the line type arresters, are not able to provide certain protection against direct strokes at the arrester terminals, it does not seem likely, in the present state of the art, that it is economical to supply line type arresters capable of protecting against direct strokes. If it can be shown that practically all of the transmission line flashovers are due to direct strokes then the forms of transmission line type arresters now being tried out are inadequate. If, on the other hand, a large proportion of flashovers is due to induced discharges on lines, then the application of the present design of transmission type arresters should greatly reduce the number of outages. The adequacy of the transmission line type arrester as now designed can only be determined as the result of trial.

# Extinction of a Long A-C. Arc

BY J. SLEPIAN*
Fellow, A. I. E. E.

*Synopsis.—The extinction of an a-c. arc is analyzed as depending on two factors, the rate of recovery of dielectric strength of the arc space after current zero, and the rate at which voltage tending to re-ignite the arc is applied by the external circuit. In the short arc, most of the recovered dielectric strength resides in a deionized layer next to the cathode but in the long arc the rest of the arc space contributes largely to the dielectric strength. The breakdown gradient of the still ionized arc space is defined, and using a thermal ionization theory, a formula for growth of breakdown gradient is derived.*

*The extinction of long a-c. arcs in the open is greatly influenced by the sectional area which the arc stream has at current zero. By confining arcs to slots and holes, the rate of deionization at current zero is greatly increased, and so large voltages per cm. of arc can be interrupted.*

*A gas blast passing turbulently through an arc stream greatly accelerates deionization at current zero and so is effective in increasing the capacity of the a-c. arc to interrupt high-voltage circuits. The expulsion fuse is an example of a gas blast circuit interrupter, the gas blast resulting from the decomposition of the fiber fuse case.*

*The oil circuit breaker is also a gas blast circuit interrupter, the blast arising from the gases produced by the decomposition of the oil. Means which increase the rate of oil decomposition improve the operation of the breaker. The magnetic blow-out in oil breakers is effective by causing an increased rate of oil decomposition.*

*Electrostatic unbalance may lower the volts per cm. which a long arc can interrupt. The use of static balancing devices may then become advisable.*

## I. Introduction

In a preceding paper,[1] the author has considered the mechanism of the extinction of an arc in an a-c. circuit. It was pointed out that the extinction or re-ignition of an a-c. arc following a current zero depended upon the outcome of a kind of race between two contending factors, one depending principally on the arc space alone, and the other principally on the external circuit alone. The first is measured by the rate at which the arc space recovers dielectric strength as a result of disappearance of ions throughout the whole or certain favored portions of the arc space. The second factor is measured by the rate of building up of the voltage applied to the arc terminals by the external circuit and tending to re-ignite the arc. For determining this factor in extinction of the a-c. arc, the normal frequency voltage, current, and power factor are not enough to characterize the circuit. The transient characteristics must also be considered.

From this analysis it follows that the interrupting capacity of an a-c. switch may vary considerably, depending on the nature of the circuit in which it is tested. This has been amply verified in the experience of the author and has been noted by others.[2,3] In particular, the testing plants of manufacturers of oil circuit breakers are much more severe upon circuit breakers than the circuits of power distribution systems.[3] The way in which voltage builds up on the arc space terminals after current zero can, in theory at least, be predetermined from the constants of the external circuit according to well known principles of electrical engineering. The predetermination of the way in which the arc space recovers dielectric strength, however, calls for an understanding of the nature of the arc which in general has not yet been attained. In the case of the short arc the situation is somewhat better, and theory predicts qualitatively for a short arc space a manner of recovery of dielectric strength which has been found experimentally.[1]

Although, as yet, the theory of the long arc has not been developed to the same degree as that of the short arc, nevertheless such theory as is available is of great aid in studying the operation of a-c. switches with long arcs. It can suggest what factors are of importance in favoring the extinction of the arc in various cases and how these factors may be intensified. It can show how the distribution of the electrostatic field following the extinction of an arc is important in some cases so that the use of a static balancing device becomes worth while. It can qualitatively explain the effectiveness of the narrow slot arc chute, the air blast switch, the expulsion fuse, and the oil circuit breaker, and suggest how the effectiveness of these devices may be increased. The purpose of this paper is to show how the theory may accomplish these results.

Before defining the long arc and considering the theory of its extinction it will be well to review briefly the theory of the extinction of a short a-c. arc.

## II. Extinction of a Short A-C. Arc

In the preceding paper,[1] it was shown that almost instantly after the current zero, a layer of gas immediately adjacent to the cold (that is thermionically inactive) cathode becomes almost completely deionized and thus acquires some dielectric strength almost instantly. To again carry any considerable current, this space must be broken down, and being almost completely deionized, its new breakdown is quite similar as a phenomenon to the breakdown or sparkover of an ordinary un-ionized gas between metallic

*Consulting Research Engineer, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. *Extinction of an A-C. Arc*, J. Slepian, A. I. E. E. Trans., Vol. 47, 1928, p. 1398.
2. Biermann, *E. T. Z.*, 50, July 25, 1929, p. 1073.
3. Kesselring, *E. T. Z.*, 50, July 11, 1929, p. 1005.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

electrodes. This breakdown takes place through the mechanism of ionization by collision, and at ordinary pressures requires an electric gradient of the order of 10 to 100 kv. per cm.

Since even the thinnest layers of an un-ionized gas require several hundred volts to be broken down, the space next to the cathode acquires the ability to withstand such voltages almost instantly. The rest of the arc space loses ionization more slowly, and as its deionization proceeds, the deionized cathode layer increases in thickness. With this increase in thickness comes an increased dielectric strength of the cathode layer. Thus after the first few hundred volts, the cathode layer gains dielectric strength relatively slowly.

From a series of experiments on short arcs with cold electrodes, a curve showing the recovered dielectric strength of the cathode layer against time after the current zero was calculated.[4] This calculation was done by an approximate method, however. A more exact calculation from the same data leads to the curve shown in Fig. 1.

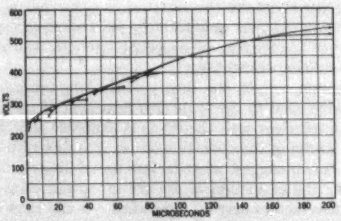


Fig. 1—Recovery of Dielectric Strength of Arc Space of Short Arc Voltage Required to Reignite Arc Immediately After Current Zero Air at Atmospheric Pressure

In identifying the dielectric strength of the short arc space with the dielectric strength of the deionized cathode layer it is assumed that the rest of the arc space contributes only negligibly to the dielectric strength. This may be taken as the definition of a short arc. In considering the extinction of an a-c. arc, we shall define the arc as short if immediately after the transient rise to open-circuit voltage of the external circuit, practically all the dielectric strength resides in the cathode layer.

An arc short in this sense will usually also be short in the ordinary physical sense, that is, its length will be a fraction of an inch. If, however, special means are used to make the arc space remote from the cathode layer deionize or recover dielectric strength very rapidly, this remote arc space may contribute to the dielectric strength during the extinction period, and the arc is to be regarded as long, or at least not short, even though in the ordinary sense the arc would be described as short.

4. *Theory of the Deion Circuit Breaker*, J. Slepian, A. I. E. E. Trans., Vol. 48, 1929, p. 523.

Since the transient immediately following the current zero at arc extinction in ordinary circuits has a duration of the order of 10 microseconds, and since in this length of time the cathode layer recovers the ability to withstand some three hundred volts, in general, if an a-c. arc extinguishes in a circuit which impresses only a few hundred volts upon it shortly after current zero, the arc will be short in the sense defined above. If, however, the arc extinguishes in a circuit which impresses more than a few hundred volts upon it, then use is made of recovered dielectric strength away from the cathode layer, and the arc is to be regarded as not short.

It is clear that if an arc is sufficiently long in the physical sense, it cannot be short in the special sense defined above, for, although the arc space outside the cathode layer recovers dielectric strength comparatively slowly per unit length, nevertheless in a finite time it does recover some ability to withstand voltage, and if it is sufficiently long, the total dielectric strength for its whole length, which it recovers during the extinction period, may be comparable with the dielectric strength recovered by the cathode layer.

## III. The Long A-C. Arc

We define the long arc as one in which during the extinction period the larger part of the recovered dielectric strength resides in the space away from the cathode layer. We now inquire into how this space recovers dielectric strength.

We must first make more precise the notion of dielectric strength, and define what is meant by the breakdown gradient of the space. While the arc is playing, the space is highly conducting because of the intense ionization there. During the extinction period, following current zero, the ionization disappears, not suddenly, but in a relatively gradual manner. The space then continues to have conductivity throughout the extinction period, but nevertheless it has a continually increasing breakdown gradient defined as follows:

In an ionized space, ions are continually being lost in two principal ways: one, by direct recombination of ions of opposite sign within the space, and the other by the passing of ions outside the boundaries of the space, by diffusion only, or assisted by electric fields, air blast, or other means. If the space is to maintain its conductivity, these losses of ions must be made up by some ionizing agent. Although their nature is not well understood, the ionizing agents capable of producing ions sufficiently rapidly to replace the losses which occur in an arc space are directly dependent on the impressed electric field, and the intensity of these ionizing agents varies with the intensity of the impressed field.

At any particular instant, there is a particular electric gradient for which the ionizing agents are just sufficiently intense to make up the ionization which is being lost in the arc space. If this gradient is impressed, the conductivity of the space will continue to maintain itself. If a smaller gradient is impressed ions will be

lost at a rate faster than that at which they are being generated, and the space conductivity will diminish. If a larger gradient is impressed the space conductivity will increase. This critical gradient at which the conductivity of the space just maintains itself, we shall call the breakdown gradient.

The intensity of the ionizing agents depends not only upon the intensity of the electric field but upon the state of the ionization of the space. In general, the greater the degree of ionization of the space, the more active will be the ionizing agents for a given electric gradient. Hence, the less the degree of ionization of a space, the greater will be the breakdown gradient. Immediately following the current zero for a long a-c. arc, the ionization of the space decreases, and the breakdown gradient increases. If the impressed gradient remains less than this increasing breakdown gradient, the space continues to lose conductivity, and the arc extinguishes. If at any time, however, the impressed gradient equals or exceeds the breakdown gradient, the space conductivity stops diminishing and the arc does not extinguish.

## IV. Extinction of a Long A-C. Arc

We shall now give the ideas of the preceding section mathematical form, but do so only for the purpose of clarifying them, without implying that the quantities involved may be calculated with any degree of precision. We shall base the mathematical equations upon the Compton thermal ionization theory of the positive column of an arc, but point out here that this theory, although plausible, is not necessary for our argument, and that any other theory of the ionizing agent which produces the ions in the arc stream would lead to equations of essentially the same form.

Compton[5] has shown that for the electric gradients which exist in the arc stream at atmospheric pressure ionization by collision is entirely inadequate to supply the ions which are being lost. Similar calculations show that ionization by collision is also negligible at the gradients which are impressed upon the arc space after arc extinction, in ordinary circuit interrupters. Compton suggests that the high temperature in the arc stream is responsible for the ionization, and supports this proposal by calculations from the equation for thermal ionization of Saha.[6]

In Fig. 2 are given curves for a few gases showing the density of ionization, $N$, (number of ions per cm.$^3$) which is maintained entirely as a consequence of high temperature, according to Saha's equation. The significant feature of these curves is that appreciable ionization does not occur until a high temperature is reached, and then the ionization increases very rapidly with further increase of temperature. We shall substitute for the curves of Fig. 2, the full curve of Fig. 3, and say that there is no thermal ionization until a critical temperature $T_0$ is reached and that at that temperature a profuse ionization sets in.

Let us consider an arc stream or positive column of an arc of a given section, when intensely ionized, and carrying current at the temperature $T$. It is losing energy because of its high temperature, but principally because it is losing ions, and because each pair of ions required energy for its formation. The ions are lost by diffusion to the boundary of the positive column or by

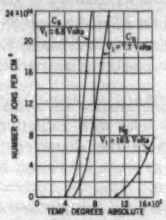


Fig. 2—Thermal Ionization of Gases

recombination within the positive column. The ions diffusing away recombine in the cooler surrounding gas or upon the bounding walls if the arc stream is confined in a chamber. When the ions recombine within the arc stream, their energy is changed to radiation which is lost to the walls or surrounding space. The loss of ions by diffusion is proportional to the density of ions in the arc stream, and the loss of ions by direct recombination is proportional to square of the density of ions.[7] Thus, if $n$ is the number of ions of one sign in one centimeter

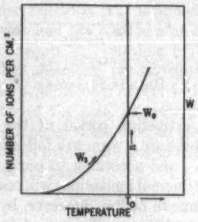


Fig. 3

length of the arc stream, there will be an energy loss per second, $W_1$, given by:

$$W_1 = A\,n + B\,n^2 \qquad (1)$$

where $A$ and $B$ are constants depending on the nature of the gas in the arc stream, its temperature, $T_0$, pressure, and its cross section.

This loss of energy must be made up by the energy input from the electric field, which is, for unit length of arc,

$$W_2 = X\,I \qquad (2)$$

where $X$ is the electric gradient and $I$ the current.

5. *Phys. Rev.*, 21, 1923, p. 286.
6. *Phil. Mag.*, 40, 1920, p, 472.
7. Townsend, "Electricity in Gases," *Oxford*, 1913, Chap. VI.

The current in the arc is due to the motion of the ions in the electric field. The velocity which the ions acquire is proportional to the electric field so that:

$$I = k\,X\,n\,e \tag{3}$$

where $k$ is a constant depending on the nature of the gas, its temperature, and pressure and $e$ is the charge carried by one ion. Thus we get:

$$W_2 = k\,e\,n\,X^2 \tag{4}$$

For the steady state we have $W_1 = W_2$ or

$$k\,e\,n\,X^2 = A\,n + B\,n^2 \tag{5}$$

We note in passing that combining Equations (3) and (5) gives a volt ampere characteristic in which the electric gradient increases with current. Such rising volt ampere characteristics are actually observed for arcs confined to holes with insulating walls. Fig. 4, for example, shows the characteristic obtained by R. C. Mason for an arc in a 0.178-cm. hole in soapstone. For an unconfined arc, the section increases with increase of current, and this increase of section causes both the constants $A$ and $B$ of Equations (1) and (5) to decrease. This decrease of $A$ and $B$ is sufficiently great to cause the volt ampere characteristic of an arc in the open to be a falling one.

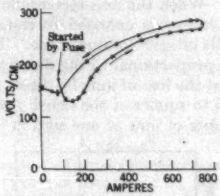


FIG. 4—CHARACTERISTIC OF DISCHARGE IN 0.178 DIAMETER HOLE IN SOAPSTONE

During the extinction period of the a-c. arc, the temperature of the arc stream will fall below the critical temperature $T_0$, and according to our hypothesis, the ionizing agent (thermal ionization) will cease its activity. Ions will continue to be lost, however, by diffusion and recombination so that we will have:

$$-\frac{d\,n}{d\,t} = \frac{A}{E}\,n + \frac{B}{E}\,n^2 \tag{6}$$

where $E$ is the energy required to form an ion pair. Equation (6) thus describes the way in which the ions disappear. If $A$ is the predominating factor in (6), and if we may neglect its variation with temperature, integrating (6) gives:

$$n = n_0\,e^{-\frac{A}{E}t} \tag{7}$$

where $n_0$ is the initial density of ionization and $t$ is the time in seconds. If $B$ is the predominating factor of (6) and if $n_0$ is very large, integration of (6) gives:

$$n = 1/\frac{B}{E}\,t \tag{8}$$

If both $A$ and $B$ must be considered in Equation (6), a more complicated expression is obtained which is not worth while writing as our object is clarification of ideas rather than quantitative calculation.

During the extinction period of the a-c. arc the temperature of the arc stream will be falling, and there will be a loss of energy per cm. length at a rate $W_3$, due to the decreasing thermal energy of the neutral molecules of the gas, apart from the energy stored in the ions. This is the energy loss which an un-ionized column of gas would suffer at the same temperature. This energy loss is an increasing function of the temperature, and depends also on the section of the arc stream. In Fig. 3, the dotted curve shows the dependence of the $W_3$ with temperature for some particular arc stream. The value of $W_3$ at the critical temperature, $T_0$, we shall call $W_0$. In general, means which increase the rate of loss of ionization, such as bounding walls, or gas blast, also increase $W_3$ and in particular increase $W_0$.

If during the extinction period of the a-c. arc, the impressed electric gradient $X$ is so large that with the existing state of ionization the electrical energy input $W_2$ is equal to $W_3$ for the temperature existing for the moment, then the temperature will remain constant momentarily; but since this temperature is less than the critical temperature $T_0$, thermal ionization will not set in, but the space will continue to lose ionization. If the electric gradient is such as to make the electrical energy input greater than the instantaneous value of $W_3$, but less than $W_0$, then the temperature will rise, but it will not reach the critical temperature $T_0$, and again thermal ionization will not set in, and the ionization will diminish. If, however, the electrical input is greater than $W_0$, then the temperature may rise to the critical temperature $T_0$, and the ionization will increase.

For our qualitative, idea clarifying purpose, we may take as the condition for re-ignition of the arc that the electrical input exceeds $W_0$, or for the breakdown gradient,

$$W_2 = W_0, \text{ condition for breakdown gradient} \tag{9}$$

Substituting Equation (4) we get

$$k\,e\,n\,X^2 = W_0 \tag{10}$$

or

$$X = \left(\frac{W_0}{k\,e}\right)^{\frac{1}{2}} \frac{1}{n^{\frac{1}{2}}} \tag{11}$$

If the condition of Equation (7) apply we get:

$$X = \left(\frac{W_0}{k\,e\,n_0}\right)^{\frac{1}{2}} \epsilon^{\frac{A}{2E}\,t} \tag{12}$$

with the breakdown gradient increasing exponentially with the time. If the conditions of Equation (8) apply,

$$X = \left(\frac{W_0}{k\,e}\,\frac{B}{E}\right)^{\frac{1}{2}} \times t^{\frac{1}{2}}$$

and the breakdown gradient increases only as the square root of the time.

## V. Extinction of Long A-C. Arcs in the Open

In trying to apply the ideas expressed in the preceding section to arcs in the open, a difficulty is at once met in the question as to what is the cross section of the arc stream at current zero. If the current in an arc remains constant, the positive column takes an appropriate section, probably determined by the condition that for that section, the electric gradient is a minimum. Experiment shows that the sectional area and the density of ions in the arc stream increase with the current.[8] In the a-c. arc, however, the current does not remain constant, and therefore the arc section is not that which corresponds to the current flowing at the moment, but depends on the current which has been flowing previously. If the current previously has been larger, the section will be larger than that corresponding to the momentary current, because the ions over the larger section will not have had time to disappear. In particular, at current zero, the arc stream section, that is, the area which is still highly ionized, is not zero but finite. The arc stream section at current zero, then, will depend on the rate at which the current is decreasing, that is, on the product of current and frequency.

The coefficients $A$ and $B$ of Equation (1) which give the energy loss due to loss of ions both decrease as the section of the arc stream increases. $A_n$, which gives the loss per unit length of arc due to diffusion to the arc stream boundary, will clearly depend on the product of the periphery, and the density of ions per unit volume, $N$; $n$, however, is equal to the sectional area multiplied by $N$. Hence,

$$A \text{ depends on } \frac{\text{Periphery}}{\text{Area}} \tag{14}$$

$B\,n^2$ gives the loss due to direct recombination in the arc stream per unit length. It depends on the area multiplied by $N^2$, and since $n^2$ equal (area)$^2 \times N^2$ we have,

$$B \text{ depends on } \frac{1}{\text{Area}} \tag{15}$$

If the arc section is circular, Equations (14) and (15) show that $A$ and $B$ vary respectively inversely as the first and second powers of the diameters.

$$A = \frac{F}{d}; \qquad B = \frac{G}{d^2} \tag{16}$$

Since the rate of recovery of dielectric strength of the arc stream space depends very largely on the factors causing the ions to disappear, that is, upon the coefficients $A$ and $B$, the extinction of a long a-c. arc in the open depends principally on the arc stream section at current zero, that is upon the arc current multiplied by the frequency. Very few systematic data are available for the extinction of long a-c. arcs in the open. This is principally due to the fact that except for disconnecting switches, long arcs in the open are not used in practical circuit interrupting devices, but the arcs are confined to chute boxes, fuse cartridge cases, or gas bubbles in oil, or are subjected to gas blasts as in the expulsion fuse or oil circuit breaker. It is of course well known that the difficulty of extinguishing a long a-c. arc in the open increases rapidly with increase of current and frequency. At 60 cycles, for currents of the order of 1000 amperes, r. m. s., and in circuits in which the time for the transient rise to open circuit voltage after current zero is about 10 microseconds, about 50 volts r. m. s. may be interrupted per cm. length of long arc.

## VI. Extinction of Long A-C. Arcs in Holes and Slots

The extinction of long a-c. arcs in holes and slots with insulating walls is easier to consider than the extinction of long a-c. arcs in the open because if the hole is small enough, or the slot narrow enough, then the arc section at current zero is definitely determined as filling the hole or the width of the slot. Consider first the extinction of arcs confined to cylindrical holes.

With the arc confined to a small section hole, the loss of ions by recombination upon the walls of hole in comparison with the number of ions occupying the section of the hole will take place at a very much higher rate than for an arc of the same current and frequency in the open with a much larger section at current zero. Hence the arc in the hole will recover dielectric strength after current zero at a very much faster rate than a corresponding arc in the open.

If we consider Equation (12) as applying we see that the principal effect of the confinement of the arc is to increase the constant $A$, according to Equation (16). The factor $W_0$, according to our simplified thermal ionization theory, we should expect to be proportional to the diameter of the hole, or more probably to the square of the diameter of the hole, as the heat loss from the gas is probably principally due to radiation from the whole section of the gas.

$$W_0 = H\,d^2 \tag{17}$$

We get then for the breakdown gradient:

$$X = \frac{1}{(k\,e\,n_0)^{\frac{1}{2}}}\,(H\,d^2)^{\frac{1}{2}}\,\epsilon^{\frac{F}{2\,d}\,t} \tag{18}$$

In this equation, $n_0$ is still undetermined in its relation to the hole diameter $d$. It seems likely, however, that it will not differ much from the density of ions which would exist in a steady arc which in the open would occupy the same section as the hole. From the results of Nottingham,[8] therefore, we would conclude that $n_0$ varies a little faster than proportional to the square of the diameter of the hole. We get then,

$$X = M\,d^{-2}\,\epsilon^{\frac{N}{d}\,t} \tag{19}$$

8. Nottingham, *Franklin Inst. Jl.*, 207, 1929, p. 299.

for the dependence of the breakdown gradient upon hole diameter, where $M$ and $N$ are constants, and $x$ is a small number.

Equation (**19**) shows how the extinction of long a-c. arcs is facilitated by confining them to holes of small diameters. The following experimental data on the extinction of arcs in holes in soapstone bear this out. The arcs were started by fine fuse wires, and the external circuit consisted of transformers for which the transient time required to impress open circuit voltage upon the arc space after current zero was of the order of ten microseconds. With a hole 0.378 cm. diameter, and 3.81 cm. long, 545 amperes was interrupted in a circuit of 1150 volts r. m. s. A hole 0.193 cm. diameter and 2.54 cm. long also interrupted this current and voltage. Taking the instantaneous open circuit voltage after current zero from oscillograms, and subtracting 250 volts for the dielectric strength of the cathode layer, and dividing by the length of the hole, the gradients after current zero were found to be 228 and 456 volts per cm. respectively. Evidently the volts per cm. which can be interrupted by an arc in a hole are very much larger than for an arc in the open.

Arcs confined to holes are used in completely closed fuses, but usually the gases generated by the decomposition of the material of the fuse case play an important part in the extinction of the arc as will be brought out in the next section. If an inert filler powder is used in the fuse, then the arc plays in the interstices between the powder particles and the arc is perhaps better described as playing in narrow slots. Arcs confined to small holes are little used in switches because of the difficulty of drawing an arc in such a place and the rapid destruction of the hole wall with use. Arcs confined to slots are, however, very generally used in switches, for the usual arc chute in magnetic blow-out switches is of restricted width, and may properly be described as a slot. That the volts per cm. which may be interrupted are greatly increased by using a narrow arc chute is well known.[9,10]

In applying Equation (**12**) to a slot of width $d$, let $b$ be breadth of the slot occupied by the arc at current zero, so that the sectional area is $b\,d$. The loss of ions per cm. length of arc $A\,n$, will be proportional to $b$, while $n$ will be proportional to $b\,d$. Hence, $A$ will be proportional to $1/d$. $W_0$ will be proportional to $b\,d$, and $n_0$ proportional to $b$ and some small power of $d$. We are thus led to expect that Equation (**12**) will reduce to an equation of the form

$$X = P\,d^{-y}\,\epsilon^{\frac{Q}{d}t} \qquad (\mathbf{20})$$

where $P$ and $Q$ are constants and $y$ is a small number.

Fig. 5 gives the results of some experiments on the extinction of a-c. arcs in slots with soapstone walls of varying width in a circuit consisting of transformers for which the time of recovery of open circuit voltage immediately after arc extinction at current zero was of the order of ten microseconds. Evidently, the volts per cm. which can be interrupted increases rapidly as the slot width is reduced.

Equations (**19**) and (**20**) must be regarded as giving only very roughly the way in which the breakdown gradient varies with hole diameter or slot width. Equation (**20**) for example, predicts a straight line relation between log $X\,d^y$ and $\frac{1}{d}$. The data of the

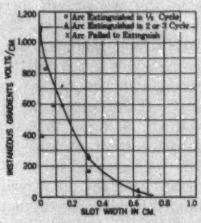


Fig. 5—Extinction of Arc in Slot

curve of Fig. 5 will fit such a relation with small value of $y$ for the wider slots, but the point for the 0.0178-cm. slot will be considerably below the straight line through the other points.

## VII. The Expulsion Fuse

In the usual expulsion fuse, an arc plays in a cylindrical hole open at one end, the bounding walls being horn fiber. Quite high volts per cm. are interrupted by such

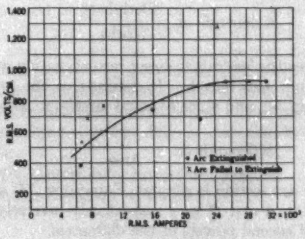


Fig. 6—Expulsion Fuse Slot 0.635 Cm. Wide

fuses. For example, in a 1.58 cm. internal diameter fiber tube 2500 amperes at 60 cycles could be interrupted at 400 volts r. m. s. per cm. length of tube in a circuit in which the time to recover open circuit voltage after arc extinction at current zero was of the order of 10 microseconds. In a hole with soapstone walls of like diameter, only about 40 volts r. m. s. per cm. length could be interrupted.

Similar results were obtained on the extinction of arcs in slots with fiber walls as shown in Fig. 6. Here, the

9. Title, A. I. E. E. Trans., Vol. 41, 1922, p. 262.
10. McNary, A. I. E. E. Trans., Vol. 48, 1929, p. 547.

slot had a width of 0.63 cm., a breadth of 1.90 cm., and a length of 2.54 cm., and was closed at one end and open at the other. The volts per cm. which could be interrupted increased rapidly with the current, and were high in comparison with what could be done in a slot of like width with soapstone walls where according to Fig. 5 only about 60 volts r. m. s. per cm. length could be interrupted.

It is evident that some factor other than the mere confining of the arc to the hole or slot is responsible for the extinction of the arc in the expulsion fuse, and Fig. 6 shows that this factor is increased in intensity as the arc current increases. Measurements of the amount of wall material destroyed in the operation of the fuse reveals the nature of this factor.

In one series of tests at about 2500 amperes, 60 cycles with a cylindrical fiber fuse case of 1.27 cm. internal diameter and 2.54 cm. length, it was found that about 0.25 gr. of fiber was decomposed per half cycle of arc. Assuming that decomposition of 1 gr. of fiber would give rise to 750 cm.$^3$ of gas at 0 deg. cent. 760 mm. this would correspond to 187 cm.$^3$ of gas generated per half cycle. For this gas to pass through the 1.27 cm.$^2$ sectional arc of the tube in one-half cycle, the gas would need to have a velocity of 180 meters per second. With the temperature of the gas much higher than 0 deg. cent., the gas velocity will be correspondingly higher.

The arc in the expulsion fuse then depends for its extinction upon an intense blast of gas generated by the decomposition of the material of the fuse case. On this account, the expulsion fuse loses its effectiveness at small values of current. If the fuse case were made of refractory material, it would also lose its effectiveness at larger currents. The expulsion fuse is a gas blast interrupting device.

## VIII. The Gas Blast Switch

The expulsion fuse teaches us that an intense blast of gas passing longitudinally through an a-c. arc greatly increases the rate at which the arc space recovers dielectric strength after current zero, and so greatly increases the volts per cm. which may be interrupted by an arc in practical circuits. This is confirmed in practise.[2,11] How does theory account for this great effect of a gas blast in the extinction of a long a-c. arc?

Referring to Equation (12), it might be thought that the effect lies principally in increasing the factor $W_0$, that is, in the direct cooling of the arc space by the blast. A little reflection shows, however, that a greater effect is to be expected in an increase in the quantity $A$, that is, an increase in the rate of recombination of the ions. The gas passing through the arc stream is in highly turbulent motion, and at any instant, and particularly at current zero, there will be small volumes of fresh, relatively cool, un-ionized gas dispersed throughout the arc space. The recombination of ions in a cold gas takes place at a tremendously greater rate than in a hot gas.[12] Thus the tiny volumes of cold gas scattered through the arc space act as nuclei which remove ions from the more densely ionized portions of the arc space, and then because of their lower temperature there, the ions which enter these cold nuclei spaces recombine at a much more rapid rate than they would in the hot gas which has just been carrying current. We may say that these small volumes of cold un-ionized gas present an immense internal surface at which deionization takes place in the arc space, or we may say that the ratio of perimeter to area of the section of the arc space which is actually highly ionized at current zero, is enormously increased. All these points of view lead us to expect that a blast of gas through an arc space will enormously increase the rate of deionization so that the volts per cm. which can be interrupted are greatly increased by this means.

If the motion of the gas in the blast is not turbulent, but is of smooth stream line character, the blast will still cause the rate of deionization to be greatly increased by causing the section of the arc stream to be greatly reduced at current zero. However, it would seem that such a blast would be much less effective than one which mixes turbulently with the ionized section, and since it is practically impossible to obtain an intense blast which is not turbulent, therefore the consideration of a non-turbulent stream line blast is not important.

The important thing in applying a gas blast for the extinction of an arc is to make sure that the blast enters turbulently over the whole section of the arc stream. This is best done by making the blast pass longitudinally through the arc space. If a perpendicular blast is used, then the arc is merely carried along with the blast without mixing, and the only effect is a lengthening of the arc, if its terminals are fixed. If the arc is stopped by coming against some barrier or "arc splitter," then the blast becomes longitudinal and effective.

## IX. The Oil Circuit Breaker

In the oil circuit breaker, the arc drawing contacts separate under oil, but the arc which forms plays in a gas bubble formed by decomposing oil. With large currents this gas bubble may attain considerable size.[11] Although the arc thus appears to be playing in a chamber of gas (the gas bubble) of considerable size, and therefore should not be very different from arcs in the open, nevertheless, the volts per cm. which can be interrupted are very much greater than for arcs in the open, amounting to several hundred volts per cm. Several suggestions were made by the author in a preceding paper,[1] as to the reason for this great arc extinguishing power of the oil circuit breaker. Now as a result of further work several of these suggestions may be dismissed as being of only minor influence.

The confining action of the gas bubble in the oil can

11. Wedmore, Whitney, Bruce, *I. E. E. Jl.*, 67, May 1929, p. 557.

12. Slepian, *Flames from Electric Arcs*, A. I. E. E. Quarterly Trans., Vol. 49, January 1930.

be dismissed as a cause of the arc extinguishing power, when the cross section of the bubble is compared with sections of slots or holes necessary to cause like volts per cm. to be interrupted. To interrupt 200 volts per cm. in air, at atmospheric pressure, according to the curve of Fig. 5, a slot would need to be less than 0.37 cm. wide, but the linear dimensions of the section of the gas bubble in an oil breaker at 500 amperes is 10 to 20 cm. The greater pressure and the nature of the gas in the oil breaker can hardly be expected to be responsible for this very great difference.

The suggestion may now also be dismissed that the hot oil in contact with the arc might be conducting and thus act as a momentary resistance shunt in parallel with the arc space, slowing down the rate of application of re-ignition voltage by the external circuit. Mr. C. L. Denault in a careful oscillographic investigation has failed to find current leakage through the oil immediately after arc extinction of sufficient magnitude to affect appreciably the transient of the circuit.

The suggestion that drops of oil or carbonized residues of such drops float in the arc space and act as deionizing centers for the ions remains good, but now we may greatly improve this suggestion by making these deionizing centers or nuclei consist of volumes of relatively cool, un-ionized gas, arising from the decomposition of the oil and mixed turbulently into the arc space. That this is the principal cause of the arc interrupting capacity of the oil circuit breaker seems overwhelmingly certain after the two preceding sections of this paper. Here then is the secret of the oil circuit breaker. *The oil circuit breaker is a gas blast switch*, the gas blast arising from the decomposing oil.

This point of view leads to conclusions diametrically opposite to those usually held as to desirable and undesirable features in oil circuit breakers. From this point of view, the decomposition of the oil instead of being entirely undesirable is the very feature which makes the oil breaker function. To improve the oil breaker, the rate of formation of gas should be increased, not decreased, provided of course that the gas formed is thoroughly mixed with the ionized gas which is carrying the arc. As a matter of fact liquids more volatile than the usual switch oil are used quite successfully in certain types of fuses.

In the oil circuit breaker the attempt should be made to cause the oil to be decomposed at as rapid a rate as possible, and to cause the gases formed to pass turbulently over the whole section of the arc stream. In this way the length of arc needed for a given voltage will be reduced and the arcing time lessened, so that in spite of the increased rate of gas evolution per unit time and per unit length of arc, the total amount of gas generated in a particular switching operation will be lessened.

The growth of the gas bubble in the oil breaker is a factor which works against the extinction of the arc, because clearly it causes the oil boundary to be at a considerable distance from most of the arc section, and therefore causes the rate of decomposition of the oil to be reduced. For moderate currents the volts per cm. which can be interrupted decreases with increasing current since the gas bubble increases in size with current. For large currents, however, the bubble does not increase fast enough to compensate for the increased destructive effect of the arc, and so the volts per cm. which can be interrupted increase with current as in the expulsion fuse, Fig. 6. For the larger currents, however, there is an additional favorable factor arising from the strong magnetic field.

It is well known that a so-called "blow-out" magnetic field in an oil circuit breaker causes the volts per cm. which can be interrupted to be greatly increased, and it is usually assumed that as in the air magnetic blow-out switch the effect of the field is to bend the arc out to a greater length. However, calculation shows that the forces involved in the time available can move the arc only a short distance in so dense a fluid as oil, and

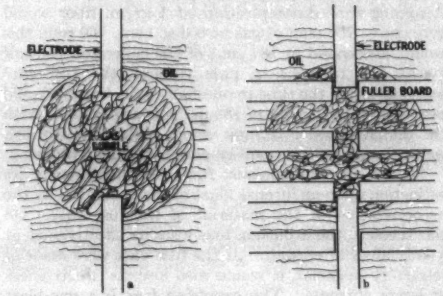


Fig. 7

a. Gas bubble in oil circuit breaker
b. Gas bubble in fuller board structure in oil circuit breaker

direct observation fails to show any bowing out of the arc containing bubble. It seems more likely that the effect of the field is to cause the arc to be displaced in the bubble itself, so that instead of the greatest current density being at the center of the bubble, it is driven to one side close up against the oil wall. This causes a greatly increased rate of gas formation, which mixes with the ionized gas and at current zero accelerates the arc extinction.

Since it is the growth of the gas bubble which causes the interrupting capacity of an oil breaker to diminish, it is clear that any means which will prevent the oil-gas bubble surface from receding from the arc will aid in the arc extinction. This was found to be the case in the following experiment.

A two break breaker of usual construction, with a 21.5-cm. stroke was used to interrupt 3500 amperes at 7620 volts, 60 cycles. It was found that nearly the full length of stroke was needed, the average total length of arc being 40.5 cm. The extinction thus took place at a gradient of 188 volts r. m. s. per cm. of arc.

The structure shown in Fig. 7B was then built around the arc path. It consisted of plates of fuller board, 1.26 cm. thick with a central hole 1.58 cm. in diameter, spaced 1.9 cm. apart. The two arcs were drawn in the central holes of the two structures. The fuller board was highly porous and of course became oil soaked. When the arc was drawn, a gas bubble was generated, and the oil moved away from the arc. The oil soaked fuller board was immovable, however, and so it kept oil surfaces down in the heart of the arc in spite of the receding gas bubble boundary. The rate of gas formation must then have been greatly increased, and this gas was thrown directly into the ionized gas. An improvement in the operation of the breaker was therefore to be expected.

This improvement was found. In the same circuit as above the average total arc length for extinction was 16 cm. so that the gradient was 475 volts r. m. s. per cm., more than twice the gradient obtained when the structure was not used.

## X. Electrostatic Balance in the Extinction of a Long A-C. Arc

While a long arc is playing, the voltage gradient along the arc stream is a fairly uniform one. This is because the resistance of the arc stream is low so that the charging currents which flow out of the sides of the arc due to the potential of the arc relative to surrounding objects, are small in comparison to the conduction currents flowing through the arc, and so these charging currents have little effect in distorting the voltage gradient along the arc stream. During the extinction period following current zero conditions are otherwise.

The extinction of the a-c. arc is a high-frequency phenomenon. In the extinction period, the voltage applied to the arc terminals rises from a low value to a high value in a few microseconds. The charging currents therefore may be quite high during this period. On the other hand the resistance of the arc space is rapidly increasing and the conduction current becomes correspondingly small. The charging currents may then become comparable to the conduction current, and considerable distortion of the gradient along the arc stream may result. After the arc is extinguished, the voltage gradient along what was the arc stream will become that corresponding to the electrostatic field produced by the electrodes and other charged parts. In most practical interrupters, this field gives a highly distorted voltage gradient distribution along the arc path.

It is clear that this electrostatic distortion of the voltage gradient along the arc may very greatly diminish the average volts per cm. which may be interrupted by an arc in any particular switch. This is illustrated by some tests with a two break oil breaker of usual construction. The distribution of the electrostatic field in the open breaker was determined by Mr. B. P. Baker by setting a model of the open breaker in a bath of electrolyte, and determining the equipotential surfaces when current was allowed to flow into one terminal and out of the other, this last terminal being connected to the tank. Fig. 8 shows the location of the 10 per cent voltage equipotential surface. This shows that with the breaker open, more than 90 per cent of the applied voltage appears across the first break and less than 10 per cent across the second break. It was then to be expected that if this voltage distribution was approached during the extinction period, the second arc would be of little assistance in interrupting a circuit. The first arc would take most of the voltage building up across the switch terminals, and if it was overstressed, it would break down and throw nearly full voltage on the second arc.

Experiment shows that this was the case. It was found that the arcing time was no greater when one break was shunted out by a flexible conductor, than when both breaks were used. Table II gives the test results. The tests were made at 60 cycles, with the short circuit grounded. The table shows the arcing times for the single break tests to have been actually

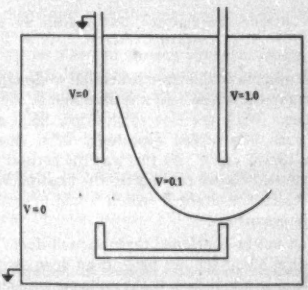


Fig. 8—Equipotential Surfaces in an Open Oil Circuit Breaker

TABLE II

| Circuit voltage | Arc current | Number of breaks | Arcing time |
|---|---|---|---|
| 22,000 volts | 4000 amperes | Two breaks | 9 cycles |
| 22,000 " | 4000 " | One break | 7 " |
| 22,000 " | 1700 " | Two breaks | 12 " |
| 22,000 " | 1700 " | One break | 9 " |

shorter than for the two break tests, but the differences are no greater than occur in repetitions of the same test. If a large number of tests had been made, and averages taken, it is probable that the single break tests would show about the same arcing time as the double break tests.

If the charged conducting parts of an open breaker are arranged so that the electrostatic field they produce gives a uniform gradient along the arc path, then there will be no distortion of the voltage gradient in the arc stream during the extinction period, and there will be no lowering of the average volts per cm. for the arc length which can be interrupted.

This is illustrated by some experiments of F. C. Todd with an experimental narrow slot type switch. In these experiments the a-c. arc was driven by a magnetic field into a slot 0.158 cm. wide between soapstone walls. The arc was 43 cm. long, and tests were made at 60 cycles in a transformer circuit, in which the open circuit voltage could be varied in steps. At 2000 amperes r. m. s. the switch failed in every test when the circuit voltage was raised to 13,800 volts, although it operated successfully at 11,500 volts. There was then placed adjacent to the slot walls, a static shield, which consisted of micarta with imbedded tinfoil so designed that a uniform electrostatic field was produced in the narrow slot space. With the slot so shielded, 2000 amperes r. m. s. was interrupted repeatedly in a single half cycle at 13,800 volts. As this was the highest voltage which the test circuit could give, the limiting volts per cm. at which the shielded switch would operate could not be determined.

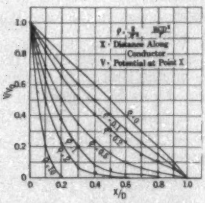


Fig. 9—Voltage Distribution Unbalanced by Electrostatic Capacity

It must not be concluded that a non-uniform voltage distribution along the arc path in an open switch will always lead to a reduction in the volts per cm. which can be interrupted by the arc. It depends on how hard the arc space is worked during the extinction period, that is upon the volts per cm. and the shortness of the extinction time, as well as upon the arc length. If the volts per cm. are low during the extinction period, then the resistance of the arc stream may still be low at the end of the period without breakdown occurring, so that the conduction current through the arc space is still large compared to charging currents. The subsequent further increase of resistance of the arc stream then takes place in the 60-cycle régime where charging currents are small.

Hence, in many types of present day switches, addition of electrostatic balancing means will give no improvement in the interrupting capacity. But, in switches having very long arcs, or in which means are used to obtain an especially rapid deionization of the arc space during the extinction period, static balance will be important.

This will perhaps be better understood by reference to Fig. 9, which shows the distribution of voltage along a conductor of length $D$ cm., with a resistivity of $R$ ohms per cm., and having a uniformly distributed capacity to space of $C$ farads per cm. and to the terminals of which a voltage is applied which builds up at a uniform rate to $V_0$ volts in $T$ seconds. The distribution of voltage then depends on the quantity $\zeta = \frac{2}{\pi^2} \frac{R C D^2}{T}$. Thus if an arc length is taken as $D = 30$ cm., and $C$ is taken as $1.33 \times 10^{-13}$ farads per cm. corresponding to a 1-cm. diameter arc space, and if the extinction time is taken as $T = 10^{-6}$ seconds, then to make $\zeta = 0.2$ which would make the maximum gradient along the arc space twice the average, $R$ would need to be $2.5 \times 10^8$ ohms per cm. Hence, for this arc static balance will be important if the rate of deionization is sufficiently great to make the resistivity $R$ of the arc space reach $2.5 \times 10^8$ ohms per cm. in the time $T = 10^{-6}$ seconds.

## Discussion

For discussion of this paper see page 441.

# The Use of Oil in Arc Rupture

## With Special Reference to System Stability

BY B. P. BAKER*
Associate, A. I. E. E.

and H. M. WILCOX*
Member, A. I. E. E.

*Synopsis.—The relationship of the rupturing ability of oil circuit breakers to system stability problems is discussed, and conclusions are drawn as to the effectiveness with which the oil must be used in arc rupture if the requirements of stability are to be met. Past attempts to improve the rupturing performance of oil circuit breakers are reviewed and the results of an investigation of the processes of a-c. arc extinction in oil are discussed, from which conclusions are drawn as to the degree of efficiency with which oil has been used in conventional oil circuit breakers.*

*A description is given of a new device, known as the deion-grid, developed to permit the application of scientific principles to arc extinction in oil, and its theory of operation is discussed together with the results of interrupting tests in both the laboratory and field. Conclusions are drawn as to the effectiveness of this device in improving the rupturing performance of oil breakers and its suitability for use where questions of system stability are involved.*

* * * * *

### Introduction

THE importance of system stability as evidenced by the increasing interest in discussions of this problem, has given rise to a growing demand on the part of the power companies for circuit interrupters which are capable of removing a fault before operation of the connected system and apparatus becomes jeopardized.

The time involved in disconnecting the faulty portion of a system may be divided into three distinct elements: first, the relay time, necessary to detect the fault and energize the tripping circuit of the circuit breaker; second, the mechanical time, necessary to unlatch the breaker and move the contacts to the point of drawing an arc; and third, the arcing time, or the time required for the arc to be extinguished and the circuit interrupted. The first element, relay time, is a separate problem and may be considered as quite independent of circuit breaker operation. The second element deals largely with mechanical details which need not be discussed here. It is the purpose of this paper to discuss recent investigations dealing with the third element, arcing time, with particular reference to more efficient use of oil in arc rupture.

A year ago three papers[1,2,3] were presented before the Institute, discussing the development of a distinctive new type of interrupter, the Deion circuit breaker, which has proved particularly successful in interrupting high-power short circuits without the use of oil.

However, there is at the present time among the power companies of this country and Europe, an immense investment in oil-filled switching apparatus together with the equipment and organization necessary to maintain that apparatus. In fairness to those who in good faith have made this investment, opportunity should be offered for securing a just return. However desirable it may be to eliminate the use of oil from high-voltage switching service ultimately, any development which serves to make more efficient use of oil in the apparatus now in service, or in that which must inevitably be installed for some time to come, will find a distinct field of usefulness. A device developed with this purpose in mind is discussed in this paper.

It may be noted in passing that the circuit breaker discussed here bears no particular relation to the Deion air-break circuit breaker and should not be confused with it since the two are different in construction and theory of operation. They may both, however, be regarded as the result of an intensive research development dealing with fundamental arc phenomena, which has been carried on for a number of years by the organization of which the authors are members.

### Preliminary Investigation

Investigation of results heretofore obtained with conventional, double-break, oil circuit breakers showed an astonishingly wide range in interrupting performance under differing circuit conditions. For instance, short circuit tests on a resistance circuit of high power factor showed these breakers to have a rupturing ability of 10,000 volts or better, per inch of total contact separation in the two breaks. This is a very good performance; but the same breaker, tested at the same voltage, on a highly reactive circuit of low power factor with oscillatory characteristics, showed consistently a rupturing ability of less than 1000 volts per inch of total break distance due largely to transient circuit conditions often found in testing circuits where the effect of a parallel system is missing. This is a relatively poor performance, resulting in a period of arcing much longer than is desirable if faulty portions of the circuit are to be disconnected in keeping with the requirements for system stability. High power factor conditions are obtained for the most part on operating systems, even under a short circuit, but it was realized that a fault may introduce other conditions temporarily, making it

*Circuit Breaker Engg. Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. *Theory of the Deion Circuit Breaker*, J. Slepian, A. I. E. E. Trans., Vol. 48, 1929, p. 523.
2. *The Structural Development of the Deion Circuit Breaker up to 15,000 Volts*, R. C. Dickinson and B. P. Baker, A. I. E. E. Trans., Vol. 48, 1929, p. 528.
3. *Field Tests of the Deion Circuit Breaker*, B. G. Jamieson, A. I. E. E. Trans., Vol. 48, p. 535.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

more difficult for the breaker to interrupt the circuit at the very time when speedy and reliable interruption is most essential. Obviously, some means was necessary for bringing the rupturing performance under the worst conditions more nearly in line with that under the best circuit conditions; in other words, to make more efficient use of the oil in arc rupture.

In a paper[4] presented before this meeting of the Institute, Slepian has concluded as a result of his studies of an a-c. arc in gases, that the extinction or re-ignition of such an arc following a current zero is dependent principally on two factors: first, the rate at which the arc space recovers dielectric strength after current ceases to flow; and second, the rate at which the voltage applied to the arc terminals by the external circuit builds up. The first of these factors depends very largely on the arc space, while the second depends principally on external circuit conditions. Reviewing the test results set forth in the preceding paragraph in the light of this conclusion, it was evident that the interrupting medium, the arc drawing members and the surrounding oil, was the same in the two types of tests and that conditions in the arc space must have been substantially the same, at least up to the point in contact travel at which that space successfully withstood 10,000 volts per inch of break distance. If, then, the rate at which the arc space recovered dielectric strength was substantially the same in both cases, the factors which produced the wide variation in performance must have been associated with the way in which the restored voltage was applied to the arc terminals by the external circuit, that is, the generated voltage at the time of current zero, the nature of oscillatory frequency of the connected circuit, and the amount of "overshooting" accompanying this oscillation.

Since it is outside the province of the circuit interrupting medium to control the external conditions governing the rate at which recovery voltage builds up after the current zero, the alternative was to speed up the rate of recovery of dielectric strength in the arc space to a point at which it could successfully withstand the voltage impressed across it. The tests made under the best circuit conditions showed that up to a certain point in the rate of rise of recovery voltage, the oil circuit breaker as heretofore used was capable of giving a very satisfactory interrupting performance. It remained only to find some means of increasing the rate of rise of dielectric strength in the arc space in order to extend this satisfactory performance over the entire range of circuit conditions.

The actual processes of arc extinction in oil have been heretofore very poorly understood. The phenomenon of the "gas bubble," that area in the vicinity of the arcing space in which oil is either entirely absent or present only in small quantities, has been known for some years, and various European engineers, notably Altbuerger,[5] have secured photographs with various special test equipment showing the existence of such an area or "bubble" in connection with the drawing of an arc in oil. The process by which this gas-filled area is formed by the volatilization of the oil adjacent to the arc, the manner in which it is maintained during the existence of the arc, and the way in which it is finally dissipated, have been fairly well understood from analysis based largely on theoretical considerations. The effect of this gas on arc rupture, however, has not been so clearly understood and in many quarters this generation of gas has come to be regarded in the light of a necessary evil to be borne only until such time as someone should develop a quenching liquid with other and more desirable characteristics. Such theories as have been evolved up to the present time concerning the extinction of an arc in oil have been more or less vague but in general have been associated with oil films or pressure built up by the sudden expansion and generation of gas in a relatively immobile body of oil. Variable rupturing performance, generally described as erratic, has been noted for many years but, far from being explained, it has come to be regarded as characteristic of oil circuit breaker operation.

A review of the various attempts made during the history of oil circuit breaker development to improve the rupturing performance throws further light on the impressions prevailing concerning the processes of arc extinction in oil. Many of these attempts have been directed toward forcing oil into the arc stream by some means for increasing the pressure in the arcing area such as, increasing the head of oil above the contacts to gain the additional hydrostatic pressure; increasing the pressure locally by semi-enclosed chambers designed to retain the gases generated by arc action and release them only slowly after the arc is extinguished; barriers arranged to deflect or divert oil into the arcing area; and various other devices all of which improved the performance in degree only and gave no promise of increasing the rate of recovery of dielectric strength throughout the entire arcing space that was desired in this particular investigation. Analysis of tests made with an increased number of contact breaks showed clearly that no increase in the rate of recovery of dielectric strength was to be obtained in this manner; in fact, it was noted that the decrease in time duration of arcing was by no means proportional to the increased length of arc drawn, some tests made with six breaks showing practically no improvement over those made with four breaks. Substantial improvement in performance was obtained by the use of quick-break or high-speed contacts designed to draw the arc at such speed as to insure that that portion of the arc nearest its moving contact terminal was always out of the gas-filled area and in cold oil. This undoubtedly increased

4. *Extinction of a Long A-C. Arc*, J. Slepian, see p. 421.

5. "Experimental Investigation of the Process of Interrupting a 6000-Volt Circuit under Oil," P. Altbuerger, *Archiv f. Elektrotech.*, Vol. 21, No. 1, 1928, p. 61.

the rate of recovery of dielectric strength over a small portion of the arc space but it was desired to extend this effect over a much larger portion of the arc drawing space.

The oil jet as a device for improving rupturing performance has intrigued circuit breaker designers for a great many years. Patent Office files show that as early as 1908 ideas had crystalized along this line and various devices had been developed for injecting into the arc stream a jet of oil, generally directed from orifices in the movable contact member so shaped as to use the natural displacement of oil due to contact movement as a driving force. External sources of pressure, released by the tripping operation of the breaker contacts, have also been used for the purpose. A considerable series of tests made by the authors and their associates, using various forms of oil jet, forced the conclusion that no appreciable improvement in performance was to be obtained by the use of a jet within the range of pressures that can be generated by oil displacement due to contact movement. It was not until nozzle pressures of from 150 lb. per square inch upward were used that any marked improvement was noted and then the results were extremely erratic, the maximum duration of arcing in a single series of similar tests being twelve times that of the minimum duration. Only after something approaching a "sea of oil" was moved into the arcing area were anything like consistent results obtained.

Analysis of these test results opened up a new line of thought. The condition of conducting members in the vicinity of the contacts after tests with the oil jets at heavier pressures, indicated that in some cases the arc had assumed a new position outside the range of the jet and had persisted, unaffected by it. The picture was then presented of a relatively mobile arc with negligible inertia playing in a gas-filled area, free to bend and twist, assuming with ease a new position in the gas to avoid a jet of oil directed toward it or, at the lighter nozzle pressures, possibly moving freely ahead of the jet, carrying its own ionized atmosphere with it in a fairly homogeneous stream. With this picture in mind, the futility of attempting to direct a fixed jet of oil against an arc which was free to move about through a relatively large area was apparent. At the same time, it was obviously impracticable from the point of view of operating service to move sufficient quantities of oil into the arcing area to fill it completely, leaving no means for the arc to avoid it although sufficient tests were made along this line to satisfy the authors as to the correctness of their theory.

One fact remained outstanding throughout this investigation. Along the upper range of short circuit current values, 20,000 amperes and above, rupturing performance so far as duration of arcing is concerned was uniformly good. One-half to one cycle of arcing, with an occasional maximum of one and one-half cycles on a 60-cycle wave, was the usual performance in heavy current switching. Regardless of the type or construction, with or without any of the various devices for improving rupturing performance, all breakers met on a common ground in this field and the rate of recovery of dielectric strength in the arc space was adequate for all conditions. This phenomenon has been recognized for a great many years and has generally been ascribed to the inherent blowout effect due to the current loop formed by the arrangement of terminal leads and contact members in the conventional oil circuit breaker chamber, although no very convincing theory has heretofore been advanced to explain how the rupturing ability of the breaker was increased by this blowout effect other than that the arc was "stretched" to greater length, due to the looping effect, and thus exposed to action of the oil over a greater surface. In any except the very high voltage breakers, the two sides of this loop, the terminal leads, are sufficiently close together to result in very considerable blowout forces at heavy currents.

Some time ago, one of the authors of this paper presented before the Institute a paper[6] discussing a high-speed oil circuit breaker designed for 12,000-volt, a-c. railway electrification. In this breaker, the inherent blowout effect in the breaker loop was supplemented by a powerful blowout magnet which enabled it to give a rupturing performance at 2000 amperes equal to or better than that given by conventional breakers without such a magnet at 20,000 amperes. In the light of the conclusions drawn from the results of the oil jet tests, the effect of heavy blowout forces assumed a new significance. A new element had been introduced; the arc no longer retained its general mobility with freedom to move about at will over the gas-filled area, but was now mobile in one plane only, the plane in which the blowout force was acting. However, this blowout force constituted a distinct driving force which tended to move the arc outward in that plane so that, although the arc terminals were relatively fixed on the contact members, the middle portion of the arc with negligible inertia was looped out sharply and very rapidly. But the blowout forces have no such effect on the gases surrounding the arc stream and as a result, the arc no longer played in a relatively still, hot, ionized atmosphere of gas but was forced against what may be described as the outer wall of the gas-filled area or "gas bubble," in other words, against cold oil, and was exposed to the deionizing action of that oil through at least a large percentage of its length. Furthermore, it was held there, unable to move away to a better conducting path, and was forced farther into the oil with any tendency of the gas field to increase in size in that direction.

For the space of time required to extinguish an a-c. arc, the body of oil in the breaker chamber is relatively immobile. The arc itself, however, has a rather high

6. *High-Speed Circuit Breakers for Railway Electrification*, H. M. Wilcox, A. I. E. E. Trans., Vol. 47, 1928, p. 1285.

mobility. Consideration of these facts led to the conclusion that the logical course was not to move oil against the arc, an immobile body against a mobile one, but to move the arc against the oil, utilizing the natural mobility of the one and the immobility of the other to hold them in intimate contact. At the higher transmission voltages, short circuit current values are so small as to have little inherent blowout effect, and the conventional blowout magnet offers grave difficulties in the way of insulation in circuit breakers for this class of service. It was realized, however, that if the degree of immobility of the oil could be increased, for instance, held on or adjacent to surfaces from which it could not escape except to be given off into the arc stream, only moderate forces might be required to move the arc toward the entrapped oil and thus secure intimate contact between the arc and oil.

Fig. 1—Inside View of the Oil Circuit Breaker Equipped with Deion Grids

With this object in view, there has been developed for use in conventional oil circuit breakers, a device which at the present time has shown very marked improvement in the rupturing performance of such breakers and which will be referred to in the following descriptive paragraphs as the deion-grid.

## Construction and Operation

Except for the details in the vicinity of the contacts, breakers now made with this device are the same in all respects as the standard breakers which have been supplied for service for a number of years. As the application of the new device broadens, it is quite possible that modifications in the design of other details of the breaker may be found desirable in order to secure full benefit from the improved rupturing performance and arc control, but for the present these details remain unchanged, insuring the application of the device to breakers now in service.

Fig. 1 shows the contact arrangement inside the chamber of a single-pole breaker unit. The conventional condenser terminal leads, each with a stationary contact element at its lower end, and the bridging, movable contact element constitute the conducting current loop while the interrupting elements in which the two arcs are drawn, are supported, one from each stationary contact. The current-carrying contacts are

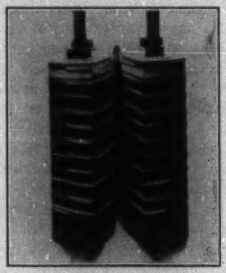

Fig. 2—The Arc Extinguishing Structure, Referred to as the Deion Grid, Ready for Mounting in an Oil Circuit Breaker

of the plain-break butt-contact type, the movable member being of rigid but light construction well adapted to rapid acceleration for fast opening speed. The stationary contacts are equipped with the conven-

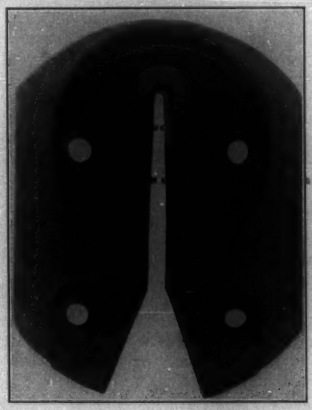

Fig. 3—An Elemental Group or Unit of which the Deion Grids are Made Up, Showing the Arrangement of the Iron and Insulating Materials

tional bells or static shields common to circuit breakers for high-voltage service.

The interrupting element or stack of grid plates from which it has derived its name is shown in Fig. 2, one of these grids being supported from each stationary

contact element as shown in Fig. 1. The particular grid shown here is designed for 110-kv. service and is made up of eleven similar units such as are shown in Fig. 3, each unit in turn being made up of plate elements of insulating and magnetic material as shown in Fig. 4. Each individual grid plate carries a slotted opening, the purpose of which will be explained later, and four holes so arranged that when the several units are stacked up in the completed grid, insulated studs can be passed through for the purpose of clamping the units firmly together and for supporting it from the stationary contact element. The bottom plate or lowermost unit of the stack as shown in Fig. 2, is a single plate of insulating material serving as an anchorage for the clamping studs as well as a guide to insure accurate entry of the movable contact element into the grid during the closing contact movement.

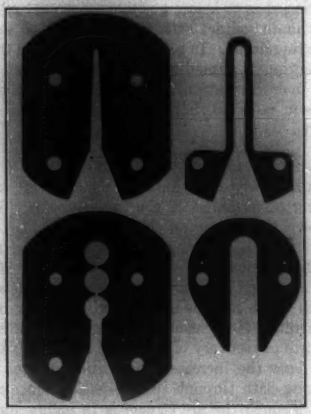

Fig. 4—The Elements of Iron, Fiber, and Fullerboard Used in Building Each Unit of the Deion-Grids

As shown in Figs. 2 and 3, the slotted openings in each individual plate element all register in the completed grid to form a single deep and relatively narrow groove, extending throughout its length. This groove is closed at one end of the grid but open for its entire length at the other end, the two grids in any pole unit being arranged so that the long axes of these grooves lie in the plane of the movable contact element with the open end of the two grooves facing each other. The ends of the movable contact element extend through the open ends of the grooves well into the narrow portion, one end of the contact in each grid. As the contacts part on opening, the movable element passes downward through the groove and on to the end of the stroke, well out of the grids, leaving an ample space of clean oil between the contact surfaces and the bottom of the grid to insure adequate insulation in the open position of the breaker. The arc produced by parting of the contacts is then drawn and extinguished in this narrow groove, closed on all sides except for the opening at the

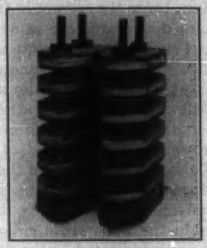

Fig. 5—The Open Type of Deion-Grid Construction

inner end necessary to permit contact movement and the openings at the top and bottom of the grid.

The iron plate elements in the grid are inserted to produce a magnetic field for the purpose of moving the arc toward the closed end of the groove after it is drawn. As shown in Figs. 3, 4, and 6, each individual

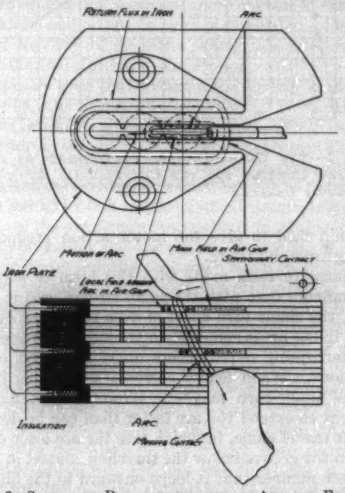


Fig. 6—Schematic Relationship of the Arc and Elements of the Grid Structure, Showing the Manner in which the Driving Force on the Arc is Produced

iron plate is roughly horseshoe shaped, forming a partial magnetic circuit with an air-gap corresponding to the slotted opening in the insulating plate elements. As the contacts part when opening the breaker, an arc is

drawn between the stationary and moving elements in the narrow groove of the grid. As the contact moves downward toward the open position, the arc is drawn through the air-gap of the iron plate, giving rise to a magnetomotive force in the iron circuit and across the air-gap of one turn times the current in the arc. As the contact continues downward, the same effect is produced in the next succeeding iron plate and so on until the arc is extinguished. These magnetomotive forces are applied almost entirely across the air-gaps in the several grid plates, distorting and strengthening the magnetic field around the arc in such manner that the arc is moved toward the closed end of the magnetic circuit which is also the closed end of the groove. The main field produced in the iron plates is indicated in Fig. 6 in the conventional manner by dots in the air-gap and crosses in the iron return circuit. The local field around the arc is indicated by the dots and crosses in circles. This local field reacts in the usual way with

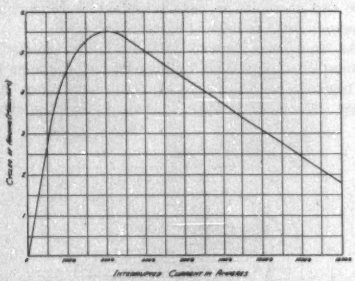

Fig. 7—The Characteristic Relationship of Arcing Time and Current for the Conventional Quick-Break Oil Circuit Breaker

the main field to give the motor action producing a driving force on the arc.

Exhaustive tests made with this form of magnetic field indicate that with the small air-gap used in these plates, the single-turn effect of even the lowest current values in the arc is sufficient to produce a field adequate for interrupting requirements under the worst circuit conditions. When heavy currents are flowing in the arc the single-turn magnetic blowout effect may be sufficient to extend the arc faster than can be done by contact travel alone, in which case the arc loops downward in the groove below the traveling contact in much the same manner that it loops outward in the hitherto conventional oil breaker. In both cases the result is the same; the arc is extinguished very rapidly.

From the description here given it will be apparent that the construction of these grids admits of a large number of variations or modifications which may prove desirable or necessary to meet any particular circuit condition. The number of unit groups in the grid may easily be increased or decreased to meet service voltage requirements; the number of iron plates and the amount of iron in each plate may be varied without difficulty; the size of the slots, the size of the plates themselves, or even their material, may all be changed at will. The grid shown in Figs. 1 and 2 are built up solid, that is, the groove is entirely closed at the outer end except for openings at the top and bottom. For certain classes of service, it may prove desirable to space the unit groups apart by washers around the clamping studs, as shown in Fig. 5, to permit a more open groove. There are still other conditions in which it may be desirable to use a grid closed even more than the one shown in Figs. 1 and 2. Certain fundamental requirements must be observed, however, and whatever the size, shape, or amount of materials used, to be operable, the opening within the grid must be capable of entrapping oil and holding it intact while the magnetic field must be so proportioned as to insure positive movement of the arc into intimate contact with the entrapped oil until the arc is extinguished. In general, it may be said that it is the intention to extend the use of a single set of grid details over as wide a range of service voltages as possible in order to simplify maintenance and service problems.

## Theory of Operation

From his study of the long a-c. arc as observed in the rupturing performance of the expulsion fuse, Slepian[4] has drawn the conclusion that an intense blast of gas passing through an arc greatly increases the rate at which the arc space recovers dielectric strength after the current zero, and so greatly increases the volts per unit of length which may be interrupted by an arc in practical circuits. He concludes further that this increase in the rate of recovery of dielectric strength is derived largely from the increased diminution of ions in the conducting path through recombination, since the gas passing through the arc stream is in highly turbulent motion and, particularly at the current zero, supplies small volumes of fresh, relatively cool, un-ionized gas which, dispersed throughout the arc space, act as nuclei about which the recombination of ions takes place at a tremendously greater rate than would be possible in the hot gas of the arc stream alone.

The vastly improved rupturing performance of conventional oil circuit breakers when heavy blowout fields are present, as discussed earlier in this paper, may be explained in the light of this theory. The arc, immobile except in one plane, but moved in that plane by a powerful driving force, assumes a position against what may be described as the outer periphery of the gas-filled area. It may even be assumed that the arc, extremely mobile in this one plane, cuts into the wall of surrounding oil and continues to loop outward, tending to increase the size of the gas-filled area in this direction by leaving a field of gas behind it as it proceeds.

The intimate contact between the arc and the oil

body, produced by this cutting movement of the arc through the oil, results in decomposition of that portion of oil immediately in front of the arc and the generation of a continuous supply of gas. This gas must find some means of escape to the gas-filled area behind the arc and, in view of the forces involved, the path of least resistance lies directly through the arc stream itself. We have then a continuous supply of fresh, relatively cool, un-ionized gas passing laterally through the arc stream in highly turbulent motion throughout at least a large percentage of its length. The nuclei about which recombination of ions rapidly takes place are thus freely dispersed throughout the arc stream and the rate of recovery of dielectric strength is very measurably increased. Under these conditions, one or two re-ignitions at the current zero has been the usual performance in the past and many cases have been noted, particularly in the high-speed oil breaker, in which there was no re-ignition at all, the circuit being interrupted at the first current zero.

Fig. 8—Oscillogram of a Single-Phase Interruption on a Single-Pole Circuit Breaker Equipped with Deion Grids

In contrast to this the rupturing performance when blowout forces were absent has been, heretofore, quite different. The curve in Fig. 7 shows the characteristic relation between duration of arcing and current interrupted for a conventional double-break oil circuit breaker. It will be noted that for current values in the range of normal switching operations, the period of arcing is short. As current values increase into the range of those encountered on short circuit, the duration of arcing increases up to the point at which inherent blowout forces begin to exert an influence, and then decrease to the point in very heavy currents at which the conditions discussed in the previous paragraphs are obtained.

This apparent decrease in the rate of recovery of dielectric strength when blowout forces are absent may be attributed to the tendency of the arc to play about in the gas-filled area with little opportunity for fresh unionized gas to be injected into the arc stream. Deionization in this case may be brought about largely through diffusion of ions from the surface of the arc to the surrounding gas and by turbulence in the oil body making accidental contact between the arc stream and the oil. For the lower current values, the arc being of relatively small cross section, the ratio of cross section of the arc to its perimeter is small and the diffusion of ions from the surface of the arc stream into the surrounding, relatively cooler gas is sufficient to produce the necessary rate of recovery of dielectric strength. Furthermore, the gas field in this case is small and may be regarded as a slender, comparatively long tube of gas surrounding the arc, easily distorted or broken, so that contact with the surrounding oil at some point in the arc stream is assured.

As the current in the arc increases in value, however, the cross section becomes larger, the ratio of cross section to periphery increases, and deionization by diffusion at the surface of the arc stream becomes of relatively less effect so that the rate of recovery of dielectric strength is decreased. Also, the gas field in this case is larger and may be regarded as a sphere or bubble, with considerable mechanical stability, so that a relatively greater degree of turbulence in the oil body is necessary to distort or disrupt it. As a consequence the possibility of adequate contact between the arc and the oil is lessened or at least delayed. As the current in the arc increases still further in value and blowout forces begin to be effective, more and more contact is obtained between arc and oil until a point is reached at which the rate of recovery of dielectric strength is adequate to reduce the arcing period to a minimum.

It appears then that to be most effective in a-c. arc extinction, the oil circuit breaker must be capable of drawing and maintaining the arc continually in contact with fresh oil, that this contact between arc and oil must be sufficient to produce a high rate of decomposition of the oil, and the surroundings must be such as to force all of the gas and other products of oil decomposition to penetrate the arc stream, throughout its entire length. The investigation and tests made by the authors and their associates indicate that when these conditions are fulfilled, the rate of recovery of dielectric strength in the arc stream after a current zero will be adequate to cope successfully with the rate at which recovery voltage may build up across the arc terminals under any circuit conditions to be found in practical service.

It was in an endeavor to meet these requirements for most effective arc extinction, in other words to make more efficient use of the oil in arc rupture, that the deion grids described in this paper were developed. As stated previously, the aim was to utilize to better advantage the relative immobility of the oil and the extreme mobility of the long arc using the natural forces inherent in these two elements to secure the desired results.

From the description of its construction and operation given in earlier paragraphs, it will be noted that the arc is drawn between the parting contacts in a vertical, relatively narrow, deep groove formed by slots in the

several plate elements of the grid and closed at the outer end. Plates of magnetic material, spaced at intervals throughout the grid and so arranged as to form a partial return circuit, provide a magnetic field when an arc is drawn through the air-gap which is a part of the groove. This magnetic field operates to move the arc steadily toward the closed end of the groove. Since the grid is submerged in oil, the groove is filled with oil which cannot escape except through the small openings at top and bottom and which for the short interval of time that the arc exists is for all practical purposes solidly entrapped. Furthermore, the groove is very narrow and the arc, drawn longitudinally through it, fills practically the entire open end of the groove.

From this it will be apparent that an arc moving toward the closed end of the groove is in effect being forced against a solid wall of oil throughout its entire length, resulting in a high rate of decomposition of the oil with an accompanying continuous and adequate supply of fresh un-ionized gas. This gas cannot escape except through the arc stream since the arc fills the open end of the groove. Due to the driving power behind the arc, the gas is forced to pass through the arc stream, diluting it with small volumes of un-ionized gas, while current is flowing, which act as deionizing surfaces after the current zero is reached. An additional deionizing effect is obtained from the sides of the groove where the arc impinges as it moves. The insulating plate elements in the grid are of absorbent material containing in their submerged condition considerable oil content. As the arc passes over the edges of these grid plates exposed in the sides of the groove, the heat forces this material to give off its oil which is also volatilized and thrown turbulently into the arc stream. This characteristic of giving off oil and creating a gas film along the edges of the plate elements also serves to protect them from burning under the heat of the arc. Large numbers of interrupting tests have been made with a single set of grids without appreciable burning.

In review it is possible to formulate the theory of operation of the deion grid or of any oil circuit breaker in the following statement: The efficiency of rupturing performance of an oil circuit breaker, or the rate at which the arc stream regains its dielectric strength after the current zero, is directly proportional to the effectiveness of the means for preventing the escape of gases generated in the vicinity of the arc without passing through the arc stream.

## Laboratory Tests

Power for development tests of the deion grids was supplied by two 20,000-kv-a. generators either direct-connected or feeding through a bank of three 33,333-kv-a. transformers. The voltage and current applied to the test breaker was controlled by connections on the generators, transformers, and a bank of air-core reactors which were always connected between the generators and transformers when the latter were in use. The high-voltage power transmission line between the transformers and the test breaker was only a very short overhead system. The time constants and oscillatory characteristics of the circuit were very poor, sometimes causing "over-shooting" to twice the nominal restored voltage. The tests on the grids shown in Figs. 1 and 2 were all made at 60 cycles with currents ranging from 20 amperes to 15,000 amperes, and at voltages of from 13,200 to 176,000. The maximum energy for any test was the plant capacity of approximately one-quarter of a million kv-a. single phase.

Fig. 8 shows a typical oscillogram of a single-phase short circuit taken during these tests. The initial voltage on this test was 86 kv. across a single pair of contacts. However, due to the decrement of the generators the restored voltage was reduced to 77 kv. The current at the time of drawing the arc was 1200 amperes. The arc was extinguished in 2.5 cycles or

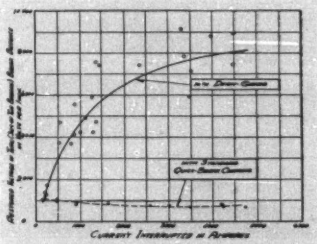

Fig. 9—Relationship of Current Interrupted to Restored Volts R. M. S. Per Inch of Break Distance in an Oil Circuit Breaker when Equipped with Quick-Break Contacts and with Deion Grids

approximately 30 per cent of the opening stroke, during which time 100 kw.-seconds of energy was dissipated, producing a maximum pressure of 18 lb. per square inch as registered by the pressure indicator attached to the bottom of the tank. The contact separation at the time of extinction was only 5½ in., which is equivalent to 7000 volts per inch of total break distance (11 in.). This value of volts per inch is considerably larger than might be expected from the upper curve in Fig. 9, but it may be noted that the voltage for this test is higher than that of the tests used for obtaining the relation shown in the curve. Fig. 9 shows the r. m. s. restored volts across the contacts per inch of total break distance plotted as a function of current interrupted; that is, the ordinates are obtained by measuring the restored voltage across the breaker upon arc extinction and dividing this voltage by twice the amount of contact separation at the time of arc extinction. The tests from which these data were obtained were all made on a standard single-pole oil circuit breaker tested at 38 kv. across a

single pair of contacts. The lower curve shows the results of tests using standard quick-break contacts. The upper curve shows the operation of the same breaker under the same test and circuit conditions, with a set of deion-grids as shown in Fig. 1. The operating characteristics as shown by the two curves are self-explanatory and need no further comment other than to point out that the upper curve may be expected to continue almost horizontally as the current is increased, while the lower one will undoubtedly rise in accordance with the characteristics shown in Fig. 7. Although these two curves may be expected to approach each other it is improbable that they will cross.

Fig. 10 shows the relation of arc energy to current interrupted for the quick-break contacts and for the grids in the preceding tests. The upper curve shows the

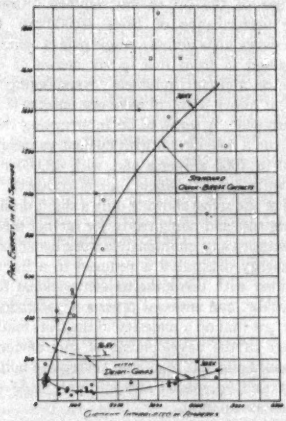


Fig. 10—Relationship of Current Interrupted to Arc Energy in an Oil Circuit Breaker when Equipped with Quick-Break Contacts and with Deion Grids

arc energy in kw.-seconds plotted as a function of current for the quick-break contacts, while the lower curve shows the same relation for the grids. The large arc energy and the scattering of the points in the upper curve illustrate the inefficiency and lack of control of the deionizing agencies inherent in the less effective use of oil hitherto obtained.

Slepian[4] points out in his paper that the rate of gas generation just preceding the point of extinction is the important factor, rather than the total arc energy or the average arc power over the arcing period. In other words, the effectiveness in raising the breakdown value of the arc path is a direct function of the rate at which turbulent, cool, un-ionized gas is thrown into the hot ionized gas of the arc stream. It is therefore evident that not only the rate of gas generation, but the effectiveness with which all the gas generated is directed into the arc stream determines the efficiency of the oil circuit breaker as an interrupting device.

In the design of the grids, it is the aim to keep the arc energy to a minimum, the gas generated low, and therefore eliminate excessive and unnecessary oil deterioration and the possibility of high and dangerous pressures. In one set of 95 single-phase interrupting tests at currents ranging from 250 to 4500 amperes, the majority of which were in excess of 1000 amperes, and at voltages between 38 and 88 kv. the voltage gradient necessary to break down the oil was reduced from 28 kv. per tenth of an inch before the tests to 25 kv. per tenth of an inch after the test. This slight deterioration of the oil together with the small amount of burning of the arc drawing members and the perfect condition of the grids indicated that the breaker was still in condition for continued interrupting service.

Since the gas generated, and therefore the total pressure developed in the tank, is proportional to the arc energy, it is evident that with the grids, they will be less than in the more conventional type of oil breaker. While at heavy currents the forces generated within the grid assumes larger proportions, these forces are confined to the grid itself except for the reaction of the gas stream passing out the open end of the groove after traversing the arc space. The main force may be assumed as having its origin in the iron circuit of the magnetic field, that is, the field exerts a primary force on the arc, which is transmitted to the entrapped oil and gas in the groove. The oil and gas in its attempt to move away from the arc exerts a force on the closed end of the grid, which in turn is transmitted back to the iron plates. No distortion or movement of the stacks was noted in a series of interrupting tests over the current range up to 15,000 amperes at 13,200 volts and 6000 amperes at 69,000 volts.

## Field Tests

At the time this paper was prepared the deion-grid has been subjected to field tests on only one operating system. These tests were divided into two series, both of which were made on a 66-kv., 60-cycle overhead transmission line, the maximum short circuit current available being approximately 7000 amperes. A three-pole, 600-ampere, 110-kv. electrically-operated oil circuit breaker already installed was equipped with grids and used for both series of tests.

Practically all tests were on the open-closed-open cycle of operation and were made for the most part in sets of three interruptions with a pause for changing films in the oscillograph. As a measure of the duty to which the breaker was subjected, it may be noted that on one series of tests 40 circuit interruptions were made within an elapsed time of one hour and forty-four minutes, one pole of the breaker being involved in 30 of these interruptions.

Both series of tests involved single-phase and three-

phase short circuit interruptions, the single-phase tests being made at 42,000 volts line-to-ground except for 10 tests which were made at 69,000 volts line-to-line. All three-phase tests were made with the system neutral grounded through resistance.

The first series of tests involved 35 short circuit interruptions, 12 of which were on a three-phase basis, the remainder being single-phase line-to-line and line-to-ground. Current values for the three-phase tests ranged from 2500 to 5500 amperes, and for the single-phase tests from 1000 to 7000 amperes. The average duration of arcing for the 35 tests was approximately 1.8 cycles, which means that interruption was being obtained in less than one-quarter of full contact separation when opening at approximately 7.5 feet per second (average lift rod speed). No oil was thrown on any of these tests, and no other disturbance was noted as an indication of heavy duty on the breaker. The average dielectric test of the oil for the three poles before the start of the tests was 24, 20, and 22 kv. and at the completion of the series of 35 tests was 20, 17.7, and 18.3 kv., the same oil being used for all tests. This shows an average decrease in dielectric test of 3.3 kv. for the complete series. The grids showed no indications of depreciation except for a trace of carbon between the interstices of the grid plates, and no maintenance work whatever was performed on the breaker before the following series of tests, except to renew the oil in order that comparative results between the two series of tests might be obtained.

The second series of tests consisted of 50 short circuit interruptions, 10 of which were on a three-phase basis, the remainder being single-phase tests line-to-ground. Current values for all tests ranged from 1000 to 3900 amperes. The average duration of arcing for the 50 tests was approximately 1.9 cycles, the minimum and maximum duration being 1.0 cycle and 3.5 cycles, respectively. In this series of tests the average lift rod opening speed was about 7.7 feet per second, which means that interruption was being obtained at one-fourth of full contact separation. The dielectric test of the oil before the second series of tests was 21.6, 22, and 21.7 kv. for the three poles, while at the conclusion of the tests it was 21.6, 21, and 21.3 kv., the same oil being used for the complete series of tests. This shows a negligible decrease in dielectric for the three poles, and it is quite apparent that the breaker might have been subjected to a repetition of the complete series without the oil being deteriorated to the point of requiring renewal. The grids showed no indications of depreciation from the two series of tests beyond a trace of carbon lodged in the interstices of the grid plates and were in a condition to continue interrupting service without maintenance. No repairs or alterations were made in the grids at any time during the two series of tests.

In view of the fact that rupturing tests involving such numbers of circuit interruptions would have resulted in marked oil deterioration as well as depreciation of the contacts with hitherto conventional oil circuit breakers, these tests are regarded as demonstrating the far superior efficiency of the grids in making more effective use of oil in arc rupture. They may also be regarded as substantiating the theory previously laid down in this paper, that an oil circuit breaker is working at maximum efficiency when and only when the rate of gas generation is high and when all of the gas generated is made to pass into the arc stream before being allowed to escape.

## Conclusions

The results of over 2000 short circuit tests with currents ranging from 20 amperes to 15,000 amperes, and at voltages of from 13,000 to 176,000 r. m. s. across a single pair of contacts, have demonstrated the effectiveness of the deion-grids as a means of making more efficient use of the oil in arc rupture. Consistent rupturing performance of from 60,000 to 100,000 r. m. s. recovery volts across a single pair of contacts has been obtained in from five to six inches of contact separation on a circuit in which "overshooting" up to 100 per cent above nominal recovery voltage is a common occurrence. A series of 50 interrupting tests has been made on a field circuit with current values ranging from 1000 to 7000 amperes and with 42,000 r. m. s. recovery volts across a single pair of contacts, the oil at the end of the series showing only a slight diminution in dielectric test and being ready for further interrupting duty without any maintenance work being required. The arc energy dissipated is reduced to a fraction of that obtained with the hitherto conventional form of circuit breaker, and internal pressures are reduced to such an extent that on a majority of the tests made with one breaker in the development of this device, only half the tank bolts and man-hole coverplate bolts were in position and no special attempt was made to pull even these bolts up tight.

With the duration of arcing on a slow speed (8 ft. per second) circuit breaker in the transmission class of voltages reduced to two or three cycles, the grids appear to be particularly applicable where system stability problems are present. Dependable relays are in service today which will detect a short circuit and energize a tripping coil within one-half cycle on a 60-cycle wave. With these two elements known, of the total time necessary to detect and interrupt a short circuit, there remains only the design of an adequate mechanical linkage with suitable acceleration to obtain consistent interruption of short circuits over the range of destructive current values within the time found to be necessary to insure stability of any given system.

With the use of deion grids, circuit interruption within ten to twelve cycles of short circuit should be obtained consistently at the higher transmission voltages with the conventional mechanical design now supplied in breakers for this class of service. Interruption within seven to eight cycles of short circuit in the

same class of voltages seems to be quite feasible at a moderate increase in cost of the breaker. Breakers designed for speeds of operation higher than this require careful attention in design and manufacture, with the use of high grade materials and the cost must necessarily increase rapidly as the period of short circuit duration is decreased.

The predominating field of usefulness for the grids would seem to be in breakers designed for service in the transmission class of voltages, say from 50,000 volts upward. For the generating class of breakers where the applications are largely indoors and the use of oil in switching service becomes a potential hazard, the deion breaker, operating without oil, and with its short duration of arcing, seems best adapted for use where questions of stability demand that faults be cleared with a minimum duration. For the higher-voltage outdoor applications where the potential hazard of oil is much lessened, the grids with their greatly improved rupturing performance and their vast decrease in maintenance requirements, seem particularly well adapted.

No discussion of this development would be complete without a word of appreciation for the assistance and cooperation of those associated with the authors in carrying out this development work, particularly to Messrs. L. W. Dyer, E. G. Kees, and H. L. Rawlins for their arduous and exacting labor in conducting short circuit tests; to Mr. W. M. Leeds for his careful and searching analysis of test results, and to Mr. L. Denault for his painstaking study of details.

## Discussion

### EXTINCTION OF A LONG A-C. ARC

(Slepian)

### USE OF OIL IN ARC RUPTURING

(Baker and Wilcox)

New York, N. Y., January 27, 1930

**R. D. Evans:** The recent developments in high-speed breakers as described by Messrs. Slepian, Baker, and Wilcox will be of particular importance from the standpoint of limiting the effects of disturbances resulting from faults. In this connection, results of calculations showing the benefits of high-speed breakers and relays may be of interest.

Fig. 1 herewith indicates the basis of the calculation and some of the results. The diagram gives the distribution of reactance taking the over-all reactance as unity.

The system is typical of long-distance transmission. The fault is assumed to be on one line near the high-voltage bus at the sending end and is cleared by the opening of the two breakers simultaneously. The calculations were made for the four different types of fault shown. The curves are plotted in terms of the time required for the isolation of the fault, and the ratio of the power can be transmitted to the power limit corresponding to the switching out of one line. The dotted lines show the loads which can be carried with sustained short circuits of the various types, assuming quick response excitation systems capable of preventing demagnetization of machines.

It may be pointed out that the conventional high-voltage breakers and relays are so slow that from the stability point of view the limits correspond to sustained faults. Thus the increases in power limit through the use of high-speed breakers are readily shown by comparing the dotted line values for slow-speed breaker, with the solid line values which correspond to various operating times of high-speed breakers. It should be understood that the calculations are based on the most severe fault location. The curves have been based on the isolation of the fault in a single step. For sequential operation, the individual breaker time will be less than that shown but need not be reduced to half value. This, of course, is due to the fact that the stability conditions are generally much improved when the first breaker operates.

The curves, although based on long-distance transmission, apply rather generally, provided the power limit for the switching operation be taken as the basis. The most important connection is due to inertia. The curves assume hydro type generators and receiving end machines of relatively high inertia. If the receiver is of low inertia the time scale may be reduced to perhaps 70 per cent of the values shown. On the other hand for sending end machines of the steam turbo generator type the time scale should be doubled. Of course, for short transmission lines, the switching limits closely approach the steady state limits. In any event for long or short transmission it is necessary to maintain an adequate margin to insure stability under the normal steady state conditions.

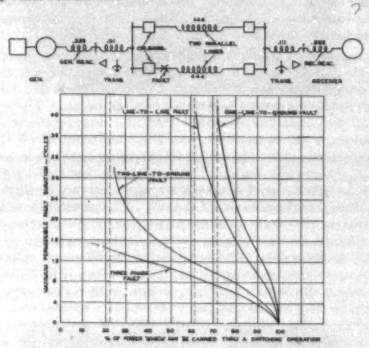


Fig 1—Relation Between Speed of Fault Isolation and Transient Stability Limits

High-speed breaker and relays offer great promise for improving stability conditions. They tend to reduce all faults to main switching operations. They make it possible for systems to withstand very severe faults, such as three-phase short current which otherwise would frequently be impossible. One can confidently predict that high-speed breakers and relays will find extensive application.

**R. M. Spurck:** The studies described by Dr. Slepian are of assistance in explaining many of the results obtained from high-voltage circuit interrupting apparatus, particularly oil circuit breakers.

Messrs. Wilcox and Baker are to be congratulated on their ability to utilize these theoretical studies of Dr. Slepian in the development of the improved oil circuit breaker they have described.

Inasmuch as the breaker described by Messrs. Wilcox and Baker was no doubt undertaken primarily to meet high-speed operation requirements dictated by the necessity for system stability, it is not unusual that other similar independent investigations were in progress. These investigations led first to the development of the all-insulated moulded explosion chamber and also gave data which resulted in improving the operation of the explosion chamber on high voltages.

In order to determine the effect of the improvements under system conditions, interrupting tests at 220,000 volts were made during the past summer at the Plymouth Meeting Station of the Philadelphia Electric Company. Although both closing-opening and opening tests were made, it is particularly interesting to note the results obtained during the opening tests. Fourteen such tests were made at short-circuit currents ranging from 1200 amperes to 3100 amperes. The system voltage varied from 222 kv. to 271 kv. The equivalent short circuit kv-a. varied from 500,000 kv-a. to 1,300,000 kv-a. In these tests the minimum arcing time was 0.5 cycle, the maximum arcing time 4 cycles, and the average 2.25 cycles. No pressure was obtained above the oil during these tests. Values of volts per inch of contact separation were in a number of cases in excess of 15,000 volts. Other tests made at other voltages indicate that these favorable results will apply to all high-voltage systems.

**Philip Sporn:** In connection with the papers of Dr. Slepian and Messrs. Baker and Wilcox, I should like to emphasize one feature of the construction here utilized for extinction of an arc. The deion grid gives, so far as I know, the first structure in which the force tending to disrupt the arc increases with the arc travel. In other words, the number of elements that are introduced tending to act favorably on the extinction of the arc increases as the contacts travel away from each other.

The question of stability discussed by Mr. Evans is important, but I should like to point out that this design, as well as any other designs that will accomplish the same thing, for the first time gives the operator a semblance of a fair break. There is no question but that the standard Institute duty cycle is not a satisfactory cycle considered from the standpoint of oil circuit breaker maintenance. Many of the breakers that are in service today, and that have been built to conform to that cycle, actually have to be taken out of service after rupturing two or three arcs due to heavy carbonization of the oil. The possibility of being able to forget the breaker after as many as 50 or 100 interruptions, will, I am sure, be welcomed by every operating engineer.

**H. G. McDonald:** You have heard Dr. Slepian explain the theories evolved from his study of long a-c. arcs. Mr. Baker has shown how he has combined these theories with certain principles of magnetic field action and has worked out a mechanical structure known as the deion grid which under laboratory tests gave promise of being the most effective circuit interrupting device ever produced. How will this deion grid device perform under the crucial test of operation on an actual modern high-power system? Mr. Baker in his paper has given the result of a set of field tests on 66 kv. which were available at the time his paper was prepared. Several of the largest operating companies evinced their fine spirit of cooperation by offering facilities for further testing the new device against the greatest power concentrations and on the highest voltages ever used in circuit breaker tests.

Two of the largest systems in the world in their respective classes and one of the highest voltage systems in the country placed large blocks of power at concentration points at the disposal of the Westinghouse Company.

The Duquesne Light Company's 66-kv. system furnished 240,000 kv-a. of test power. The Alabama Power Company's 110-kv. system concentrated 525,000 kv-a. in generator capacity and an additional 47,500 kv-a. in synchronous load in their Bessemer Station. The Philadelphia Electric Company segregated from their load 500,000 kw. of combined steam and hydro generation and an open end 48-mile transmission line as a test set-up.

In all cases tests were arranged to cover a wide range of current values up to the limit of the available power. Complete records were made of all phenomena connected with tests. Repeated tests were made on all set-ups, this being essential to establish the sufficiency of a new device. In the 66-kv. and 110-kv. tests, old breakers which had been in service for 8 or 9 years were stripped of the old contacts and the new deion grid contacts substituted, but no effort was made to make modern structures out of them or to obtain high speed of contact travel. In the 220-kv. tests, a unit duplicate of the breakers in use at Conowingo was used with the deion grids replacing the old contacts and with an increased speed of contact travel. Contact travel on the 66-kv. breaker was at rate of 8 to 9 ft. per sec., on the 110-kv. breaker 5 ft. per sec., and on 220 kv., 14 ft. per sec., all slow or moderate speeds. Tests were made phase to ground—phase to phase—and grounded and ungrounded to get all operating conditions.

66-*Kv. Tests.* On 66 kv. a total of 85 tests was made at currents from 1000 to 6970 in all combinations of CO—OCO—single-phase to ground, three-phase, phase to phase across a single pole, etc. On the first two days 38 tests were made without inspection of breaker during tests. Reclaimed WEMCO "C" oil used, testing 24-22-20 from the 3 tanks before. After tests, 21-18-18.5 from the same locations. Average arcing time 1.9 cycles. Average length of arc 6 in. (2 arcs in series) or at rate of 7000 to 10,000 volts per in. Compare this with 1500 to 2500 volts per in. on conventional breaker on same circuit. On third day, 50 tests were made in 2 hr. and 18 min. total elapsed time. Current range 1000 amperes to 3700 amperes, without inspection. Oil tests after practically same as before. Inspection after tests showed no deterioration on deion grids and only very slight burning on contacts. To observers accustomed to witnessing circuit breaker tests, the absence of any evidence of distress, oil throw, or motion of breaker on its foundation was a revelation.

110-*Kv. Tests.* The 110-kv. series consisted of 14 tests at currents from 900 to 3800 amperes CO and OCO—three-phase ungrounded, line to ground and line to line across single pole. On the three-phase tests the arc kv-a. interrupted, 692,000 was 115 per cent of breaker rating. The line to line across single pole tests were at a three-phase equivalent of 1,170,000 kv-a. or practically double the rating. Average arcing time 1.5 cycles. No distress on breaker; oil test same after tests as before. To demonstrate absence of oil expulsion a sheet of white paper was placed beneath each of the free vent pipes. At completion of series of tests, no trace of oil was found on any of the papers. Inspection of the deion grids after tests showed no deterioration; small burning on arc drawing contacts.

220-*Kv. Tests.* Three sets of 220-kv. tests were conducted,—56 breaker operations in all. The first set of 16 tests consisted of CO and OCO tests, line to ground, currents ranging from 1100 to 2950, followed by 5 tests with full 202 kv. across the S. P. unit for purpose of obtaining data on application of deion grids on 330 kv. The line to ground tests showed an average arcing time of 2.8 cycles, an average short-circuit time of 8.5 cycles including one cycle relay time, or 7.5 cycles from energizing trip coil to arc extinction. The 4 CO tests at full 220 kv. cleared without distress and the OCO test cleared but with somewhat longer arcing time than desired. The second set included 12 line to ground tests, 1100 to 3300 amperes and one full 220-kv. test. This 220-kv. test was unsatisfactory due to improper venting of the grid stack. A third set of tests was arranged to clear up this defect. This third set of tests again covered the entire range from 1100 to 3300 amperes in 16 tests, CO and OCO, phase to ground, and 7 additional satisfactory tests with full 220 kv. across one pole with 2200 amperes. Note that the set of 23 tests was made without inspection and that the more severe line to line across the single pole tests were made after the 16 line to ground tests. Oil samples before the set showed 23 kv. on 2 samples and after the set 2 samples showed 28.9 kv. It is not claimed the oil is improved by circuit interruption but it does show negligible oil deterioration. The deion grids were inspected after the set of tests and showed practically no deterioration. The stacks were subjected after tests to one minute voltage test of 300 kv. without failure.

Analysis of records of the tests on these three systems reveal several outstanding features.

1. Short time of arcing.
2. Short time duration of short circuit.
3. Very low arc energy.
4. High interrupted volts per inch of travel.
5. Small contact burning.
6. Negligible oil deterioration.
7. Practical absence of measurable pressure within breaker.

Equally as important as the diminished stresses in the breaker structure is the assurance that short circuit time is so reduced as to provide easy solution to problems of system stability. Further, the hazard which has become associated with oil circuit breaker operation has been largely eliminated by the performance without oil throw and without flame or violent gas ejection.

**E. C. Stone:** It is believed that this is a very important development in circuit breaker design.

Last fall the Duquesne Light Company performed a series of system tests on a Westinghouse 115-kv. G-2 circuit breaker equipped with deion grids. The original rating of this breaker was 7200 amperes at 66 kv.

A run of standard duty cycle tests (2-000 each test) was made on this breaker starting with 1250 amperes and running up to 7400 amperes. Seventeen tests, 34 shots in all were made, the last four shots being above 7300 amperes. No changes were made during the entire run either to the contacts or oil. The above tests were run with a six-in. mechanism.

At the end of each run the deion grid was in as good shape as at the start, the arcing contacts were not unreasonably burned, and the oil dielectric had dropped only from 22 kv. to 16 kv.

At a late date another test was made with the old four-in. mechanisms. This group of tests consisted of twenty-five, 50 shots, with currents ranging from 1140 amperes to 4300 amperes.

It must be concluded that this type of breaker goes a long way toward solving the problem of multiple short circuit interruptions without inspection and maintenance work after each duty cycle.

**D. C. Prince:** From the research standpoint, these two papers bring up two aspects of switching of comparable importance. In the first place, Dr. Slepian has presented very valuable studies of what actually goes on in a long arc, with his interpretation of how these phenomena can be taken advantage of in a certain way.

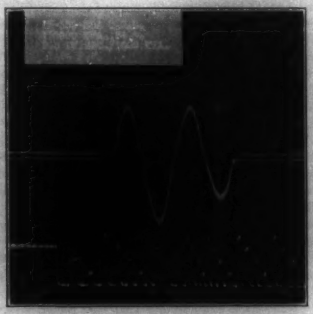

Fig. 2

Messrs. Baker and Wilcox have elaborated on the actual method employed by them. It is submitted that there are at least three different ways in which a-c. arcs may be ruptured by a switch. For instance, the losses in the arc may be run up by various means such as introducing obstacles, plates, chutes, explosion chambers, and the like, as described by the authors of these papers and covered by them. Or, without introducing unnecessary losses into the arc, advantage may be taken of the very brief period during which the current is zero, and there is no great voltage across the switch terminals to whisk the arc products away. Or in the last case, a rectifying device may be introduced into the circuit, in which case as soon as the current naturally attempts to reverse it will be prevented from so doing.

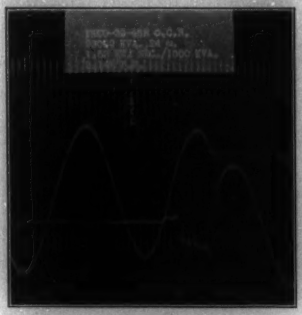

Fig. 3

In any case, the measure of the switch, the amount of material that must be supplied, is going to be determined by the amount of energy which this switch and its contents have to absorb.

Fig. 2 is presented for the purpose of reference and shows the operation of a plain break, oil circuit breaker of the usual type. The highest trace shows the arc voltage; the second shows the short circuit current. In this case it will be apparent that the arc voltage is gradually building up and consequently a considerable amount of energy is liberated in the switch. The actual figure in this case is 9.3 kw. sec. per 1000 kv-a. ruptured.

Fig. 4

The corresponding explosion chamber is covered by Fig. 3. The difference between the explosion chamber and the plain break is that the explosion chamber introduces very vigorously

into the arc a considerable quantity of oil and the arc energy is run up rapidly, but only for a very short time, because the circuit is then interrupted. The arc energy in this case is 1.52 kw. sec. per 1000 kv-a. interrupted, as compared with 1.23, the figure which I have calculated from Fig. 10 of Messrs. Baker and Wilcox's paper.

Fig. 5

As an example of the third class, Fig. 6 shows an oscillogram taken from the vacuum switch. The vacuum switch operates as a rectifier so that at the first reversal of current there is no possibility for the current to be reestablished in the other direction and the circuit is clear, the conditions for the conduction in the first place having passed by then.

The conditions under which these two sets of tests were made are of course very decidedly different; although it is not possible to reconcile them absolutely, at least it is apparent that the effectiveness of the two switches is of the same order.

Fig. 6

Fig. 4 shows for comparison an air break switch of the arc chute type. In this case the arc energy is somewhat larger, being 2.48 kw. sec. per 1000 kv-a., interrupted. It is apparent that the arc drop is rising progressively as the arc is drawn out into the chute.

Fig. 5 shows a special explosion chamber which is now being tested, and attempts to operate on the second one of the principles described, namely, that the arc products are whisked away in the interval that the current is substantially zero. It will be apparent that there is practically no arc drop on the film and the arc energy corresponds to only 0.48 kw. sec. per 1000 kv-a. interrupted.

It is possible to make independent tests on the losses in the vacuum switch, but taken on the scale at which these other tests have been made you can't see it.

We hope we shall have more information to present on these two types of switches as they approach a readiness for commercial application.

**J. B. MacNeill:** A year ago at the Winter Convention we placed before you an outstanding development in circuit interruption involving radically new and fundamental ideas of arc control in the deion air circuit breaker. Those papers covered laboratory investigations, high-power tests at the factory, and field tests on a large operating system.

Again it is our privilege to bring before you an outstanding development in circuit rupture, even more important, in a way, than the deion development because of the large commercial field it has been practicable to cover in a brief period of time. Here too you are given results of laboratory investigations, high-power tests at the factory, and field tests on some of the larger operating systems of the country for several of the more important transmission voltages, 66 kv., 110 kv., and 220 kv.

In the last year or two the most difficult problem that has faced the designers of switching equipment, has been that of securing high-speed circuit breaker operation at high voltages, where the moving parts of the device are relatively heavy and require time as well as great accelerating force to secure necessary separation of contacts for proper circuit interruption.

What could be more desirable at this time, therefore, than the invention of a method of circuit interruption which provides arc opening with a minimum arc length so that high-speed physical operation is not essential, and at the same time reduces arc energy to a small fraction of previous values, thus greatly reducing oil and contact deterioration, increases rupturing capacity, and reduces circuit breaker maintenance.

Dr. Slepian has told you of his investigations on the nature of long a-c. arcs. This investigation was necessary to a proper understanding of arc action, so that means for controlling the same could be evolved. Mr. Baker has told you of the manner in which he came to associate magnetic field principles with the ideas of arc handling in restricted slots and holes that Dr. Slepian has dealt with. It has been known for years that powerful magnetic action on an arc produced speedy and satisfactory arc interruption. The exact means by which this was accomplished has not been well understood previously. As far back as 1921 in a paper covering Baltimore tests, this magnetic blowout effect on arc action was discussed. Again in June of 1928 an outstanding application of this principle to secure high-speed circuit interruption was presented at the Denver Convention.

By a program of exceedingly ingenious experiments, Mr. Baker was led to associate the possibilities of such magnetic action with the handling of arcs in confined spaces, referred to by Dr. Slepian, and thus produce an oil circuit breaker which is a radical improvement over anything previously known.

Some months ago these ideas had been demonstrated to the extent of our high-power facilities at East Pittsburgh, and gave such promise that an elaborate set of field demonstrations was decided upon. It is unfortunate that the Baker-Wilcox paper had to be prepared before all of these field tests were completed. These tests, however, have been covered briefly by Mr. MacDonald. The outstanding conclusion to be drawn from them is, that here we handle arc voltage at the rate of 10,000 volts per inch of single arc length, and the arc energy is a small fraction of that obtained with previous circuit breaker constructions.

Let us see for a moment what we have here. First, a device built up of units in series, each unit being capable of handling approximately 10,000 volts, which gives us the ability to vary

the interrupting device at will, according to the voltage to be handled. Second, the length of the slot in the plate and the number of oil pools can be varied with the current to be handled, and also the design of the magnetic plate can be varied to secure the best results over the current range desired. Third, the range of physical speed of contact separation for which the device is good is very large, and there exists for each voltage the best physical speed readily obtainable without excessive inputs to the operating mechanism or excessive shocks to the breaker structure due to the closing and opening operations.

To summarize, therefore, we have individual factors of stack length, stack area, and physical speed to work with in combination, which is a condition that has never before been obtained on switching equipment, and which offers for the future a good hope for radical improvements in circuit interruption involving any speed yet found necessary for system stability, which reduces duration of arcing and of arc energy, and a minimizing of breaker maintenance due to reduced oil and contact depreciation.

**J. W. Bennett:** (communicated after adjournment) The paper presented by Messrs. Baker and Wilcox is very interesting in its description of the use of deion grids in the conventional type of oil circuit breaker. The results of their tests would seem to indicate that considerable progress is being made in the improvement of that hitherto weak link in the transmission system, the high-voltage oil circuit breaker. While the tests described in this paper indicate that the addition of the deion grids greatly improves circuit breaker operation, they should not be considered a remedy for all of the ills that have beset circuit breakers in the past. Additional tests of breakers, equipped with this device, on various operating systems, should be of interest.

**Joseph Slepian:** Mr. Prince's analysis of the ways in which an arc may be extinguished, recalls to my mind a sentence that I wrote in one of my previous papers and which I should now like to enlarge upon. I said that the arc in the circuit breaker, in general, is not merely a nuisance but that it plays a very necessary and useful role in the circuit interruption. The general tendency has been to regard the arc as entirely undesirable, to be eliminated if possible. But in that paper I said that if the arc had not appeared spontaneously we should have had to invent it, or a substitute for it which would take over the necessary functions of the arc.

There are two ways in which the arc may exercise its function: the one can be best illustrated by referring to a d-c. circuit. Suppose it were possible to open the contacts of a switch in a d-c. circuit without an arc, would that give us something satisfactory? As electrical engineers we know Faraday's Law of Electromagnetic Induction and use it for generating the voltage and current in our circuits. Although, during a short circuit, we change our minds about the desirability of generating electrical power at that particular moment, we do not expect Faraday's Law of Electromagnetic Induction to abrogate itself for our convenience, and then resume its sway after the short circuit, but expect it to operate right through the short circuit. Therefore we know that if it were possible to open the d-c. circuit instantly, without any arc, the instantaneous collapse of the magnetic field associated with the short circuit current would induce high voltages which would surely destroy our machines. Bearing Faraday's law in mind, we wish to interrupt the short circuit rapidly, but not so rapidly as to induce dangerous voltages.

Here then is the function of the arc in the d-c. circuit. In a well designed switch it opens the circuit not too rapidly, but just rapidly enough to be safe. The function of the arc in the d-c. circuit interrupter is to dissipate safely and harmlessly the magnetic energy stored in the current carrying circuit.

In the a-c. circuit, it would appear possible to avoid this embarrassment arising from Faraday's law because twice per cycle, there are moments of zero current, and at those moments of zero current there is no magnetic energy stored in the circuit. Therefore if it were possible to open the circuit at such a moment, Faraday's law would not be involved because there would be no magnetic field at that moment to induce voltage. If a switch is made in which the separating of the contacts is accurately timed to coincide or synchronize with a zero of current, then no arc would occur, and no arc would be necessary.

But consider how difficult it would be to construct a switch with this remarkable synchronized opening of the contacts. Consider all the variations in the relation between current and voltage phase which may occur in practise. Consider how difficult it would be to give the contacts, which necessarily have mass, an instantaneous velocity which would get them apart while the current is still zero. Now the arc relieves us of these exceedingly difficult electromechanical problems. With the arc in the switch it is not necessary to synchronize the opening of the contacts. The contacts may separate when they will, as the arc will permit the current to continue to flow. Then, if the switch is well designed, at a moment of current zero, the arc itself changes over from being a good conductor to being a good insulator, and the circuit is interrupted. Thus the arc, which occurs spontaneously, takes over this synchronizing function which it would be almost impossible to accomplish mechanically. In a-c. switches, we may choose to accentuate the one useful function of the arc or the other. Obviously, it is better to make use of the synchronizing function of the arc rather than the energy dissipating function, since the less energy dissipated in the switch, the better.

There are many ways of improving the synchronizing function of the arc, or increasing the tendency of the arc to change over to an insulator at current zero. Some ways are naturally better than others. All the practical ways so far developed also increase the energy dissipated in the period of arcing. This is unfortunate, but appears to be a necessary price we must pay. To have the deionizing means in the arc space when the current is zero, it is necessary, with such means as we now know, to put it there some time in advance. Because it is there some time in advance, the rate of dissipation of energy in the arc is increased.

There is one means, the vacuum switch, which does introduce a strong deionizing action at current zero without greatly increasing the deionizing action during the period of arcing. When such a switch is developed, it will be a question as to whether it pays to deal with vacuum apparatus, pumps, possibility of leaks, and so forth, for the sake of getting the ideal (from this standpoint) performance that the vacuum switch will offer.

At the present state of development of vacuum apparatus, I am inclined to think that it would not pay, that the reliability of the oil circuit breaker with improvements that we give it, is far greater than we can expect of any vacuum apparatus at the present time. The oil breaker depends for its functioning, upon the decomposition, at a rapid rate, of the oil by the arc. Nothing, I think, can be more certain than that the arc will always be hot enough to decompose oil rapidly. The vacuum switch, however, depends upon the maintenance of a high vacuum, and the maintenance of such a vacuum has a certainty of an altogether different order of magnitude than the certainty that the arc in the oil breaker will be hot. Therefore I am inclined to think that in spite of the more ideal performance of the vacuum circuit breaker, from the standpoint of energy dissipated, for a long time in the future we shall depend upon more fundamentally reliable, although less ideal, methods for deionizing the arc.

**H. M. Wilcox:** It is indeed gratifying to hear that others have also been engaged in a study of switchgear to meet the requirements of system stability. Mr. Spurck, unfortunately, is not able to give us any very extensive details of the switchgear he referred to, but mentions a result of 15,000 volts per inch, which is indeed a very good performance.

Mr. Baker pointed out, I believe, in presenting this paper, that the point that originally led to this investigation was the fact that it had been discovered that the then conventional oil circuit breaker was giving an interrupting performance of 10,000 volts per inch, or better, on certain types of circuit. The same breaker tested at the same voltage on other circuits was falling off very considerably. In the material that has been given you in the paper, care has been taken to give results, comparative results so far as possible, on the same type of circuit, which so far as laboratory results are concerned was a rather difficult circuit to interrupt.

While we may congratulate Mr. Spurck on the performance of 15,000 volts per inch, we may perhaps reserve decision until some further basis of comparison can be given as to the type of circuit.

Mr. Prince has given us some very interesting figures on kilowatt seconds of energy obtained with certain types of breakers. Once more, the type of circuit on which these tests were made is not quite clear. As I recall, going over the slides hurriedly, he showed results of from 1.5 to 2.5 kw-sec. per 1000 kv-a., or a ratio between arc energy and arc kv-a., that is, arc energy in kw-sec. divided by arc kv-a. interrupted, of from 0.0015 to 0.0025 if I have taken his figures correctly.

I should like to cite one or two figures from the material which Mr. MacDonald gave so far as arc energy is concerned, although that material was not included in the original paper. Making a comparison between the performance of the convention breaker hitherto used and a breaker equipped with this new device, the only real opportunity so far obtained is in the case of a 110-kv. circuit, in which a hitherto conventional breaker interrupted a three-phase short circuit of 3480 amperes, or about 221,000 kv-a. per pole. The arc energy resulting from that test was 2740 kw-sec., and the ratio, that is, arc energy in kw-sec. divided by arc kv-a. interrupted, is 0.0124, which compares favorably with the ratio of a similar breaker given by Mr. Prince.

On the same breaker tested on the same circuit, again a three-phase test, at 110,000 volts, with approximately the same current, there was 218,000 arc kv-a. interrupted, and the arc energy was 136 kw-sec. That is less than 5 per cent of the original arc energy, and the ratio of the arc energy in kw-sec. divided by the arc kv-a. interrupted, is 0.00062. These results were obtained in actual rupturing tests on an operating system.

# Calculation of Induced Voltages in Metallic Conductors

BY HERBERT BRISTOL DWIGHT*

Fellow, A. I. E. E.

***Synopsis:***—*A review is given of the rules and procedure used in electrical engineering for the calculation of induced voltages in metallic conductors, not including radiation effects. For the e. m. f. in a closed circuit* $e = -d\varphi/dt$, *the restriction is stated that the circuit is a closed loop of infinitesimal cross section and without parallel branches. More complicated circuits are to be calculated by replacing them by a number of elementary circuits. Where there are moving contacts and conductors of finite cross section, the rule* $e = B\,l\,v$ *should be used. A discussion is given of calculations by considering magnetic fields to have velocities and the restriction is stated that, in general, the resultant magnetic field should not be used with the* $B\,l\,v$ *rule, when it is made up of component fields having velocities which differ in magnitude or direction.*

* * * * *

A recapitulation of rules and methods for calculating induced voltages in metallic conductors, not including radiation effects, is desirable for use with the variety of problems encountered in electrical engineering. A careful wording of these rules, made as complete as possible, is needed in order to make them consistent.

It is believed that this paper does not present any general methods or rules for calculating induced voltages in conductors not already used by authoritative writers on electrical calculations. There are presented in this paper, however, certain restrictions which it is believed should be given along with the different rules for calculating induced voltages. These restrictions are moderate. The standard according to which they have been drawn up is that when a rule is found given in a textbook with certain wording, and when the plain, every-day meaning of the English wording can be applied to a definite problem so as to obtain an incorrect result, then a restriction is needed on the application of the rule or in the definition of its terms.

In order not to try to take away unnecessarily, from electrical engineers, useful and safe working tools, the writer has in no case stated that a rule must be discarded. It is believed that moderate restrictions are all that is required.

If it is believed by others that the restrictions presented herewith are not severe enough and should be made more sweeping, all that is required is for them to describe a practical and definite problem and show that the plain meaning of the rule with its moderate restriction gives a wrong result. This would probably still not be evidence that the rule should be discarded, but merely that the restriction should be re-worded.

It is not right for any one to say that a certain rule used by authoritative writers should be completely given up, merely because he has a more complicated alternative method of making the same calculation and so never needs to use the rule. It should be shown in addition that the rule is unreliable in definite cases, and that it is apparently impossible to make it reliable by re-wording it or restricting it.

For example, many books on elementary physics and electrical engineering give no hint as to how to calculate the e. m. f. induced in a short length of straight conductor by neighboring a-c. circuits, and yet such a calculation is described in other elementary books and the result is obtainable according to modern electromagnetic theory. As another example, many books do not mention moving magnetic fields, and yet many others describe the induced e. m. f. of an a-c. generator as caused by the magnetic lines of force of the poles moving along with the poles as they revolve.

The writer who would state that either of the above well-known rules should never be used by electrical engineers is attempting something much more radical than the mere statement of a moderate restriction. The rules are in sufficiently common use that a book which purports to give a complete statement of the calculation of induced e. m. fs. for electrical engineers should give a recommendation for or against their use. When such a book does not mention a certain rule used by engineers, one does not know whether to interpret it as a recommendation not to use the rule, or otherwise. The question of where the rules are reliable should be faced and not dodged.

There are many problems handled by the engineers by their working rules, which the physicists would find inconvenient to solve by Maxwell's equations unless they first proved some working rules, the same as or similar to the ones now in use. The physicists would do a real service to the engineers if they would prove some working rules and advocate them. This would automatically bring out the necessary restrictions.

According to Faraday's law, if there is any closed linear path in space and if the amount of magnetic flux surrounded by the path varies with time, then an electromotive force is induced around the path, which is equal in amount to the negative rate of change of the flux $\varphi$ in lines or maxwells per second. Thus,

*Professor of Electrical Machinery, Massachusetts Institute of Technology, Cambridge, Mass.

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$$e = -\frac{d\varphi}{dt} \text{ abvolts} \tag{1}$$

where $t$ is time measured in seconds.

The closed linear path or circuit is the boundary of a surface through which the magnetic flux passes. It is a geometrical line and has length, but no finite thickness. Since it is the boundary of a single area, it cannot have branches in parallel. At the time considered, it can be changing in shape or position. However, if it changes its position, this is done by moving from one position to the other and traversing the intermediate space.

If a loop of wire of negligible cross section occupies the same place, and has the same motion, as the path in space just considered, the electromotive force $-\frac{d\varphi}{dt}$ tends to drive a current of electricity around the wire. This electromotive force can be measured by a voltmeter or galvanometer connected in the loop of wire. As with the path in space, the loop of wire is not to have branches in parallel if the e. m. f. is to be given by Equation (1). In general, if the wire loop is not a closed linear circuit, of infinitesimal cross-section and without branches in parallel, it is not to be assumed that the e. m. f. in it will be given directly by Equation (1). The problem must be solved by starting with elementary parts to which the fundamental equations apply, and putting the results together as the conditions of the problem demand.

If a closed wire loop has branches in parallel, the problem of calculating the electromotive force indicated by an instrument is more complicated than the calculation of an e. m. f. only, and involves the resistance of the branches and the determination of circulating currents which in general will flow in them.

A metallic circuit having finite cross-section is equivalent to a number of filamentary circuits in parallel and for accurate results, the simple Equation (1) cannot be used directly. In some cases, a finite conductor can be divided into filaments, the induced e. m. f. and resistance of each of which can be computed. From these the average induced e. m. f. along the finite conductor can be determined. Such a calculation usually includes finding the current in each infinitesimal filament, and the total resistance loss. The problem will be recognized as being a skin effect or proximity effect problem. To assume that the current is uniformly distributed over the finite cross-section, and then to compute the average induced e. m. f., is only a partial solution, and one which is applicable only at practically zero frequency. Calculations of inductance using geometrical mean distances are of this zero-frequency type.

If a coil has $N$ turns of wire in series closely wound together so that the cross-section of the coil is negligible compared with the area enclosed by the coil, or if the flux is practically all confined within an iron core and so is enclosed by all $N$ turns alike, the e. m. f. induced in the coil is

$$e = -N\frac{d\varphi}{dt} \text{ abvolts} \tag{2}$$

In such a case, $N\varphi$ is called the number of interlinkages of lines of magnetic flux with the circuit.

The effect of the cross-section of a coil of fine wire is taken into account if $\varphi$ is taken equal to the average amount of flux surrounded by the various turns. It is to be noted that the average e. m. f. per turn in a coil made up of fine wires or filaments is the same whether the filaments are in series or parallel only if the filaments all carry equal currents. This provision is not true except at zero frequency for the case of filaments in parallel, that is, the case of conductors of large cross-section.

The minus sign in Equation (1) denotes that the direction of the induced e. m. f. is such as to produce a current opposing the change of flux. If the flux is changing at a constant rate, the e. m. f. in abvolts is numerically equal to the increase or decrease in lines in one second.

The change in magnetic flux referred to in Equation (1) may be due to a variety of causes: it may be due to relative motion between the coil and the portion of apparatus which causes the magnetic flux, as in a rotating field generator; it may be due to a change in the reluctance of the magnetic circuit, as in an inductor type alternator; it may be due to changes in the primary current producing the flux, as in a transformer; it may be due to variations in the current in the same coil in which the voltage is being induced, as in the case of self-inductance; or it may be due to change in shape occurring in a flexible secondary coil.

The restrictions given in this paper as to what is meant by a linear path or circuit for use with Equation (1) preclude the possibility of changing the amount of flux through the circuit by connecting on some parallel branches and disconnecting others. This, of course, does not induce an e. m. f.

When the flux $\varphi$ surrounded by a loop of fine wire varies with the time according to the sine law, we have

$$\varphi = \varphi_m \sin 2\pi f t \tag{3}$$

where $\varphi_m$ is the maximum value of the flux and $f$ is the frequency in cycles per second. From this we obtain by Equation (1),

$$e = -\frac{d\varphi}{dt} = -2\pi f \varphi_m \cos 2\pi f t \text{ abvolts} \tag{4}$$

In problems involving sinusoidal alternating currents, it is thus not necessary to calculate the rate of change of flux in a loop, but merely the maximum value of flux surrounded by the loop. This simplifies the calculations to some extent.

In making calculations of flux, use is often made of

Ampère's law that a magnetomotive force is produced around any closed linear path, equal to $4\pi$ times the current surrounded by the path, absolute units being used. Here, the linear path is a geometrical line and the current may have a finite cross-section. If a condenser is included in the electric circuit, as in Fig. 1, the current $i$ supplies charges $q$ and $-q$ to the plates of the condenser. Then, if the conductivity of the dielectric is negligible, and if appropriate units are used,

$$i = \frac{dq}{dt} = \frac{1}{4\pi}\frac{d\psi}{dt} \tag{5}$$

where $\psi$ is the dielectric flux passing from one plate to the other. A magnetomotive force is produced around a closed linear path, proportional to $\frac{d\psi}{dt}$, where $\psi$ is in this case the dielectric flux surrounded by the linear path. The quantity $\frac{1}{4\pi}\frac{d\psi}{dt}$ is called the displacement current. If a surface is taken of which the linear path is the boundary, the total m. m. f. around the linear path is the sum of the m. m. fs. produced by the

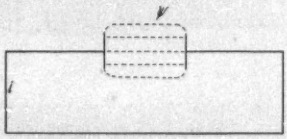



FIG. 1—ELECTRIC CIRCUIT INCLUDING CONDENSER

rate of change of dielectric flux $\psi$ crossing the surface and by the current $i$ crossing the surface.

While the e. m. f. $e$ is equated to $-\frac{d\varphi}{dt}$ in Equation (1), the two phenomena do not occur at exactly the same time. The e. m. f. at a distant place occurs after a lapse of time sufficient to allow the effect to travel from the first place to the second at a finite high velocity. There is a similar velocity in the case of m. m. f. produced by current. Such a velocity is involved in the calculation of radiation effects.

It is frequently convenient in electrical engineering to calculate the e. m. f. induced in a short length of conductor. It may be mentioned that such a result is obtainable according to modern electromagnetic theory, including cases of short conductors in the neighborhood of a-c. circuits. If a closed loop of very fine wire having no parallel branches, as described for Equation (1), is moved through a non-uniform magnetic field, which is not changing with time, the only way in which the loop of wire can surround additional magnetic flux is by cutting across magnetic lines of force. The induced e. m. f. around the loop of wire is equal to the net number of lines of force which have been cut across in such a way as to bring them inside the loop of wire. If there is assigned to each part of the wire an e. m. f. equal to the number of lines per second which have been cut across by that part of the wire, the familiar rule is obtained:

$$e = B\,l\,v \text{ abvolts} \tag{6}$$

where $B$ is the magnetic flux density in lines per sq. cm. at the location of the part of wire considered, $l$ is the length of the part of wire in centimeters, $v$ is the relative velocity between the portion of wire and the magnetic flux and where the directions of $B$, $l$, and $v$ are perpendicular to one another. If $B$, $l$, and $v$ are not mutually perpendicular to one another, their projections at right angles to each other are to be multiplied together so that $e$ is equal to the number of magnetic lines of force which cut the portion of wire per second. The wire is considered to be of infinitesimal cross-section, and the portion is sufficiently short that it can be considered straight and the magnetic field adjacent to it, uniform.

The following discussion gives a justification for the assigning of e. m. fs. to the parts of a loop of metallic wire which are cutting corresponding amounts of magnetic flux. It may not necessarily apply to cases where components of magnetic fields are considered to have different velocities.

Let a straight portion of wire of length $l$ lie in a uniform magnetic field $B$, considered stationary, whose direction is perpendicular to the wire. Let the wire carry equal positive and negative charges, $+e$ and $-e$ abcoulombs per cm. If the wire is given a motion sidewise at a velocity $v$ cm. per sec. in a direction perpendicular to the wire and to the field, the moving charges are the same as electric currents. Considering the positive charges first, the total positive charge is $e\,l$, the corresponding current is $e\,l\,v$, and the force exerted by the magnetic field is $B\,e\,l\,v$ dynes along the wire. The force acting on each unit positive charge is $B\,v$ dynes. Similarly, there is a force acting on each unit negative charge, of $B\,v$ dynes in the opposite direction.

Where there is a force of $B\,v$ dynes in one direction on each unit positive charge and an equal force in the opposite direction on each unit negative charge, absolute electromagnetic units being used, there is by definition an electric field of $B\,v$ abvolts per cm. The induced voltage between the ends of the portion of wire of length $l$ is $B\,l\,v$ abvolts.

Observations on flexible conductors and on streams of electrons show that the force exerted on a current or current-carrying conductor by a magnetic field, acts on the part which lies in the magnetic field. When this force appears in the form of an e. m. f. induced in a conductor, as described in the preceding paragraph, the e. m. f. is induced in the part of the conductor which lies in the magnetic field, and which moves with respect

to the field. See "The Theory of Electrons," by H. A. Lorentz, 1923 Ed., p. 15, par. 8.

The application of Equation (6) can be extended to other cases than that described by considering that magnetic flux can have a velocity. In electrical engineering, it is customary to consider the magnetic lines of force produced by an electromagnet or other magnet as moving along with the magnet when it is moved to new locations. For example, the magnetic flux associated with the poles of the rotating field of an a-c. generator is usually spoken of as cutting the stationary armature conductors and inducing voltage in them. It may be mentioned that it is frequently a help to deal with a complete magnetic circuit instead of only a portion of it.

A further extension of this general method can be made by using Equation (6) to compute the voltage induced in a short length of conductor by a short element of alternating current,[1] both the conductor and the element of current being of infinitesimal cross-section. According to the Ampère rule the magnetic field in air due to a short element of current lies in circles around the straight line in which the short element lies, radiation effects not being included. The strength of the field[2] at a point $P$ is

$$\frac{i\,d\,l \sin\theta}{r^2} \tag{7}$$

where $d\,l$ is the length of the element of the conductor which carries the current of $i$ abamperes, $r$ is the distance from the point $P$ to the element of current, and $\theta$ is the angle between the lines $d\,l$ and $r$. A rule can be used that when the current dies to zero, the circular lines of force collapse, each in its own plane, and in doing so each line cuts any conductors extending through that plane and induces voltage in them. For example, in connection with Equation (98), in Scientific Paper No. 169 of the Bureau of Standards, Washington, D. C., by E. B. Rosa and F. W. Grover, there is the following sentence: "The mutual inductance of two parallel wires of length $l$ . . . . is the number of lines of force, due to unit current in one, which cut the other when the current disappears." (See also p. 77 of "Theory of Alternating Currents" by Alexander Russell, Vol. 1, 2nd Ed.)

If the current varies as a sine wave, the total number of lines $\varphi_m$ which cut a conductor in a quarter cycle should be computed by integrating maximum flux densities from the conductor outward. The maximum voltage will be given by Equation (4). If effective flux is calculated from effective current, effective volts will be obtained.

A restriction is to be applied in dealing with moving magnetic lines of force when using Equation (6). The magnetic field is not to be the resultant of component magnetic fields having velocities in different directions or of different magnitudes, if the use of the resultant field does not give the same result as is given by the use of the component fields in the calculations. When the component fields are used, the e. m. fs. from them are determined separately and then combined.[3]

A simple example showing the need for this restriction when magnetic fields are considered to be in motion, is depicted in Fig. 2. A wire $A$ lies between two north poles of equal strength. The poles are moving in opposite directions, as indicated by the arrows, and each pole is considered to carry its own magnetic lines of force with it. The poles will induce e. m. fs. in wire $A$ in the same direction, and the total e. m. f. will be twice as great as that due to either pole alone. The resultant magnetic field at the location of $A$ is practically zero, and the correct e. m. f. induced in a short portion of $A$

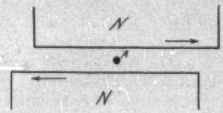



Fig. 2—Wire in Zero Resultant Magnetic Field

cannot be calculated by using the value of the resultant field. This is evidently a case where the e. m. fs. due to the component fields must be computed separately and then combined.

It may be mentioned that a small block of iron placed in the air-gap close to $A$ will not change the voltage which is being induced in $A$, if the block of iron is in a location where the resultant magnetic field is zero. The permeability of the iron depends on the resultant magnetic field.

Another example is the case illustrated in Fig. 3, where alternating currents $I$ and $-I$ are carried by two thin tubular conductors centered on the same axis. A wire $A$ is placed at the axis of tubes and is insulated from them.

Dividing the current $I$ into small elements of current each equal to $i$, the e. m. f. induced in $A$ by each elementary current is the same and is

$$j\,\omega\,2\,i \operatorname{logn}(u/a)$$

counting flux up to a certain large distance $u$, and writing logn to denote the natural logarithm. The quantity $\omega = 2\,\pi\,f$, where $f$ is the frequency. All such e. m. fs. are to be added together, giving a total

$$j\,\omega\,2\,I \operatorname{logn}(u/a)$$

Similarly, the e. m. f. induced in $A$ by $-I$ in the larger tube is

$$-j\,\omega\,2\,I \operatorname{logn}(u/b)$$

Adding the two e. m. fs. together, gives

$$j\,\omega\,2\,I \operatorname{logn}(b/a) \text{ abvolts per cm. of } A \tag{8}$$

1. "Elements of Electromagnetic Theory," by S. J. Barnett, p. 337.

2. "Elements of the Mathematical Theory of Electricity and Magnetism," by J. J. Thomson, 4th Ed., Art. 211.

3. "Induced Voltages in Conductors," by H. B. Dwight, *Electric Jl.*, April 1928, p. 174.

No matter how large a value of $u$ might be taken, the result would be the same.

The same result would be given by Equation (1) if wire $A$ as well as the two tubes, which are shown in cross-section in Fig. 3, were extended around so as to make closed circuits.

It is to be noted that wire $A$ lies in a region of zero resultant magnetic field and therefore the value of the voltage per cm. in $A$ given by (8) cannot be calculated from the value of the resultant magnetic field in which wire $A$ lies.[3]

Since an e. m. f. is induced in each centimeter of wire $A$, as shown by (8), the region inside the tube, although it has zero resultant magnetic field, is not in as quiescent a state as a region remote from all currents, where no voltage would be induced in a wire.

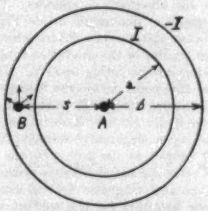



Fig. 3—Wire in Current-carrying Tubes

If a parallel wire is outside the smaller tube as in the position $B$, Fig. 3, the drop per cm. due to $I$ is

$$j\,\omega\,2\,I\,\log\mathrm{n}\,\frac{u}{s}$$

and the drop due to $-I$ is

$$-j\,\omega\,2\,I\,\log\mathrm{n}\,\frac{u}{b}$$

using the expressions for geometrical mean distance from a point to a circle excluding and including the point. The total drop is

$$j\,\omega\,2\,I\,\log\mathrm{n}\,\frac{b}{s}$$

This value is also obtained by integrating the total lines of the resultant field from $B$ to the outer circle. The component fields due to the filamentary currents making up $I$ in the inner tube are not all in the same direction, as is indicated by the three arrows pointing upward from $B$. The component fields due to the elements of current making up $-I$ in the outer tube point in every direction from $B$. If the wire is outside of both tubes, the e. m. f. is zero and the resultant field is zero. Evidently, when a wire is outside the inner tube, the e. m. f. is correctly calculated from the resultant magnetic field, but when the wire is inside the inner tube, the resultant field at the location of the wire cannot be used in calculating the e. m. f. in a short portion of the wire. The criterion is the calculation based on the fundamental expression for filamentary currents.

In the class of cases where there are sliding and moving contacts between conductors of finite cross-section, as in d-c. generators and motors, and in homopolar generators, of which the well-known Faraday disk is an example, Equation (6) should be used to compute the induced e. m. f. per cm. for the various parts of the

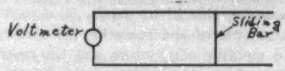



Fig. 4—Sliding Contacts with Infinitesimal Conductors

conductors. These e. m. fs. can then be summed up or integrated. In cases such as a d-c. machine or a homopolar generator, there is usually at all times a conducting path for current to flow, and this may quite properly be called a circuit, but it is not a closed linear circuit without parallel branches and of infinitesimal cross-section, and therefore it is not strictly allowable to apply Equation (1) directly to such a circuit. If such a practical circuit or current path be made to enclose more magnetic flux by a process of connecting in one parallel branch conductor in place of another, then such a change in enclosed flux does not correspond to an e. m. f. according to Equation (1), because the circuit is not the kind to which Equation (1) applies. Equations involving $d\,\varphi/d\,t$ are not to be used directly on circuits where there are sliding or moving contacts between conductors of finite cross-section or between conductors connected in parallel. Since practical conductors have a finite cross-section, and since sliding contacts in rotating machines, especially commutator machines, involve conductors connected at least temporarily in parallel, it seems advisable to adopt a practical rule not

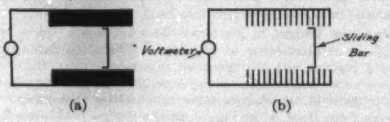



Fig. 5—Sliding Contacts with Finite Conductors and Parallel Branches

to use equations involving $d\,\varphi/d\,t$ where there are sliding or moving contacts.

A circuit containing sliding contacts which is frequently described, is shown in Fig. 4. The conductors have infinitesimal cross-section, and the e. m. f. indicated by the voltmeter can be calculated by both (1) and (6), the same result being obtained.

The case shown in Fig. 4 is often shown as a general case. In reality, it is a special case, and only such special cases involving sliding contacts can be solved by a single equation in $d\,\varphi/d\,t$. More general and

practical cases are illustrated in Fig. 5, (a) and (b), where conductors of finite section and parallel branches are involved. In Fig. 5 (b) all the conductors may be considered to have infinitesimal section, but because of the parallel branches and the sliding contacts it is not possible to equate the e. m. f. to the rate of change of the flux enclosed by the path for the current. The e. m. f. is proportional to the flux swept across by the moving bar; to calculate this e. m. f. an equation such as Equation (6), which distinguishes between the moving and stationary parts, should be used.

The statements of the rules for calculating induced voltages in metallic conductors and the restrictions to be applied to them, are subject to modification as new and unusual problems are investigated; in the form given in this paper they are not arranged to include voltages produced by radiated fields. Where the word "rule" is used, a practical method of calculation is signified. This is to be distinguished from a "law." The criterion to be used regarding induced voltages is a calculation by Maxwell's equations and the extensions of them given by modern electromagnetic theory.

## Discussion

**Joseph Slepian:** Professor Dwight is very successful in pointing out the unsatisfactory state of the theory of the induction of e. m. fs. by varying magnetic fluxes as taught to electrical engineers, but in my opinion he has been less successful in his attempt to make that theory satisfactory. The fault with the teaching of this subject to engineers, as I see it, is that engineers are not taught that varying magnetic fluxes have associated with them, or produce, electric fields in space, even at points remote from the generating magnetic fluxes. Professor Dwight makes no mention of this in his paper.

Engineers are taught that electric charges produce electric fields at points remote from the charges and where there may be no charge; they are taught that electric currents produce magnetic fields at remote points where there may be no electric current. But they are not taught at all that varying magnetic fluxes in the same way and in the same sense produce electric fields in space even at points remote from the generating varying magnetic flux and where there may be no magnetic field.

Professor Dwight in his paper does not define the e. m. f. which he is attempting to calculate. Where the definition of e. m. f. is given with any precision, it is usually this: the e. m. f. between two points taken along some path joining the points is the integral of the electric force taken along that path. The electric force itself, at any point, or the electric field intensity at that point, is defined as the force which acts upon a unit positive charge placed at the point in question, and *at rest there*. If the unit charge is moving, then in addition to the force due to the electric field, there is another force upon the charge, whose magnitude is given by the product of the velocity of the charge, the intensity of the magnetic field at the point, and the sine of the angle between the directions of the velocity and the magnetic field intensity.

This statement shows that there is a kind of relativity about the electric field, because the electric charge which is at rest relative to one observer, will be moving relative to another. The first observer ascribes all the force acting upon the charge as due to an electrostatic field. The second observer attributes some or all of the force acting upon the charge, which is moving relative to him, as due to the reaction of the magnetic field at the point in question upon the moving charge. To determine the electric field at the point, the second observer will observe the force upon a unit charge at rest relative to himself, but for the first observer, this charge will be moving, and he will in his turn ascribe some or all of this force to the reaction of the magnetic field upon the motion. Thus the two observers "see" different electric fields, for "seeing" electric fields means merely observing the motions, or the forces upon charged material bodies, and making deductions therefrom with an arbitrary assumption as to what body is at rest. Thus there will be different electric fields for different observers, and these electric fields will differ by the vector product of the magnetic force at each point and the relative velocity of the observers. However, it is not my intention to stress this relativity of the electric field but rather to point out what is necessary to give a logical and consistent picture of the electric field to a single observer. I mention the relativity because in one of Professor Dwight's examples which I shall discuss presently, there is confusion due to lack of recognition of this character of the electric field of being relative to the observer.

Let us now consider the e. m. fs. which are induced in stationary (relative to the observer) conductors. Professor Dwight discusses two examples, illustrated in his Figs. 2 and 3. In either of these cases, a stationary electric charge placed at the point $a$, that is at a point of the conductor subject to the induction, will experience a force acting upon it. Therefore, there is an electric field at that point, an electric field as real and existent as the electric field emanating from an electric charge. In fact it is the only kind of electric field there is, namely one deduced from the reaction upon stationary charges. Current will flow in the conductor subject to the induction due to the action of this electric field upon the mobile charges within the conductor. There need not be any magnetic field at the conductor; the electric field alone accounts for the current which may flow. The electric field may be calculated in known ways from the varying magnetic fluxes at other parts of space, and may be said to be due to these varying magnetic fluxes. To fail to consider its existence, and to attribute the force acting on charges in the conductor as due to the superposition of the effects of infinitely many component magnetic fields having all directions, and moving in all directions, is to present not only a confusing picture but one which is logically inconsistent with the definition of the electric field intensity at a point. When this electric field is taken into account, there is no room left for the reaction of these hypothetical moving magnetic fields upon stationary electric charges.

Let us now consider the case of a body moving (relative to the observer) in an unvarying magnetic field. Initially at least, there is no electric field, for a stationary electric charge experiences no force. There is therefore no e. m. f. anywhere, not even in the moving body. The charges making up the moving body will experience forces, but this is due to their motion in the magnetic field, and not to the presence of an electric field. If the body is a conductor, the charges will move due to these forces, and if the conductor is open, charges will collect at the ends of the conductor producing an electric field according to the principles of electrostatics. Evidently the electrostatic field will develop until it just balances the reaction of the magnetic field upon the charges at each point of the moving conductor. With the development of this electrostatic field there will be e. m. fs. between various points, in the conductor as well as elsewhere, and because this electrostatic field just balances the magnetic reaction, the e. m. fs. in the conductor can be calculated from the magnetic field and the conductor motion by the usual "cutting" rule.

Professor Dwight's calculation of the e. m. f. induced in the moving conductor which he presents on page 449 illustrates the confusion of thought which results from the failure to recognize that the electric field is relative to the observer. Quoting from his paper "Where there is a force of $B\,v$ dynes in

one direction on each unit positive charge and an equal force in the opposite direction on each unit negative charge, absolute electromagnetic units being used, there is by definition an electric field of $B\,v$ abvolts per cm." But, the definition of electric field referred to by Professor Dwight requires that the unit positive or negative charge which experiences the force $B\,v$ dynes shall be at rest. The charges will be at rest only for an observer moving along with the conductor. For him, and for him only, will there be an electric field, and for him there will be no reaction of the magnetic field upon the charges at rest (relative to him). For him there will be varying magnetic fields at points fixed (relative to him) in space, at the boundaries of the uniform magnetic field, and from these varying magnetic fields he can calculate the electric field which he observes.

But for the observer for whom the conductor is moving, and for whom the magnetic field is unvarying there is no electric field, but only the reaction of the magnetic field upon the charges in the moving conductor. The electric field and the magnetic reaction exist only the one for the one observer, and the other for the other observer, and not both simultaneously for either observer.

When speaking of moving lines of magnetic force it must be remembered that the lines of force do not have all the reality of material objects, but that there is much arbitrariness in how we place them. We draw them in merely as a convenience in depicting the magnetic field, and the only restrictions upon them is that their directions shall be that of the magnetic field at each point, and that they shall be so spaced that their density shall be proportional to the intensity of the magnetic field at each point. This still leaves much arbitrariness in the positioning of the lines and in ascribing continuous individuality to them. Thus for a uniform field we may imagine the lines of force executing the most complicated dance among themselves that we please, so long as we keep the lines straight and parallel and spaced with uniform density, for so long will they continue to represent correctly at each point the direction and intensity of the field. But we must not expect that this assumed motion of the lines of force gives rise or corresponds to any detectable reality, so that to ask whether these motions exist or not is to ask a meaningless question. Particularly we must not expect any reaction between these "moving" lines and stationary charges.

**L. V. Bewley:** My discussion of Professor Dwight's paper will be a comparison with the point of view given in my own paper, *Flux Linkages and Electromagnetic Induction in Closed Circuits.*[1] The scheme of classification is vividly represented by the "Family Tree of Electromagnetic Induction" shown in Fig. 1, the derivation of which is given in my paper. The principal features of this classification are:

1. A change of flux linkages due to a *substitution of circuit* is interpreted as $\varphi\, d\,n/d\,t$, and does not induce a voltage.

2. Faraday's Law of Electromagnetic Induction $n\, d\,\varphi/d\,t$ is universal and general. It includes any and every case of induction.

3. The occurrence of *transformer action* or of *cutting action* is entirely dependent upon the arbitrary choice of a system of reference axes. If the circuit moves as a rigid body, then by taking reference axes fixed to the circuit, the induced voltage may be computed as entirely due to the *variational component.* If the magnetic field is a rigid distribution, then by taking the reference axes fixed to this distribution, the induced voltage may be computed as entirely due to the *motional component.* If neither the circuit nor the magnetic field distribution remain rigid, then both the *motional* and *variational* components will necessarily appear in the expression for the induced voltage.

THE FAMILY TREE OF ELECTROMAGNETIC INDUCTION

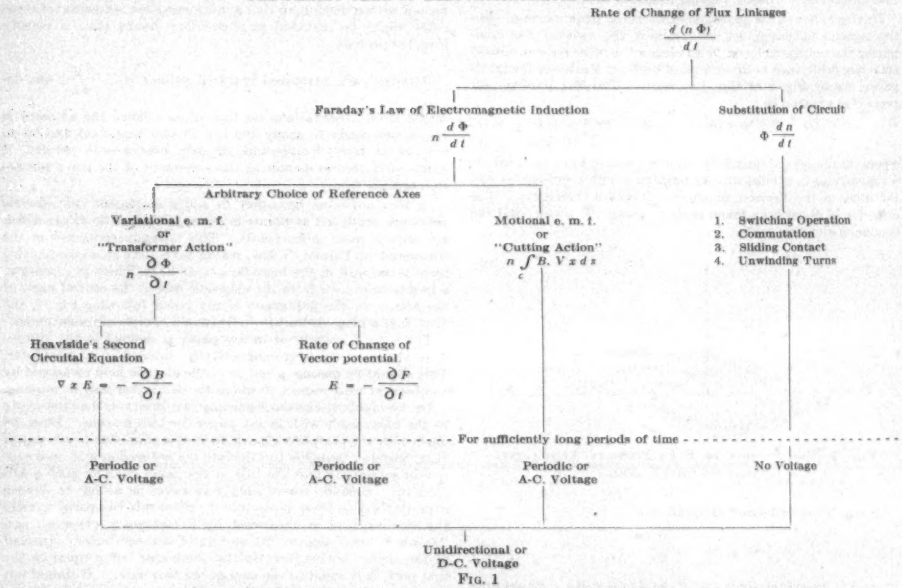



FIG. 1

1. A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 327.

4. The *second circuital equation* of Heaviside, and the *rate of change of vector potential*, both of which assign a definite induced voltage to each element of circuit, are specific expressions for *transformer action*. They are invoked in the computation of electromagnetic waves or radiation.

5. For sufficiently long periods of time, the induced voltage is either periodic or zero. A continuous unidirectional or direct voltage cannot be obtained (from electromagnetic induction) except through the agency of a substitution of circuit, although a substitution of circuit does not in itself generate a voltage.

General criteria for the induced voltage in any given case, and essential definitions of a *circuit* and of a *turn* will be found in my paper, as well as the derivation of the voltage induced in a circuit of any shape moving and changing shape at any variable rate through an arbitrarily varying magnetic field.

Having reviewed the general scheme of the phenomena of electromagnetic induction, let us establish the validity for computing the voltage induced in an element of wire by component traveling fields, such as illustrated in Fig. 2 of Professor Dwight's paper, or by Fig. 2 of this discussion. The flux density, expressed as a vector, is:

$$B = i\,\alpha + j\,\beta + k\,\gamma = i\,(o) + j\,[f_1\,(x + v_1\,t) + f_2\,(x - v_2\,t)\,] + k\,(o) \quad . \quad . \quad (1)$$

where for the sake of simplicity only two waves have been taken, —one moving in the direction of positive $x$ with a velocity $v_2$ and the other in the direction of negative $x$ with a velocity $v_1$. The direction of $B$ has been taken entirely along the $y$ axis, and the conductor along the $z$ axis.

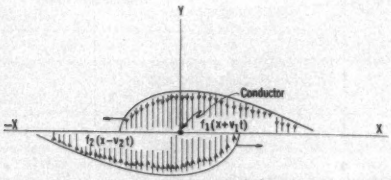



Fig 2—Distribution of Flux Density Along and Normal to the X Axis

Heaviside's second circuital equation is

$$\text{Curl}\,\bar{E} = -\frac{\partial B}{\partial t} \qquad (2)$$

where $E$ is the electric force and $B$ the flux density. Expanding (2) and substituting (1) there are the three scalar equations:

$$\left.\begin{aligned} &\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = 0 \\ &\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -V_1 f_1(x + v_1\,t) + V_2 f_2\,(x - v_2\,t) \\ &\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = 0 \end{aligned}\right\} \qquad (3)$$

And these have as a solution, compatible with the implied boundary conditions,

$$\left.\begin{aligned} &E_x = 0 \\ &E_y = 0 \\ &E_z = +v_1 f_1(x + v_1\,t) - v_2 f_2\,(x - v_2\,t) \end{aligned}\right\} \qquad (4)$$

But this is the same result as is obtained by applying the (BLV) rule separately to each component flux density wave, and superimposing the results. In particular, if $f_2 = -f_1$, and if $v_2 = v_1$,

$$f_1(o + v_1\,t) + f_2\,(o - v_2\,t) = 0 \qquad (5)$$

at the conductor; although by (4)

$$E_z = v_1 f_1(O + v_1\,t) - v_2 f_2\,(O - v_2\,t) = 2\,v_1 f_1(O + v_1\,t) \qquad (6)$$

thereby verifying Professor Dwight's conclusions, and rigorously establishing the rule for voltages induced by traveling distributions of flux.

It may be remarked that a distribution of flux can be considered as moving when it is expressible as a traveling wave.

**H. B. Dwight:** The chief purpose of my paper is to find a wording, complete with such restrictions as may be necessary, for the well-known fundamental rules used in calculating induced voltages in metallic conductors, not including effects connected with radiation, so that a more complete statement of these rules might be included in elementary books than is usually found at present.

Faraday's law, expressed by the equation $e = -\frac{d\,\varphi}{d\,t}$, was deduced from observations on fine wires. Since the attempt is sometimes made to apply the law in one single calculation to circuits of heavy conductors or with branches in parallel, it seems advisable to include in the statement of the law a restriction against this.

It does not seem necessary to add a statement that electric fields are produced at points in space by magnetic fluxes which are remote from those points. This is really contained in the statement of Faraday's law, which says that an electromotive force is induced in the boundary of an area, which is, of course, separate or remote from the magnetic flux at the central parts of the area. In the paragraph of my paper following Fig. 1, the e. m. f. at a place distant from the flux is specifically mentioned.

The e. m. f. calculated in my paper is defined in the title,—it is the e. m. f. electromagnetically induced in a conductor. This should be distinguished from the electric field measured by an observer with respect to whom the conductor may be moving.

Dr. Slepian's discussion regarding two observers does not apply to the rules dealt with in my paper for two reasons. First, he deals with the complete electric field at a point due to all causes. It is, however, possible to calculate the induced e. m. f. in a conductor separately and the title of the paper calls for such a calculation. Second, where only one cause is acting to induce e. m. f. in a conductor, he divides the effect into two parts, namely the electric field as measured by a stationary observer, and "another force" due to the motion of the conductor. Instead of the electromotive force in the conductor being equal to the first part, it is equal to the sum of the two parts. It should not be assumed that this indirect method is the only way to compute the induced e. m. f. in a conductor. The rules dealt with in the paper are used to a considerable extent and they take account of the motion of the conductor directly.

I wish to take exception to the statement of Dr. Slepian that there is no e. m. f. in a body moving in an unvarying magnetic field. When the directions are at right angles, the e. m. f. due to the motion is $B\,l\,v$, whether calculated by the rule of that name or by other methods. This is probably a matter of the meaning of the terms, but when positive charges are forced in one direction along a wire and negative charges in the other direction, there is an electromotive force in the wire. Further, as Dr. Slepian states, to an observer moving with the wire there is an electric field. The sentence quoted from my paper is in agreement with this. In refutation of Dr. Slepian's statement quoted in the first sentence of this paragraph, reference may be made to the second page of the paper by S. J. Barnett (A. I. E. E. Trans., 1919, p. 1496), where in connection with a moving

conductor it is said that "the electric intensity and electromotive force in the body due to the motion have been called the motional intensity and e. m. f. by Heaviside."

Mr. Bewley's discussion tends to confirm my conclusion that an extremely short statement of rules for induced voltage, without restrictions, cannot safely be used for practical problems about electrical apparatus. This is shown by the number of items given in his table. In contrast to Dr. Slepian's statement that there is no e. m. f. in a moving body in an unvarying magnetic field, Mr. Bewley describes the motional e. m. f. in such a case.

Mr. Bewley's use of Maxwell's differential equations with the application of boundary conditions to the problem of two traveling waves, is very interesting and it is noteworthy that he does not say that all problems, short or long, should be solved by this method. The method is powerful and reliable, and I believe that electrical engineers in this country would do well to follow the European example and make more use of this method. However, it cannot be expected that the simpler rules for calculating induced voltages in conductors will be completely given up, especially as they are being taught to twelve-year-old students in Junior High Schools, including the description of moving magnetic fields, and so it seems desirable to make the wording of these rules as safe and reliable as possible.

# Induced Voltage of Electrical Machines

BY L. V. BEWLEY[1]

Associate, A. I. E. E.

***Synopsis.***—*The object of this paper is to describe and discuss a general equation for the induced voltage of electrical machines having parallel coil sides, and which includes as special cases single and polyphase induction motors, synchronous generators, d-c. generators, synchronous converters, and static transformers. The application of the general equation to most of these cases is illustrated, and a number of interesting problems which may be solved by means of it is pointed out. A characteristic of this equation is that no restrictions are placed on the velocity of the moving conductors, or on the rates of pulsation and rotation of the flux; but these may vary in any arbitrary manner which can be given a suitable analytic expression. The several methods for the reduction of harmonic voltages are classified and their limitations discussed in such a way as to leave in mind a vivid picture of the process. Tables and curves have been prepared for comparing the effects of the skew, pitch, distribution, and phase connection harmonic reduction factors. A new method for summing the finite series of the distribution summations is given in Appendix II.*

## I. Introduction

THE purpose of this paper is to derive and discuss a general equation for the induced voltage of electrical machines having uniformly distributed parallel coil sides moving through a distribution of flux which can be represented by a Fourier series. The equation is general in that the circuit considered may have any number of phases connected in series in any arbitrary manner, and any particular phase may consist of any number of uniformly distributed, fractional pitch, skewed coil sides moving at variable speed through a distribution of flux which may pulsate and rotate at different rates. This equation includes as special cases the processes of induction found in the more familiar types of electric power apparatus, such as synchronous motors and generators, induction motors, d-c. motors and generators, synchronous converters, and static transformers. Because of its generality, this equation may prove awkward and unwieldy in dealing with a particular type of machine, since it was not derived with the idea in mind of adapting it to some special condition of symmetry affecting the choice of a coordinate system, or to the necessity of correlating with the related phenomena of currents, m. m. fs., and fluxes. There is an essential distinction between developing an equation for the complete analysis and determination of characteristics of a particular type of machine on the one hand, and deriving an equation whose purpose is to study the variation in process of some specific phenomena which occurs in several types of apparatus, on the other. In the latter case, greater flexibility is required, and the expression should be purged of all possible detail irrelevant to an understanding and classification of the ideas under consideration. For instance, certain facts become masked and obscured by the massive array of symbols associated with the complete harmonic analysis of a synchronous machine, involving the specification and manipulation of the Fourier series of currents, m. m. fs., permeances, fluxes, and voltages.

Incidentally, a study of the general equation derived in this paper permits making a critical review and classification of the available means for suppressing harmonics in the induced voltage by special arrangements of the windings. These special arrangements give rise to certain functions known as *harmonic reduction factors*, which enter the equation as ordinary coefficients. They are called, corresponding to the particular arrangement of the winding to which they apply, the *skew, pitch, belt distribution, and phase connection* harmonic reduction factors respectively. These same factors have an almost exactly analogous effect in suppressing the harmonics of armature reaction, but their consideration in that respect is outside the scope of the present paper. The full limitations of these factors are not generally appreciated. For instance, it is usually assumed that it is impossible to have a third harmonic in the line voltage of a three-phase synchronous generator if it is connected *Y*, or has coils of ⅔ pitch, or 120 deg. phase belts, or conductors skewed 120 deg. with respect to the pole; because each of these conditions is supposed to completely eliminate the third harmonic and its multiples. Yet such a harmonic will appear in the line voltage of a machine having all of these conditions, if there happens to be an even time harmonic in the air-gap flux. On the other hand, a third harmonic due to such a cause can be eliminated by a suitable arrangement of the winding. Now this is not a new discovery, but only the specialist would notice the fact in a treatise on the harmonic analysis of synchronous machines.

## II. General Discussion

If it is possible to express the distribution of flux in an electrical machine having parallel coil sides by the Fourier series

$$B = \sum_{1}^{\infty} \beta_k \sin k \left( \frac{x}{\tau} \pi + \gamma_k \right) \qquad (1)$$

then the most general equation for the induced line voltage, regarding $x_0$, $\beta_k$, and $\gamma_k$ as functions of time, is shown in Appendix I to be

1. General Transformer Engg. Dept. General Electric Co., Pittsfield, Mass.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

$$E_{line} = -2L\frac{\tau}{\pi}\frac{nN'}{10^8}\sum_{1}^{\infty} C_{sk}C_{dk}'C_{pk}C_{ck}$$

$$\left[\frac{1}{k}\frac{d\beta_k}{dt}\sin k\left(\frac{x_0\pi}{\tau}+\gamma_k+\psi_k'+\psi_k\right)\right.$$

$$\left.+\left(\frac{d\gamma_k}{dt}+\frac{\pi}{\tau}\frac{dx_0}{dt}\right)\beta_k\cos k\left(\frac{x_0\pi}{\tau}+\gamma_k+\psi_k'+\psi_k\right)\right] \tag{17}$$

where the $C$ coefficients are the harmonic reduction factors depending on the arrangement of the windings, defined in Table I.

TABLE I

| | Reduction factor | Seat of the reduction |
|---|---|---|
| Skew factor..... | $C_{sk} = \frac{\sin k\,\lambda/2}{k\,\lambda/2}$ | In the coil side |
| Pitch factor..... | $C_{pk} = \sin\frac{k\,p\,\pi}{2}$ | Between coil sides of the coil |
| Distribution factor of belt.... | $C_{dk} = \frac{\sin k\,c\,\delta/2}{c\,.\sin k\,\delta/2}$ | Between coils of the phase belt |
| Connection factor..... | $C_{ck} = \frac{\sqrt{(\Sigma\sin k\,\theta_r)^2+(\Sigma\cos k\,\theta_r)^2}}{n}$ | Between phases |

If the $n$ phases of the connection factor are uniformly displaced by the angle $\zeta$ then

$$C_{ck} = \frac{\sin k\,n\,\zeta/2}{n\sin k\,\zeta/2}$$

which is then in the same form as $C_{dk}$, and the same set of curves will serve for both. Moreover,

$$C_{dk} \simeq \frac{\sin k\,\delta\,c/2}{k\,\delta\,c/2} \text{ if } \delta\to 0 \text{ and } C_{ck} = \frac{\sin k\,n\,\zeta/2}{k\,n\,\zeta/2} \text{ if } \zeta\to 0.$$

Thus under these limiting conditions, the three reduction factors $C_{sk}$, $C_{dk}$, and $C_{ck}$ have the same form.

Associated with $C_{dk}$ and $C_{ck}$ are the distortion angles $\psi_k'$ and $\psi_k$ defined in Appendix I, and these cannot, in general, be made to disappear by a convenient choice of reference axes. In other words, a lack of symmetry and uniformity in the windings, or in the way that they are connected in series, will cause a distortion of the voltage wave by an angular shift in the relative positions of the harmonics, as well as by the reduction in amplitudes characteristic of symmetrical arrangements of the windings.

While these reducing factors have different names, they are in fact due to the same essential cause—the arrangement of the circuit so that the harmonic voltages produced in different parts are in partial or complete opposition and thus tend to cancel out over the complete circuit. Fig. 1 illustrates how this is accomplished in the case of a third harmonic.

If the conductor is skewed or spiralled so that half of it is cutting through a positive loop, and the other half through a negative loop of the harmonic of space distribution, then the voltage induced in the two halves of the conductor are always in direct opposition and therefore completely cancel within the conductor it-

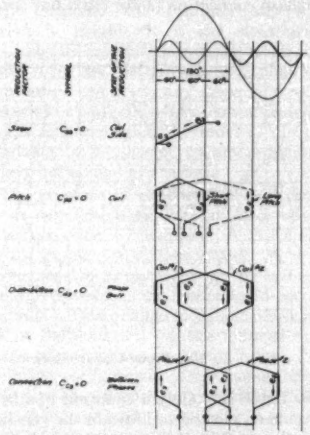


Fig. 1—Seat of Harmonic Reduction

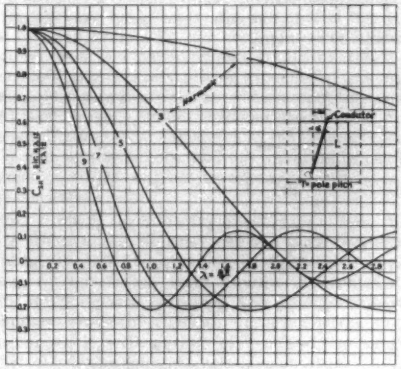



Fig. 2—The Skew Coefficient

self. The next simplest method of cancellation is to use a coil of fractional pitch so that both coil sides are cutting through positive loops of flux, but the voltages generated thereby cancel in the coil. In this case the coil may be either of short or long pitch. The distribution of the winding in more than one slot per phase

gives rise to a reduction of the harmonic voltages between the coils which make up the phase group. Finally, it is possible to eliminate those harmonics which are multiples of the number of machine phases, by connecting phases in series.

Representative curves of the skew, pitch, and distribution factors are shown in Figs. 2, 3, and 4 respectively, and the phase connection factor for a few simple cases

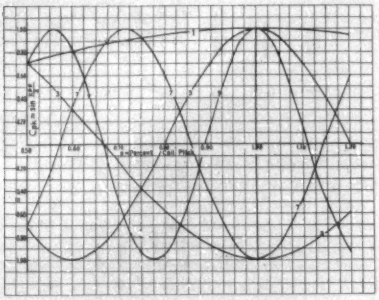


FIG. 3—THE PITCH COEFFICIENT

is given in Table II. Only a sufficient number of harmonics has been plotted to indicate the general nature of the functions. It will be noticed that the maximum value which any of these coefficients may have is unity, or more appropriately, their values lie within the range $(-1 \leq C \leq +1)$, because they have been defined as geometrical averages.

As a rule it is desirable to suppress as many harmonics as possible at the least cost to the fundamental. For all harmonics are more or less objectionable,

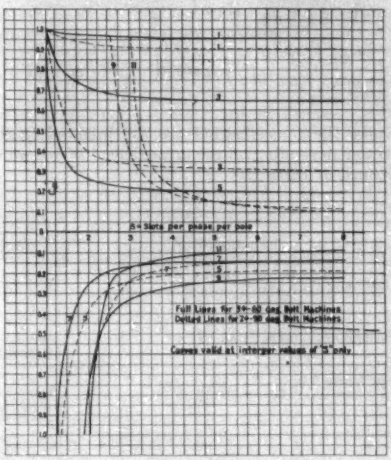



FIG. 4—THE DISTRIBUTION COEFFICIENT

but when they are suppressed in such a way as to reduce materially the amplitude of the fundamental it means more flux in the air gap, more excitation, and possibly higher losses, or even a larger sized

TABLE II

THE PHASE CONNECTION COEFFICIENT AND ANGLE

| Connection | $k$ = | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 φ Delta | $C_{ck}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | $\psi_k$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 φ Y | $C_{ck}$ | $\frac{\sqrt{3}}{2}$ | 0 | $\frac{\sqrt{3}}{2}$ | $\frac{\sqrt{3}}{2}$ | 0 | $\frac{\sqrt{3}}{2}$ | $\frac{\sqrt{3}}{2}$ | 0 | $\frac{\sqrt{3}}{2}$ | $\frac{\sqrt{3}}{2}$ |
| | $\psi_k$ | +30° | 0 | +30° | −30° | 0 | +30° | −30° | 0 | +30° | −30° |
| 2 φ | $C_{ck}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ |
|  | $\psi_k$ | +45° | −45° | +45° | −45° | +45° | −45° | +45° | −45° | +45° | −45° |
| 6 φ Star | $C_{ck}$ | $\frac{1}{2}$ | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ |
| | $\psi_k$ | −60° | 0 | +60° | −60° | 0 | +60° | −60° | 0 | +60° | −60° |
| 3 φ Zigzag | $C_{ck}$ | $\frac{3}{4}$ | 0 | $\frac{3}{4}$ | $\frac{3}{4}$ | 0 | $\frac{3}{4}$ | $\frac{3}{4}$ | 0 | $\frac{3}{4}$ | $\frac{3}{4}$ |
| | $\psi_k$ | −60° | 0 | +60° | −60° | 0 | +60° | −60° | 0 | +60° | −60° |

machine. It must be understood that other considerations than the relative efficiency have a decided bearing on the choice of a method of harmonic reduction. Thus if either skewing or fractional pitch is an available method in a given case, the fractional pitch would undoubtedly be the choice; because it is less expensive to make straight slots and coils, there is considerable saving in copper and copper losses on account of shorter end windings, and for the same reason a possibly shorter machine with less windage loss.

While $\beta_k$, $\gamma_k$, and $x_0$ in Equation (17) may be any arbitrary functions of time, yet the electromagnetic and mechanical characteristics of electrical apparatus are such that each of these items may, for practical purposes, be taken as composed of a series of terms of the type:

$$\beta_k = \beta_{0k} + \beta_{1k}\,\epsilon^{at} + \beta_{2k}\sin w\,t + \beta_{3k}\,\epsilon^{bt}\sin\omega\,t \quad (22)$$

$$\frac{d\,\gamma_k}{d\,t} = v_{0k} + v_{1k}\,\epsilon^{a't} + v_{2k}\sin w'\,t + v_{3k}\,\epsilon^{b't}\sin\omega'\,t \quad (23)$$

$$\frac{d\,x_0}{d\,t} = V_0 + V_1\,\epsilon^{a''t} + V_2\sin w''\,t + V_3\,\epsilon^{b''t}\sin\omega''\,t \quad (24)$$

Thus immediately after an unsymmetrical short circuit on a synchronous motor the flux in the air-gap

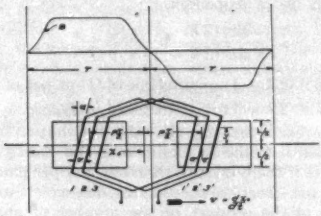


FIG. 5—GENERAL ARRANGEMENT

consists of terms such as given in (22). If the short circuit is severe enough to cause hunting, the constant velocity of the armature will have superimposed thereon an oscillation which may, if the conditions are right, continue indefinitely, die out exponentially, or even increase in amplitude until the machine falls out of step. The oscillatory passage of the teeth and slots across the pole faces will cause the distortion in the flux. Thus Equations (22), (23), and (24), represent actual possibilities. The direct substitution of (22), (23), and (24) in (17) yields a representative equation for the induced voltage in electrical machinery, but for the purpose of this discussion it is not necessary to carry out the actual substitution. It is sufficient to notice the following facts:

(a) When the flux distribution contains only rigid space harmonics, and when the coils are moving at a constant velocity; then only those time harmonics can appear in the induced voltage which are present in the space distribution of the flux, and which are not wiped out by the harmonic reduction factors. In this case, if any reduction factor for the $k$th harmonic be made equal to zero, then the $k$th time harmonic will be canceled out of the induced voltage. But every harmonic, including the fundamental, will suffer a reduction in magnitude if the slots are skewed or if the coils are made either short or long pitch, or if the total turns are distributed, or if phases are connected in series—in brief, any departure whatsoever from a straight-sided, full-pitch, concentrated winding will cause a reduction of all harmonics. In particular if the fundamental is canceled by any reduction factor, so will every harmonic be canceled.

(b) The presence of exponentials will cause either damped or cumulative oscillations, depending on the sign of the exponents, to appear in the line voltage. The abrupt change of the excitation on a machine, either by rheostat adjustment or by an automatic voltage regulator, causes the flux to build-up (or decay) exponentially. This change in $\beta_k$ and its derivative is reflected in the equation for the induced voltage, as exponential-trigonometric products, that is, as damped or cumulative oscillations. An exponential variation of $\beta_k$ may also be caused by a symmetric short circuit, or abrupt change of load occurring on a generator. If the torque of the prime mover driving a generator, or the mechanical load on a motor changes, an adjustment in speed takes place. This speed transient will contain an exponential term due to the mechanical inertia of the rotating parts. In the case of power suddenly shut off from an open-circuited generator, the speed decrement is practically a pure exponential (not rigorously so, because the friction is not constant throughout the speed range). These exponentials in speed cause the amplitudes of the harmonics in the induced voltage to change proportionally, and the wavelengths of these harmonics either contract or expand according to an exponential law.

(c) Perhaps the most important class of time variations in flux and speed are those of a purely oscillatory nature. Periodic fluctuations in flux are caused by sustained unbalanced short circuits and unbalanced loads on polyphase machines, the time harmonics of polyphase armature reaction; variation in the air-gap reluctance due to the passage of teeth and slots, and the elliptical rotating fields of single-phase motors.

Any possible product of sine and cosine terms may be expressed as the sum or difference of sines or of cosines, for example

$$2\sin w\,t\,.\,\sin k\,w_0\,t = \cos(k\,w_0 - w)\,t - \cos(k\,w_0 + w)\,t$$

It is of importance to observe from relationships of this type that it is quite possible to produce a harmonic of any order $K$ (integer or fractional) in the induced voltage, even though the reduction factors have been

adjusted for its complete cancellation. These possibilities are given by

$$w_0 K = (k\, w_0 \pm w)$$

For instance, suppose that the reduction factors will wipe out the 5th time harmonic due to a 5th space harmonic of flux distribution. But as a possibility

$$5 = (k \pm w/w_0)$$

from which it is evident that the 5th time harmonic may nevertheless appear in the line voltage if the air gap flux contains a space fundamental, $k = 1$, pulsating at $w/w_0 = 4$ times normal frequency, or a 3rd space harmonic pulsating at $w/w_0 = 2$ times normal frequency; or in general a $k$th harmonic pulsating at $w/w_0 = (k - 5)$ times normal frequency. More generally, since the periodicity of the flux pulsation may be arbitrary, it is possible to produce frequencies in the induced voltage which are not multiples of each other.

The only common sinusoidal fluctuations in speed that occur in practise are those due to sustained hunting of synchronous machines, and prime movers or drives with cyclic torques (reciprocating engines, compressors, etc.).

It is seen from Equation (**17**) that such cyclic variations in speed affect both the amplitudes and wavelengths of the induced voltage.

(d) Finally there is the class of time variations in flux and speed represented by damped (or cumulative) oscillations. Each of these appears in the voltage as a pair of damped (or cumulative) oscillations of different frequencies. They are caused by hunting, pulsating speed regulation by the governors of prime movers, and unsymmetrical short circuits of polyphase machines.

## III. Applications

Under this section of the paper, the application of Equation (**17**) to some of the more familiar types of electrical machines will be illustrated. In order to conserve space, certain simplifying assumptions will be adopted in making these applications. But it must be borne in mind that the generality of the equation is not limited by any such restrictions as may be invoked in the interests of simplicity and brevity. An extension of the analysis to include more detailed considerations will be obvious from the simple specifications given here.

*Synchronous Generator.* If all of the phenomena which occur in a synchronous machine are to be included in its analysis, then every term of Equation (**17**) will be required for the description of the induced voltage. Thus an unsymmetrical short circuit will cause a damped pulsating armature reaction with a corresponding variation of flux; the passage of teeth and slots cause the teeth harmonics of flux distribution to sweep across the pole face; and the hunting of a synchronous machine superimposes on the constant speed of rotation an oscillation which may be damped, sustained, or even cumulative. But neglecting such abnormal conditions, and taking the armature as the rotating element, there is:

$$x_0 = 2 f_0 \tau t = \omega_0 \frac{\tau}{\pi} t \text{ where } f_0 = \text{frequency.}$$

$d\beta_k/dt = 0$ since the flux distribution is steady.
$d\gamma_k/dt = 0$ since the flux distribution is fixed.
Substituting these values in Equation (**17**) there is

$$E_{line} = -4\, \tau\, L f_0 \frac{n N'}{10^8} \sum_1^{\infty} C_{ck} C_{dk}' C_{pk} C_{sk} \beta_k \cos k\,(\omega_0 t + \gamma_k + \psi_k' + \psi_k)$$

Now in commercial machines the field pole flux is rigid and symmetrical. The space harmonics are therefore of odd order and fixed in a symmetrical position. Consequently for a machine on open circuit (or supplying zero power factor current), $k$ is odd, and either $\gamma_k = \gamma_1$ or $\gamma_k = (\gamma_1 + \pi)$. When the machine is supplying an energy component of load the air-gap flux is distorted and unsymmetrical, so that the zeros of the flux harmonics are not necessarily coincident; and only consideration of the effects of armature reaction and air-gap permeance will permit $\beta_k$ and $\gamma_k$ to be completely specified.

If all phase belts of an alternator are alike (that is an integer number of slots per phase per pole) and if $Q$ is the number of phases per pair of poles, then from Equation (**9**) of Appendix I

$$C_{dk}' = C_{dk} = \frac{\sin\,(2k-1)\,\pi/Q}{c \sin\,(2k-1)\,\pi/c\,Q}$$

$$= 0 \text{ if } (2k-1) = \text{multiple of } Q \text{ but not of } (c\,Q)$$
$$= 1 \text{ if } (2k-1) = \text{multiple of } (c\,Q)$$

It is rather interesting that the distribution factor of a $Q$ phase machine will eliminate the multiple of $Q$ harmonics if there is more than one coil per phase belt, but will not eliminate those harmonics which are also a multiple of the product of the number of phases by the coils per phase belt, $(c\,Q)$. For instance, if a true three-phase machine (120 deg. phase belts) has three coils per phase belt, then the third harmonic will be completely wiped out, but the ninth harmonic and its multiples will not be reduced by the distribution. However, in a double layer winding the ninth would be wiped out by the pitch factor in this case. A single layer winding would have to be used to take advantage of the fact.

The equation for $E_{line}$ given above is based on the assumption that the armature is the revolving member. If the field revolves, then $x_0 = 0$, and $\gamma_k = \bar{\gamma}_k + \omega_0 t$ (since the flux distribution moves as a rigid system), so that $d\,\gamma_k/dt = \omega_0$. Making these substitutions, the same equation is obtained as that given above for the case of a revolving armature, except that $\bar{\gamma}_k$ replaces $\gamma_k$ as the constant angle fixing the relative position of the harmonics in the rigid distribution of flux.

*Polyphase Induction Motor.* Consider for the sake

of simplicity only the space harmonic of fundamental frequency $f$ in the revolving field of the air-gap flux, and let $f_o$ be the mechanical frequency of rotor rotation. If the direction of rotation of the revolving field be taken as positive, then the angle $\gamma_1$ in the Fourier series for the flux distribution, Equation (1), is negative, so that

$$\gamma_1 = -2\pi f t, \quad \therefore d\gamma_1/dt = -2\pi f$$
$$x_0 = 2\tau f_0 t, \quad \therefore dx_0/dt = 2\tau f_0$$

Substituting these values in Equation (17) there is

$$E_{rotor} = 4L\tau \frac{nN'}{10^8} C_{c1} C_{d1} C_{p1} C_{s1} \beta_1$$
$$(f - f_0) \cos [2\pi (f_0 - f) t + \psi_1' + \psi_1]$$

This equation shows that at standstill, $f_0 = 0$, the voltage induced in the rotor is of stator frequency, $f$. If the rotor is running at synchronism the voltage is zero and direct current. For speeds above synchronism the voltage increases in magnitude and frequency with the speed.

The equation for the stator counter e. m. f. is, of course, of the same form as that derived in the previous case of a synchronous generator.

*D-C. Generator.* The exact calculation of the voltage across the brushes of a d-c. generator would take into consideration such things as the variation of the air-gap flux due to the moving teeth and the pulsation in armature reaction caused by the oscillation about its mean position of the belt of conductors between brushes; the sector of brush overlap; the slight cyclic variation of field excitation when under automatic regulator control, etc. Assuming, however, that the number of armature conductors per pole is reasonably large, so that the effects of the belt oscillation may be neglected, and disregarding the teeth pulsations, brush overlap, etc., the following conditions obtain:

$d\gamma_k/dt = 0$ since there is no movement of flux
$d\beta_k/dt = 0$ since there is no pulsation of flux
$x_0 \pi/\tau = \xi$ = angle of brush shift
$dx_0/dt$ = (no. of poles) (rev. per min.)/60 $= 2\tau f_o$ = velocity of conductors
$\psi_k' = \psi_k = 0$ since there is only one belt between brushes.

Substituting these values in Equation (17), the induced voltage across an adjacent pair of brushes is found to be

$$E_{brushes} = -2\tau L \frac{N'}{10^8} \frac{(\text{RPM})}{60} (\text{Poles})$$
$$\sum_1^\infty C_{dk} C_{pk} C_{sk} \beta_k \cos k(\gamma_k + \xi)$$
$$= -4\tau L \frac{N' f_o}{10^8} \sum_1^\infty C_{dk} C_{pk} C_{sk} \beta_k \cos k(\gamma_k + \xi) \quad (36)$$

It is evident that the voltage is a maximum when $\gamma_k = -(\xi + m\pi)$, for then $\cos k(\gamma_k + \xi) = \pm 1$ and each harmonic contributes a maximum. The possibility of taking either sign is necessary in order to neutralize a change in sign caused by the harmonic reduction factors.

Since the "phase belt" of a d-c. machine spans a pole pitch, the distribution factor is

$$C_{dk} = \frac{\sin k\pi/2}{c \sin k\pi/2c} \simeq \frac{2}{k\pi} \sin \frac{k\pi}{2} \text{ if } c \to \infty$$

Thus even harmonics in the flux distribution will not contribute to the induced voltage. For a full pitch, infinitely distributed winding, without skew,

$$C_{pk} = \sin \frac{k\pi}{2} \text{ and } C_{sk} = 1.$$

$$E_{brushes} = -2\tau L \frac{N'}{10^8} \frac{(\text{RPM})}{60} (\text{Poles})$$
$$\frac{2}{\pi} \sum_1^\infty \sin^2 \frac{(2k-1)\pi}{2} \frac{\beta_{2k-1}}{2k-1}$$
$$\cos (2k-1)(\gamma_{2k-1} + \xi)$$
$$= -2 \frac{N'}{10^8} \frac{(\text{RPM})}{60} (\text{Poles})\, \phi = -4 \frac{N'}{10^8} f \phi$$

where

$$\phi = \frac{\tau L}{\pi} \int_\xi^{\pi+\xi} \sum_1^\infty \beta_{(2k-1)} \sin (2k-1)(\gamma_{2k-1} + \xi)\, d\xi$$
$$= \frac{2}{\pi} \sum_1^\infty \frac{\beta_{2k-1}}{2k-1} \cos (2k-1)(\gamma_{2k-1} + \xi)$$

= (flux between brushes due to the odd harmonics)

From the standpoint of telephone interference, a rather interesting problem in the design of d-c. commutating machines is the calculation of the voltage pulsation due to the oscillation of the armature conductors about their mean position with respect to the brushes. These ripples may be computed by allowing $\xi$ to vary over the oscillation range, in the above equations. While the segregation and ultimate specification of these pulsations as Fourier series is usually desirable, space will not be taken up here for such a study.

*Synchronous Converter.* The a-c. and d-c. induced voltages of a synchronous converter are found from the equations for the *Synchronous and D-C. Generators* respectively.

Substituting in the equation for the *Synchronous Generator* the values

$$n = 1,\ \psi_k = 0,\ \psi_k' = 0,\ N' = cN,\ C_{dk}' = C_{dk} = \frac{\sin k\pi/Q}{c \sin k\delta/2}$$

where $\delta = 2\pi/cQ$ = slot angle; the phase voltage is $E_{phase} = -4L\tau f_o N 10^{-8}$

$$\sum_1^\infty \frac{\sin k\pi/Q}{\sin k\delta/2} C_{pk} C_{sk} \beta_k \cos k(\omega_o t + \gamma_k)$$

The effective value of the fundamental (the applied e. m. f.) is

$$E_1 = \frac{4}{\sqrt{2}} L \tau f_s N 10^{-8} \frac{\sin \pi/Q}{\sin \delta/2} C_{p1} C_{s1} \beta_1$$

Substituting in the equation for the *D-C. Generator* the value $C_{dk} = \dfrac{\sin k \pi/2}{c \sin k \delta/2}$ gives for the d-c. voltage

$$E_{d-c} = -4 L \tau f_0 N 10^{-8} \sum_1^\infty \frac{\sin k \pi/2}{\sin k \delta/2} C_{pk} C_{sk} \beta_k \cos k (\gamma_k + \xi)$$

Therefore the ratio of the d-c. induced voltage to the effective value of the fundamental component of the a-c. induced voltage—the ratio of conversion—is

$$\frac{E_{d-c}}{E_1} = \sqrt{2} \left\{ \frac{\cos (\gamma_1 + \xi)}{\sin \pi/Q} + \sum_2^\infty \frac{\sin k \pi/2 \,.\, \sin \delta/2 \,.\, C_{pk} C_{sk} \beta_k}{\sin \pi/Q \,.\, \sin k \delta/2 \,.\, C_{p1} C_{s1} \beta_1} \cos k (\gamma_k + \xi) \right\}$$

$$= \sqrt{2}\, \Delta/\sin (\pi/Q)$$

For a detailed discussion of the voltage ratio of a converter, based on this equation, reference may be made to *The Synchronous Converter* by T. T. Hambleton and L. V. Bewley, A. I. E. E. TRANS., Vol. XLVI, 1927, p. 60.

*Synchronous Converter with Polyphase Field.* Consider a synchronous converter armature with a frequency $f_2$ applied to its slip rings, revolving in the polyphase stator field of an induction motor supplied with currents of frequency $f_1$. If $f_0$ denotes the frequency of mechanical rotation of the armature, then from the equation for the rotor voltage of a *Polyphase Induction Motor*, there is (considering only the fundamental)

$$E_{rotor} = 4 L \tau n \frac{N'}{10^8} C_{d1} C_{p1} C_{s1} \beta_1 (f_1 - f_0) \cos 2 \pi (f_0 - f_1) t$$

The condition that this voltage must have the same frequency $f_2$ as that applied to the slip rings, requires that

$$\pm f_2 = (f_0 - f_1) \quad \text{or} \quad f_0 = (f_1 \pm f_2)$$

Then $x_0 = 2 \tau f_0 t, \quad d x_0/d t = 2 \tau f_0$

$$\gamma_1 = -2 \pi f_1 t, \quad d \gamma_1/d t = -2 \pi f_1$$

The voltage at the brushes, as in the analysis for the *D-C. Generator* is

$$E_{brushes} = 4 L \tau \pi \frac{N'}{10^8} \overline{C}_{d1} C_{p1} C_{s1} \beta_1 (f_0 - f_1) \cos (\xi - 2 \pi f_1 t)$$

Thus the voltage at the brushes is of the same frequency as that of the field, but the amplitude is proportional to the frequency applied at the slip rings. If $f_1 = 0$, the field is d-c. and the equations reduce to those for the ordinary *Synchronous Converter*.

Equation (17) is also readily applicable to the case of a standard converter supplied with a-c. field excitation, or for that matter, an excitation varying in any arbitrary way.

*The Transformer.* There is no practical advantage in showing that Equation (17) includes the special case of the static transformer. The demonstration is included here merely for the sake of completeness and to show the general validity of the equation. Consider an ideal transformer having a rectangular core of section $(\tau L)$; and neglect the leakage flux. Then at any instant the flux density is uniform over the core, and the equation of its distribution in the direction of $\tau$ is that of a rectangular wave. But in a rectangular wave the harmonics are all of odd order, and their amplitudes are inversely as their order, so that Equation (1) becomes

$$B = \sum_1^\infty \frac{\beta_1}{2k-1} \sin (2k-1) \frac{\pi x}{\tau} = \frac{4}{\pi} B \sum_1^\infty \frac{\sin (2k-1) \pi x/\tau}{(2k-1)}$$

Since the turns are full pitch, and the conductors are not skewed or distributed with respect to the distribution of flux, it follows that $C_{sk} = 1$, $C_{pk} = \sin k \pi/2$, $C_{dk} = 1$, $\psi_k = 0$. Both the conductors and space distribution of flux are stationary, so that $d x_0/d t = 0$ and $d \gamma_k/d t = 0$. The coordinate to the midpoint of the coil is $x_0 = \tau/2$. The induced voltage therefore is, by Equation (17) and the above conditions:

$$E = -2 L \frac{\tau}{\pi} \frac{N'}{10^8} \frac{4}{\pi} \frac{d B}{d t} \sum_1^\infty \frac{\sin^2 (2k-1) \pi/2}{(2k-1)^2}$$

$$= -L \tau \frac{N'}{10^8} \frac{d B}{d t} = -\frac{N'}{10^8} \frac{d \phi}{d t}$$

$$\text{since } \frac{8}{\pi^2} \sum_1^\infty \frac{1}{(2k-1)^2} = 1 \text{ and } (\tau L B) = \phi$$

Although rather irrelevant to the subject matter of this paper, a discussion of the theory of induction in a transformer by "cutting action" may not be too much out of place.

In the above equations $B$ is the instantaneous value of the flux density pulsating at frequency $f$, so that $B = B_0 \sin \omega t$ and therefore

$$B = B_0 \frac{4}{\pi} \sum_1^\infty \frac{\sin \omega t \,.\, \sin (2k-1) x \pi/\tau}{(2k-1)}$$

$$= B_0 \frac{4}{\pi} \sum_1^\infty \left\{ \cos \left[ \omega t - (2k-1) \frac{\pi x}{\tau} \right] - \cos \left[ \omega t + (2k-1) \frac{\pi x}{\tau} \right] \right\} = \Sigma \beta' + \Sigma \beta''$$

The term $[\omega t \pm (2k-1) \pi x/\tau] = constant$ defines the position of any given point on the cosine wave at

any time $t$, and this point moves across the core section at a velocity $\frac{dx}{dt} = \frac{\mp \omega}{(2k-1)} \frac{\tau}{\pi}$, thus inversely proportional to the order of the space harmonic. The pulsating flux wave has thus been decomposed into two systems $\Sigma \beta'$ and $\Sigma \beta''$ of traveling waves moving at equal speeds in opposite directions. The flux density at the conductors, located at $x = 0$ and $x = \tau$, is found by substituting these limits in the expression for $B$. The induced voltage, calculated by the $(B\,L\,V)$ method, then is

$$e = \frac{-N}{10^8} \sum (B\,L\,V)$$

$$= \frac{-N\,\omega}{10^8} \frac{\tau}{\pi} L \sum_1^\infty \frac{\beta'_{x=0} + \beta'_{x=\tau} - \beta''_{x=0} - \beta''_{x=\tau}}{2k-1}$$

$$= \frac{-N\omega}{10^8} \tau\,L\,B_0 \frac{2}{\pi^2} \sum_1^\infty \frac{4 \cos \omega t}{(2k-1)^2}$$

$$= -N\omega\,(\tau\,L\,B_0) \cos \omega t$$

$$= \frac{-N\,\omega}{10^8} \phi_0 \cos \omega t = -\frac{N}{10^8} \frac{d\phi}{dt}$$

If the core section is not rectangular it may be replaced by any rectangular section having the same effective area, $\tau\,L = A$, and operating at the same density.

Although the correct result has been obtained by considering the standing waves to be composed of two series of traveling waves, and then computing the induced voltage as due to "cutting action," yet at the conductors themselves the flux density is zero, for

$$\begin{cases} \beta'_{x=0} + \beta''_{x=0} = 0 \\ \beta'_{x=\tau} + \beta''_{x=\tau} = 0 \end{cases}$$

Thus in an application of the $(B\,L\,V)$ method, the component flux densities and their individual velocities relative to the conductor must be considered separately, and only those flux densities superimposed which have equal velocities and in the same direction at the point of superposition. This interesting situation was previously pointed out by Dr. H. B. Dwight in the April 1928 issue of the *Electric Journal*.

*Additional Applications.* For those wishing to become familiar with the use of the general equation, the following problems may prove interesting and instructive.

(a) Calculate and plot representative ranges of the voltage wave of a synchronous generator on open circuit brought up to speed by a prime mover delivering constant torque, assuming friction and windage independent of speed.

(b) Plot the open-circuit voltage of a synchronous generator supplied with field excitation from a rectifying device having a second time harmonic.

(c) Plot the open-circuit voltage of a synchronous generator driven by a reciprocating engine having an exaggerated cyclic torque. Segregate out the time harmonics for different amplitudes and periods of oscillation.

(d) Each phase of a two-phase induction motor stator is excited at a different voltage and frequency. Find the slip ring voltage induced by the stator flux in a three-phase Y-connected rotor driven externally at constant speed.

(e) A d-c. generator field is excited with alternating current. Calculate the voltage at the brushes.

(f) The field of a separately excited d-c. generator is closed as the machine starts to accelerate from standstill. For a reasonable field time constant and rate of acceleration plot the voltage at the brushes.

(g) Study the effects of slots and teeth in producing voltage ripples, by analyzing flux plots and specifying as Fourier series. In particular, decide whether these flux harmonics are standing or traveling waves.

(h) Calculate the voltage ripples of a d-c. generator when the oscillation about its mean position of the belt of conductors between brushes is taken into account. Specify as Fourier series.

The author wishes to thank Mr. S. T. Maunder who verified the equations with independent derivations.

## List of Symbols

$B$ = instantaneous flux density
$B_0$ = maximum flux density
$c$ = coil sides per phase belt
$C_{sk}$ = skew factor for the $k$th harmonic
$C_{pk}$ = pitch factor for the $k$th harmonic
$C_{dk}$ = belt distribution factor for the $k$th harmonic
$C_{dk}'$ = equivalent distribution factor for dissimilar phase belts in series
$C_{ck}$ = phase connection factor for the $k$th harmonic
$e_m$ = voltage induced in the $m$th coil of a phase belt
$e_g$ = voltage induced in a single-phase group
$e_p$ = voltage induced in a complete phase
$E_{line}$ = induced line voltage
$f$ = frequency
$k$ = order of the harmonic
$L$ = effective length of stacking
$m$ = position of coil in a phase group
$n$ = number of phases in series between lines
$N$ = number of turns per coil
$N'$ = number of turns per phase
$p$ = per cent pitch
$P$ = number of poles
$q$ = number of phase groups per phase
$Q$ = number of phases per pair of poles
Rev. per min. = revolutions per minute
$t$ = time
$v$ = velocity of moving flux
$V$ = velocity of moving conductors
$x$ = coordinate of any point in the direction of motion
$x_0$ = coordinate of the midpoint of the first coil group
$y$ = coordinate of any point perpendicular to the motion

$\alpha$ = mechanical angle of skew
$\beta_k$ = instantaneous amplitude of the $k$th harmonic of flux density
$\gamma_k$ = instantaneous displacement angle of the $k$th harmonic of flux density
$\delta$ = electrical angle between coil sides
$\epsilon$ = base of Naperian logarithms
$\zeta$ = angle between adjacent phases
$\theta'$ = displacement angle of a phase group
$\theta$ = displacement angle of a phase
$\lambda$ = electrical angle of skew
$\xi$ = angle of brush shift
$\sigma$ = slot pitch distance
$\tau$ = pole pitch distance
$\phi$ = flux
$\psi_k$ = shift of the $k$th harmonic due to phases in series
$\psi_k'$ = shift of the $k$th time harmonic due to dissimilar belts
$\omega$ = $2\pi f$ = angular velocity
$\Sigma$ = sign of summation, effective as implied.

## Appendix I

### General Equation for the Induced Voltage of Electrical Machines

The following analysis applies to electrical machines having uniformly distributed parallel coil sides moving through a distribution of flux which is uniform in a direction in the plane of the coil perpendicular to its motion.

Let the space distribution of flux density due to the combined effects of field excitations, armature reactions, and leakage reactances be specified by the Fourier series:

$$B = \sum_1^\infty \beta_k \sin k \left( \frac{x}{\tau} \pi + \gamma_k \right) \qquad (1)$$

where
$k$ = order of the space harmonic
$\beta_k$ = amplitude of the $k$th harmonic
$x$ = coordinate of any point
$\tau$ = wavelength of the fundamental = pole pitch
$\gamma_k$ = displacement angle of the $k$th harmonic.

If the coil sides situated in this field are skewed with respect to the poles, the equations of the trailing and leading coil sides of the $m$th coil, counting from the trailing end of the group of coils, are respectively (see Fig. 5)

$$x_m = x_0 - p\frac{\tau}{2} - \frac{c-1}{2}\sigma + (m-1)\sigma + y\tan\alpha \qquad (2)$$

$$x_m' = x_0 + p\frac{\tau}{2} - \frac{c-1}{2}\sigma + (m-1)\sigma + y\tan\alpha = x_m + p\tau \qquad (3)$$

where
$x_0$ = coordinate of the midpoint of the coil group
$p$ = pitch of the coils expressed as a fraction
$c$ = number of coils in the coil group
$\sigma$ = distance between adjacent coil sides = slot pitch
$\alpha$ = angle of skew
$y$ = coordinate at right angles to the direction of motion, reckoned from midpoint of the coil side.

The total flux included by the $m$th coil is, by Equations (1), (2), and (3),

$$\phi_m = \int_{-L/2}^{L/2} \int_{x_m}^{x_m'} B\, d\,y\, d\,x$$

$$= 2L\frac{\tau}{\pi} \sum_1^\infty \frac{\beta_k}{k} C_{pk} C_{sk} \sin k \left( \frac{x_0\,\pi}{\tau} - \frac{c+1-2m}{2}\frac{\sigma n}{\tau} + \gamma_k \right) \qquad (4)$$

where
$L$ = effective length of the stacking

$$C_{sk} = \frac{\sin k\,(L\,\pi\tan\alpha/2\,\tau)}{k\,(L\,\pi\tan\alpha/2\,\tau)} = \frac{\sin k\,\lambda/2}{k\,\lambda/2} = \text{skew reduction factor for the } k\text{th harmonic} \qquad (5)$$

$$C_{pk} = \sin k\frac{p\,\pi}{2} = \text{pitch reduction factor for the } k\text{th harmonic} \qquad (6)$$

Now in general, $x_0$, $\beta_k$, and $\gamma_k$ are all functions of time $t$; so that the induced voltage of the $m$th coil of $N$ turns is

$$e_m = \frac{-N}{10^8}\frac{d\,\phi_m}{d\,t} = \frac{-N}{10^8}\left\{ \frac{\partial\,\phi_m}{\partial\,x_0}\frac{d\,x_0}{d\,t} + \sum_1^\infty \frac{\partial\,\phi_m}{\partial\,\gamma_k}\frac{d\,\gamma_k}{d\,t} + \sum_1^\infty \frac{\partial\,\phi_m}{\partial\,\beta_k}\frac{d\,\beta_k}{d\,t} \right\}$$

$$= -2L\frac{\tau}{\pi}\frac{N}{10^8}\sum_1^\infty C_{pk}C_{sk}$$

$$\left\{ \frac{1}{k}\frac{d\beta_k}{d\,t}\sin k\left(x_0\frac{\pi}{\tau} - \frac{c+1-2m}{2}\frac{\sigma}{\tau}\pi + \gamma_k\right) + \left(\frac{d\,\gamma_k}{d\,t} + \frac{\pi}{\tau}\frac{d\,x_0}{d\,t}\right)\beta_k\cos k\left(\frac{x_0\,\pi}{\tau} - \frac{c+1-2m}{2}\frac{\sigma\pi}{\tau} + \gamma_k\right)\right\}^* \qquad (7)$$

The total voltage for a phase group consisting of $c$ such coils uniformly distributed by the pitch $\sigma$ is, by the method of summation given in Appendix II,

*This result is obtainable by direct substitution in Equation (19) of the author's paper *Flux Linkages and Electromagnetic Induction in Closed Circuits*, A. I. E. E. Quarterly Trans., Vol. 48, April 1929, p. 327.

$$e_g = \sum_1^c e_m = -2L\frac{\tau}{\pi}\frac{Nc}{10^8}\sum_1^\infty C_{dk}C_{pk}C_{ck}$$

$$\left[\frac{1}{k}\frac{d\beta_k}{dt}\sin k\left(\frac{x_0\pi}{\tau}+\gamma_k\right)\right.$$

$$\left.+\left(\frac{d\gamma_k}{dt}+\frac{\pi}{\tau}\frac{dx_0}{dt}\right)\beta_k\cos k\left(\frac{x_0\pi}{\tau}+\gamma_k\right)\right] \tag{8}$$

where

$$C_{dk} = \frac{\sin k(c\,\sigma\,\pi/2\,\tau)}{c\sin k(\sigma\,\pi/2\,\tau)} = \frac{\sin k\,c\,\delta/2}{c\sin k\,\delta/2} = \text{distribution}$$

reduction factor for the $k$th harmonic. (9)

If the complete phase is made up of $q$ phase groups connected in series, but unsymmetrically arranged and with a different number of coils per group (as in the case of fractional slots/pole/phase) then the phase voltage is, by the method of summation given in Appendix II.

$$e_p = \sum_1^q e_g = -2L\frac{\tau}{\pi}\frac{N'}{10^8}\sum_1^\infty C_{dk}'C_{pk}C_{ck}$$

$$\left[\frac{1}{k}\frac{d\beta_k}{dt}\sin k\left(\frac{x_0\pi}{\tau}+\gamma_k+\psi_k'\right)\right.$$

$$\left.+\left(\frac{d\gamma_k}{dt}+\frac{\pi}{\tau}\frac{dx_0}{dt}\right)\beta_k\cos k\left(\frac{x_0\pi}{\tau}+\gamma_k+\psi_k'\right)\right] \tag{11}$$

where

$C_{dk}' = \sqrt{A_k^2+B_k^2}/N'$ = equivalent distribution factor of the phase, for the $k$th harmonic

$\psi_k' = \tan^{-1}(B_k/A_k)$ = displacement angle of the $k$th harmonic in the phase voltage (13)

$$A_k = \sum_1^q [c\,N\,C_{dk}]_g\cos k\,\theta_g' \tag{14}$$

$$B_k = \sum_1^q [c\,N\,C_{dk}]_g\sin k\,\theta_g' \tag{15}$$

$$N' = \sum_1^q [c\,N]_g = \text{total number of turns in the phase} \tag{16}$$

$\theta_g'$ = position of the midpoint of phase group $g$ in electrical radians reckoned from the reference point on the armature. If all groups are alike, and displaced by multiples of $2\pi$, then $C_{dk}'$ reduces to $C_{dk}$.

Two or more phases may be connected in series, either additive or subtractive, to form the line voltage. If the displacement angles of the $n$ phases *as connected in series* are $(\theta_1, \theta_2 \ldots \theta_n)$ the total line voltage is, by the method of summation in Appendix II.

$$E_{line} = -2L\frac{\tau}{\pi}\frac{nN'}{10^8}\sum_1^\infty C_{ck}C_{dk}'C_{pk}C_{ck}$$

$$\left[\frac{1}{k}\frac{d\beta_k}{dt}\sin k\left(\frac{x_0\pi}{\tau}+\gamma_k+\psi_k'+\psi_k\right)\right.$$

$$\left.+\left(\frac{d\gamma_k}{dt}+\frac{\pi}{\tau}\frac{dx_0}{dt}\right)\beta_k\cos k\left(\frac{x_0\pi}{\tau}+\gamma_k+\psi_k'+\psi_k\right)\right] \tag{17}$$

where

$C_{ck} = \frac{1}{n}\left[\left(\sum_1^n\cos k\,\theta_r\right)^2+\left(\sum_1^n\sin k\,\theta_r\right)^2\right]^{1/2}$ = connection reduction factor for the $k$th harmonic (18)

$\psi_k = \tan^{-1}\left[\left(\sum_1^n\sin k\,\theta_r\right)/\left(\sum_1^n\cos k\,\theta_r\right)\right]$ = displacement angle for the $k$th harmonic (19)

If the $n$ phases are displaced by the same amount $\zeta$ from adjacent phases, Equations (18) and (19) reduce, as shown in Appendix II, to

$$C_{ck} = \frac{\sin k\,n\,\zeta/2}{n\,.\sin k\,\zeta/2} \tag{20}$$

$$\psi_k = k\left(\frac{n-1}{2}\right)\zeta \tag{21}$$

Equation (17) is the most general equation for the induced voltage of electrical machines, if $x_0$, $\beta_k$, and $\gamma_k$ are perfectly arbitrary functions of time. Its application to the special cases of the more ordinary types of electrical machines is discussed in the main body of the paper.

## Appendix II

### The Distribution Summations

In the harmonic analysis of electrical machines it is repeatedly necessary to find the sum of certain finite trigonometric series. Those required in this paper are given below.

$$\text{Since } \frac{1-z^n}{1-z} = 1+z+z^2+\ldots+z^{n-1} = \sum_{r=0}^{n-1} z^r \tag{1}$$

it follows, upon replacing $\epsilon^{+j\alpha}$ by $z$, that

$$\sum_{r=0}^{n-1}\sin(x+r\alpha) = \sum_{r=0}^{n-1}\frac{\epsilon^{j(x+r\alpha)}-\epsilon^{-j(x+r\alpha)}}{2j}$$

$$= \frac{\epsilon^{jx}}{2j}\left(\frac{1-\epsilon^{-jn\alpha}}{1-\epsilon^{j\alpha}}\right)-\frac{\epsilon^{-jx}}{2j}\left(\frac{1-\epsilon^{-jn\alpha}}{1-\epsilon^{-j\alpha}}\right)$$

$$= \frac{1}{2j}\left[\frac{\epsilon^{jx}-\epsilon^{j(x-\alpha)}+\epsilon^{j(x+n\alpha-\alpha)}-\epsilon^{j(x+n\alpha)}-\epsilon^{-jx}+\epsilon^{-j(x+\alpha)}-\epsilon^{-j(x+n\alpha)}+\epsilon^{-j(x+n\alpha-\alpha)}}{1-\epsilon^{-j\alpha}-\epsilon^{j\alpha}+1}\right]$$

$$= \frac{\sin x - \sin(x-\alpha) + \sin(x+n\alpha-\alpha) - \sin(x+n\alpha)}{2(1-\cos\alpha)}$$

$$= \frac{2\sin\alpha/2\cos(2x-\alpha)/2 - 2\sin\alpha/2 \,.\, \cos(2x+2n\alpha-\alpha)/2}{4\sin^2\alpha/2}$$

$$= \frac{\cos(2x-\alpha)/2 - \cos(2x-\alpha+2n\alpha)/2}{2\sin\alpha/2}$$

$$= \frac{\sin n\alpha/2}{\sin\alpha/2}\sin\left(x+\frac{n-1}{2}\alpha\right) \tag{2}$$

Replacing $(\alpha)$ by $(-\alpha)$ gives

$$\sum_{r=0}^{n-1}\sin(x-r\alpha) = \frac{\sin n\alpha/2}{\sin\alpha/2}\sin\left(x-\frac{n-1}{2}\alpha\right) \tag{3}$$

Replacing $(x)$ by $(x + 90$ deg.$)$ gives

$$\sum_{r=0}^{n-1}\cos(x+r\alpha) = \frac{\sin n\alpha/2}{\sin\alpha/2}\cos\left(x+\frac{n-1}{2}\alpha\right) \tag{4}$$

$$\sum_{r=0}^{n-1}\cos(x-r\alpha) = \frac{\sin n\alpha/2}{\sin\alpha/2}\cos\left(x-\frac{n-1}{2}\alpha\right) \tag{5}$$

The more general sums, in which the angles do not differ by a regular amount, and in which different amplitudes are involved, are found as follows:

By the symbolic operators of complex notation:

$$\Sigma E_r = \Sigma E_r e^{j\theta_r} = \Sigma E_r\cos\theta_r + j\,\Sigma E_r\sin\theta_r = E_0 e^{j\theta_0} \tag{6}$$

where

$$E_0 = \sqrt{(\Sigma E_r\cos\theta_r)^2 + (\Sigma E_r\sin\theta_r)^2} \tag{7}$$

$$\theta_0 = \tan^{-1}\left\{\frac{\Sigma E_r\sin\theta_r}{\Sigma E_r\cos\theta_r}\right\} \tag{8}$$

Or transforming to trigonometric notation

$$\Sigma E_r\sin(x\pm\theta_r) = E_0\sin(x\pm\theta_0) \tag{9}$$

$$\Sigma E_r\cos(x\pm\theta_r) = E_0\cos(x\pm\theta_0) \tag{10}$$

If $E_1 = E_2 = \ldots\ldots = E_r = E$ and $\theta_r = r\alpha$ then (7) and (8) reduce to (2) and (9) as follows:

$$E_0 = E\sqrt{\left(\sum_0^{n-1}\cos r\alpha\right)^2 + \left(\sum_0^{n-1}\sin r\alpha\right)^2}$$

$$= E\frac{\sin n\alpha/2}{\sin\alpha/2}$$

$$\sqrt{\left(\cos\frac{n-1}{2}\alpha\right)^2 + \left(\sin\frac{n-1}{2}\alpha\right)^2}$$

$$= E\frac{\sin n\alpha/2}{\sin\alpha/2}$$

$$\theta_0 = \tan^{-1}\left(\tan\frac{n-1}{2}\alpha\right) = \frac{(n-1)}{2}\alpha$$

# A Cathode Ray Oscillograph with Norinder Relay

## Its Design and Application

BY O. ACKERMANN*

Associate, A. I. E. E.

***Synopsis.***—*The paper describes the Norinder cathode ray oscillograph as used in lightning investigations on transmission lines in 1928. It then describes a new model of a cathode ray oscillograph developed for the expansion of field and laboratory tests in 1929. One of the novel features of this modified instrument is the steel housing.*

*A circuit is shown for obtaining a unidirectional time axis on the oscillograms, in which the timing movement is started by an impulse from the surge to be measured.*

*In the appendix a simple and concise formula for the sensitivity of a cathode ray oscillograph is developed. This has been derived by Mr. Lewis R. Smith and takes into account the change of the mass of the electron at speeds approaching that of light.*

*At the frequently used cathode voltage of 60 kv., this phenomenon already causes a deviation of 5 per cent from the value which would be expected otherwise.*

* * * * *

IN its thirty-two years of development[1] the cathode oscillograph has gradually outgrown the status of a delicate instrument nursed along in a few scientific laboratories, to become a measuring tool useful in many branches of electrical and even mechanical engineering. One easily recognizes this fact when glancing over the electrotechnical literature of the last five years which, to the writer's knowledge, contains about 60 papers on the design of cathode ray oscillographs and on their applications, covering the fields of transformer design, choke coils, lightning arresters, insulation, transmission line characteristics, corona and hysteresis losses, the study of lightning and many other problems. Numerous types of instruments have been developed, constantly increasing their range of application.

At first only recurrent phenomena could be measured; later, single transients of very short duration were recorded successfully, provided they could be initiated at will in the proper relation to the oscillograph control circuit, and finally surges entirely removed from our control, especially lightning surges, have been brought into the measuring range of the instrument.

The later problem has its particular difficulties. The oscillograph must be kept ready to record, perhaps for an hour or more, because lightning disturbances are sometimes long in coming. Hence, although the film shutter must be kept open, the film must be protected from the main cathode beam and its stray radiation until the surge arrives. If this were not done, the rays would blacken the photographic layer in a fraction of a second. Then, when the surge has recorded itself and passed on, the film must again be shielded from the beam. All this must be accomplished with delays no greater than a fraction of a millionth of a second.

This problem has been given increasing attention in the last few years. Its solution has been attempted in two principal ways:

In the first method, the electron jet does not exist during the waiting time, but the instrument is in readiness to generate the cathode beam quickly and to project it on the film, these actions being released by a voltage impulse from the arriving surge.[2]

In the second method, the cathode ray beam is kept

FIG. 1—NORINDER CATHODE RAY OSCILLOGRAPH

established in the instrument in its normal strength, but is prevented from striking the photographic layer until a voltage change on certain deflection plates allows the electron jet to enter the recording part of the instrument through a diaphram.

This change of voltage at the beam blocking device which is a part of the oscillograph itself, is brought about either by an external relay which is tripped by the

*Westinghouse Electric & Manufacturing Co., East Pittsburgh, Pa.

1. First account by F. Braun, *Annalen der Physik*, 1897, Vol. 60, p. 552.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

2. K. B. McEachron, R. H. George; P. Sporn and W. L. Lloyd, see Bibliography.



30-37

first impact of the surge to be measured[3] or by direct action of the surge on the oscillograph without any intermediate circuit except for the potential divider. Dr. Norinder has solved the problem by the latter means. His instrument is shown in Fig. 1.

The internal construction is shown diagrammatically

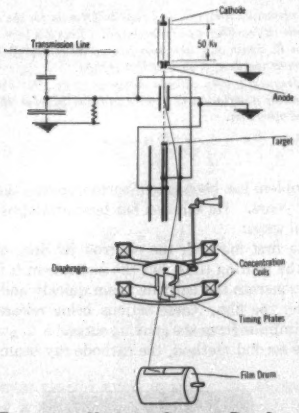



Fig. 2—Diagram of Norinder Cathode Ray Oscillograph

in Fig. 2. With no voltage on the upper set of deflection plates, the electron jet coming through the anode opening follows a straight path along the axis of the instrument, but is stopped by a narrow bar of conducting material, the target. Yet, some stray rays are always passing by the target. They would blacken the photographic film in a very short time if they were not intercepted by the diaphram which has a hole of about ¼ in. diameter in its center. The system of plates between target and diaphram is connected to the top plates and is dimensioned so that the main beam after it is deflected past the target by a voltage impressed upon the upper pair of plates is bent back and directed through the hole in the diaphram. Its deflection is proportional to the voltage applied. The two long inner plates directly underneath the target could be omitted without affecting the working principle of the system, but their presence more than doubles the field gradient which would exist if the two outer plates were used alone. This permits a considerable reduction of the instrument's length.

A set of concentration coils is placed at the diaphram. Electrons, traveling through their magnetic field and deviating from its direction are forced on a spiral path which under certain conditions results in a sharp focusing of the cathode beam on the observation screen or the photographic film.

The concentrating effect of a magnetic field usually is explained for the case where the axis of the electron jet is parallel to that of the magnetic field. Yet, it can easily be proved, that this action also takes place when the beam crosses the field at an angle. And this, it will be noticed from Fig. 2, is the case in the Norinder oscillograph. Under this condition, the beam is not only concentrated, but it is also deflected from its original path in a spiral curve. This motion has the same effect as if the vertical plane in which the voltage deflection takes place were swung through a certain angle while the beam travels through the magnetic field. In other words, the axis of the voltage deflection is twisted by the passage of the beam through the concentration coil field. Now, the timing plates must be arranged so that they deflect the beam perpendicularly to the plane of its voltage deflection.

The latter however twists, as explained above, and therefore the timing plates also must be rotated with respect to the voltage plates. This is accomplished by means of a conical joint and a set of gears from outside the instrument while the angle between the coordinates is observed on the fluorescent screen.

The photographic film is mounted on a drum of 5 in. diameter which can be rotated as fast as 7200 rev. per min. The oscillogram of a switching surge (Fig. 3) is taken with this mechanical timing movement.

Yet, for most purposes in which cathode ray oscillo-

Fig. 3—Switching Surges on 132-Kv. Line Taken with Rotating Drum

graphs are used this speed is too slow. Therefore, under normal conditions the film is left stationary whereas the cathode ray beam is moved along the time axis by means of a voltage which is impressed on the timing plates and which changes at a known rate. Subsequent sections of the film are exposed by turning the film drum by hand.

3. D. Gabor, W. Rogowski and Wolff, W. Krug, see Bibliography.

The type of oscillograph described above has been used for the lightning investigations on lines of the Aluminum Company of America in Tennessee[4] and of the Public Service Company of Northern Illinois.

Our work in 1928 indicated certain desirable modifications in the electrical as well as in the mechanical design of the instrument. Thus, a new model was developed which differed from the first one mainly in the following points:

1. The deflecting system has been divided into two sections, a pure cathode beam relay or ray blocking device and the recording part of the instrument which can be used without the Norinder relay (see Fig. 8).

2. This first change also has the advantage that now, contrary to the first design, the cathode beam traverses

Fig. 4—Westinghouse Cathode Ray Oscillograph

the concentration coil field without deviating from its axis. This simplifies the mechanical design and the adjustment of the instrument.

3. By means of a cathode ray filter the fogging of the film has been reduced.

4. The vacuum properties and the mechanical structure of the instrument have been improved.

The progress in this last point was achieved largely by following the well established design of mercury arc rectifiers.

The new oscillograph model is shown in Figs. 4 and 5. The housing consists of seamless steel tubing and steel plates welded together. All flanges are sealed with rubber gaskets, ½ in. to ¾ in. wide. The bushings are made of porcelain and soldered to the steel housing by means of a special process (Fig. 6).

To the best of the writer's knowledge, previous oscillographs, at least those in general use, have been made of bronze castings, seamless brass or copper tubes, sheet brass or even forged pieces, soldered or brazed together. The difficulties of getting such structures air tight are

Fig. 5—Westinghouse Cathode Ray Oscillograph with Norinder Relay

well known to workers on vacuum devices. It may mean days and weeks of tedious work to locate leaks on the evacuated vessel. A welded steel case can be made

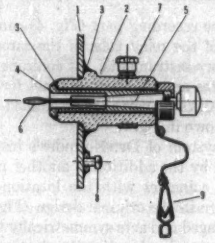



Fig. 6—Oscillograph Porcelain Bushing

1. Steel housing
2. Porcelain bushing
3. Solder
4. Brass core
5. Monel cone
6. Contact spring
7. Voltage terminal
8. Ground terminal
9. Clip connected to either voltage or ground terminal

airtight more easily in the first place, and moreover it is strong enough to withstand high inside air pressure which may be used to disclose leaks in the vessel when submerged in water or coated with soapy water.

4. Fortescue, Atherton, Cox, A. I. E. E., April 1929.

Ill effects on the cathode beam from possible magnetic sources in the steel housings have not been noticed.

Lapped joints at doors and flanges, a delicate and expensive feature in most oscillographs, have been replaced by rubber gaskets. However, where the transmission of a continuous rotating motion into the inside of the instrument is necessary, conical joints are used as shown in the design of a bushing, (Fig. 6) whose stem also serves for adjusting the distance of certain deflection plates from outside without disturbing the vacuum.

The plate system is arranged so that the instrument is divided into two parts, the recording part and the relay tube. The recording part (Fig. 4) can be used independently of the relay tube in the same manner as other laboratory instruments. It contains two pairs of deflecting plates and an electromagnet for shifting the zero point. All these parts are assembled on the small frame work shown in Fig. 7.

1. 2. 3.

Fig. 7—Inner Parts of Cathode Ray Oscillograph—Deflecting Plates and Their Supporting Structures

1. Upper relay plates
2. Cathode ray filter and lower relay plates
3. Adjusting magnet and deflecting plates

The plate system of Dr. Norinder's instrument has been modified by the addition of another pair of plates whose center coincides with the location of the diaphram aperture in the original design (Fig. 2 and Fig. 8). It is arranged and acts symmetrically to the uppermost set of plates, thus bending the electron jet back on the center line of the instrument. The beam therefore passes through the diaphram and the concentration field below without any deviation from the axis. It then enters the recording part with its two sets of deflecting plates which provide the means for measuring. The relay tube merely admits the cathode ray beam into the recording part as soon as the voltage on its plates is high enough to take the beam off the target. In instruments connected to energized transmission lines the ratio of the potential divider is chosen so that the normal line voltage moves the beam back and forth within the limits of the target. Yet, slower speed electrons which are always present in the beam and which are more sensitive, are deflected off the target even by the normal line tension. Some of them would reach the recording part and result in a certain amount of fogging on the film, if they were not filtered out. A pair of filter plates $F$ (Fig. 8) is inserted at right angles to the other relay plates at a suitable place below the target. Upon it, a constant d-c. voltage is impressed which deflects the normal speed rays through a fixed angle, given by a bend in the relay tube structure. The slower rays are deflected through a larger angle and therefore thrown off the center line of the instrument. Only comparatively few can pass through the apertures of both diaphrams ($D_1$ and $D_2$). This removes a very pronounced cause of fogging. A fluorescent screen on the upper diaphram permits observation of the adjustment of the relay through the upper window shown on Fig. 5. The diaphrams themselves consist of steel plates which confine the concentration field almost completely to the 5 in. of space between the planes $D_1$ and $D_2$. For this length, of course, the shell of the housing consists of non-magnetic material. About 550 ampere-turns are required for good concentration of the beam on the observation screen or the film, about 21 inches below. The photographic records are taken on ordinary kodak 3¼ by 5½-in., ten-exposure roll films or on a special "process film"[5] which gives better contrast.

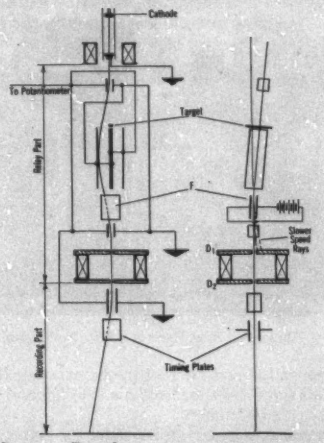



Fig. 8—Cathode Ray Oscillograph with Norinder Relay and Cathode Ray Filter

5. Manufactured by the Eastman Kodak Company.

The electron jet is emitted from a "cold" cathode, formed by an aluminum plug, the applied voltage being about 50 kv., which is obtained from a rectifying unit. A concentration coil around the anode helps considerably in focusing the beam upon the target where a small cross section electron jet is especially desirable.

The type of oscillograms obtained with this instrument is shown in Fig. 9. The record is taken with oscillatory timing movement and can be replotted in linear scale. With the oscillatory timing movement, a comparatively long surge, with all its details brought out plainly, can be concentrated on a small piece of film.

Another advantage of an oscillatory timing scale is, that the timing voltage (of a sinusoidal or a zigzag wave shape) can be applied permanently, whereas in a single unidirectional timing movement the timing voltage

Fig. 9—Lightning Surge on 220-Kv. Line

should be impressed upon the deflecting plates synchronously with the arrival of the surge which is to be measured. Of course, this process must be initiated by the arriving transient itself. Several methods for accomplishing this are known.[6] Where we applied a unidirectional timing scale in our field tests, we have used a method that had been developed in our laboratories.[7] (Fig. 10.)

In this connection, the Norinder relay can be operated so that the target shadow at the zero line (Fig. 9) is eliminated. The cathode ray beam is deflected from the target not by the surge voltage itself, but through the voltage $E$, part of which is impressed upon the relay plates as soon as the double gap $S$ breaks down. In the arrangement shown in Fig. 10 only a positive surge can trip the relay. Of course, by reversing the terminals of the rectifier tube the relay can be made to respond to negative surges. Fig. 11 shows the circuit of a relay that operates on surges on either polarity. Ordinarily the voltage between the middle and either one of the outer spheres is $\frac{1}{2}$ $E$ plus the alternating component

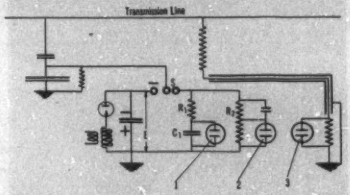



Fig. 10—Circuit for Automatic Recording with Unidirectional Timing Motion, Responding to Surges of One Polarity

1. Timing plates 2. Relay plates 3. Voltage plates

induced by the normal line potential. The gaps are set for a slightly higher voltage. A surge will cause the double gap to break down on the side whose polarity is opposite to that of the transient. This throws the full voltage $E$ across the other half of the gap so that it breaks down immediately afterwards. Now the condenser $C_1$ starts to charge through $R_1$ and the voltage on

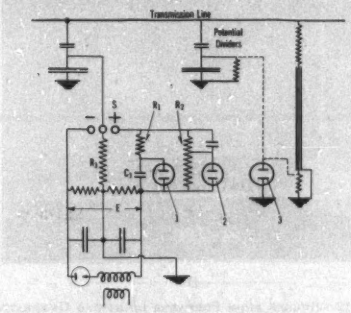



Fig. 11—Circuit for Automatic Recording with Unidirectional Timing Motion, Responding to Surges of Either Polarity

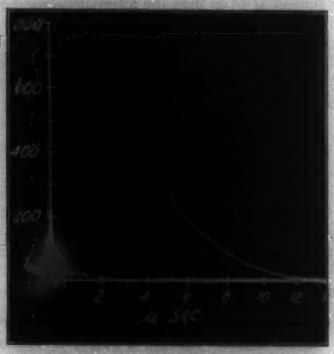
1. Timing plates 2. Relay plates 3. Voltage plates

$C_1$, changing at a known rate, causes the cathode beam to move along the timing axis. At the same time, $E$ discharges slowly over $R_2$ which makes the voltage across the relay plates decrease so that the cathode beam finally returns on the target. This terminates the exposure of the film. If the voltage measuring plates are connected to the line through a capacity potential divider, the time lag of the tripping circuit

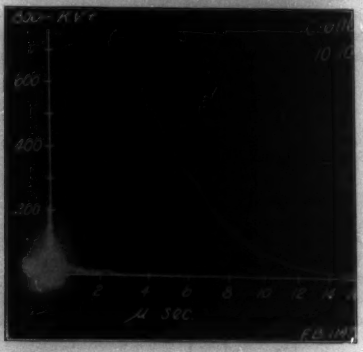
6. D. Gabor, Rogowski and Wolff, W. Krug, K. B. McEachron, see Bibliography.

7. J. J. Torok and F. D. Fielder, *Electric Journal*, July 1929.

causes the loss of the beginning of the surge record. The delay depends on amplitude and steepness of the impulse voltage, but it can be kept below ½ microsecond if the coupling between the tripping gaps and the line is adjusted correctly and if the gaps are well irradiated. Where a resistance potential divider with a delaying




A




B

Fig. 12—Surges from Portable Lightning Generator

A taken with 500 ft. of delaying cable
B taken with 1000 ft. of delaying cable
The applied cable was No. 16, two-conductor "Okocord" with 1/16 in. lead sheath. Diameter over rubber jacket 0.415 in.

cable can be used, the complete surge can be recorded as shown in Fig. 12.[8]

As pointed out above, the Norinder relay, if used in connection with unidirectional timing schemes, is not operated directly by the surge voltage—which may be of either polarity—but by the voltage of a rectifier which is fixed in polarity and amplitude. It, therefore, can be considerably simplified and reduced in size as shown in Fig. 13. The large target and the short over-all length render it a very efficient and easily adjusted ray blocking device which permits exposing the films for hours without any noticeable fogging effect.

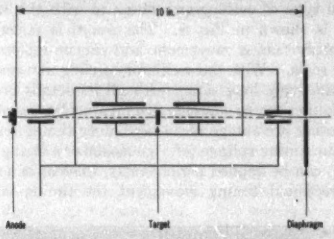



Fig. 13—Diagram of Simplified Relay Tube

## Appendix

### The Sensitivity of the Cathode Ray Oscillograph at High Cathode Voltages

The deflection $y$ of an electron jet due to a homogeneous electrostatic field is computed usually by means of the relation

$$y = \frac{1}{2}\frac{E}{V}D\frac{l}{d} = D\tan\alpha \qquad (1)$$

$E$ is the voltage impressed upon the deflection plates and $V$ the cathode voltage; the meaning of the other

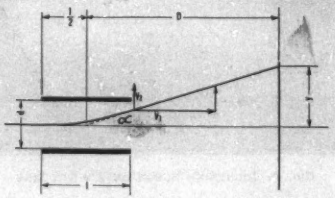



Fig. 14—Diagram of Cathode Beam Deflection

symbols is illustrated in Fig. 14. For most practical cases, this formula is accurate enough; yet, at a cathode voltage of 60 kv. it already introduces an error of about 5 per cent because it neglects those relations between mass and speed which assume importance at velocities approaching that of light.

Of course, this has long been realized;[9] but there remained the task of putting these relations into a simple and concise formula for the sensitivity of a cathode ray oscillograph. The problem belongs to the domain of the theory of electricity and magnetism and of relativity, and as such is accessible only through an elaborate system of equations. However, we can avoid developing them by accepting one outstanding

8. The applied cable was No. 16 two-conductor "Okocord" with 1/16 in. lead sheath. Diameter over rubber jacket 0.415 in.

9. MacGregor-Morris and Mines, *I. E. E.*, Vol. 63, p. 1099.

conclusion of both these theories, namely, that electromagnetic energy has momentum[10] or, in the more generalized form of Einstein's theory, that energy in any form has inertia or mass. And both these theories agree in the postulation that the mass ascribed to the energy $W$ must be

$$m = \frac{W}{c^2} \quad (2)$$

[10,11]

where $c$ is the speed of light.

In the case of an electron, the kinetic energy imparted to it by the cathode voltage is equivalent to an

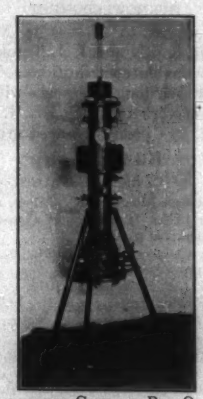


FIG. 15—WESTINGHOUSE CATHODE RAY OSCILLOGRAPH WITH RELAY TUBE OF FIG. 13

increase in mass $d\,m$ over the mass $m_0$ of the particle at rest:

$$d\,m\,c^2 = d\,W \quad (3)$$

On the other hand, this increase in energy $d\,W$ is due to the force $F$ of the electrostatic field, accelerating the electron along the distance $v\,d\,t$, where $v$ is the speed of the electron:

$$d\,W = F\,v\,d\,t \quad (4)$$

The force $F$, again, we determine as the change of momentum with respect to time:

$$F = \frac{d\,(m\,v)}{d\,t} \quad (5)$$

Eliminating $d\,W$ and $F$ from Equation (4) we obtain

$$c^2\,d\,m = v\,d\,(m\,v) \quad (6)$$

or

$$d\,m = \frac{v}{c}\,d\left(m\,\frac{v}{c}\right) \quad (7)$$

from which,

$$\left(\frac{v}{c}\right)^2 d\,m + m\,\frac{v}{c}\,d\left(\frac{v}{c}\right) = d\,m \quad (8)$$

and by integration

$$m = \frac{K}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \quad (9)$$

with $K$ as the constant of integration. If $v$ is zero, the mass is that of the particle at rest, $m_0$. Therefore $K = m_0$. So we arrive at the equation

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \quad (10)$$

On the other hand, the mass of a particle in motion can be expressed by the relation

$$m = m_0 + \frac{W}{c^2} \quad (11)$$

where $\frac{W}{c^2}$, according to Equation (2) represents the increase in mass due to the kinetic energy acquired.

In the case of an electron jet, the kinetic energy of the electron which has traveled from cathode to anode and then has passed through the anode hole, is equal to the product of the potential difference $V$ between cathode and anode, and the charge $e$ of the particle. $W = V\,e$.

Thus, from Equations (10) and (11) we derive the relation

$$\frac{m_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = m_0 + \frac{V\,e}{c^2} \quad (12)$$

from which we obtain the equations

$$\sqrt{1 - \left(\frac{v}{c}\right)^2} = \frac{1}{\frac{1}{c^2}\,V\,\frac{e}{m_0} + 1} \quad (13)$$

and

$$v^2 = V\,\frac{e}{m_0}\,\frac{\frac{1}{c^2}\,V\,\frac{e}{m_0} + 2}{\left(\frac{1}{c^2}\,V\,\frac{e}{m_0} + 1\right)^2} = v_1^2 \quad (14)$$

This $v$ represents the speed of an electron in the cathode ray beam after it has left the anode. We now call it $v_1$. When traveling through the electrostatic field of a pair of deflection plates, the electron also obtains a speed component $v_2$ perpendicular to its original direction, as shown in Fig. 14.

$$\frac{v_2}{v_1} = tan\,\alpha \quad (15)$$

where $t\,g\,\alpha$ is the same term as applied in Equation (1).

For the rigid calculation of $v_2$ we would have to go

10. J. H. Jeans, "Electricity and Magnetism."
11. P. Lenard and A. Becker, "Kathodenstrahlen, Handbuch der Experimental Physik."

through the same kind of considerations which led to the exact determination of $v_1$. However, on account of the comparatively small value of $v_2$, the deflection attained changes the absolute speed and the mass of the electron only very little from the values it had when leaving the anode. Therefore, we can calculate $v_2$ according to the rules of ordinary mechanics as produced by a force on a constant mass of the value $\frac{m_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$.

$$v_2 = a\,t = a\,\frac{l}{v_1} \tag{16}$$

where $a$ is the acceleration and $t$ the time in which the electron traverses the field of the length $l$.

The acceleration in the direction of this field is produced by the force $\frac{E}{d} \times e$.

$$a = \frac{1}{m}\,\frac{E}{d}\,e = \frac{\sqrt{1-\left(\frac{v}{c}\right)^2}}{m_0}\,\frac{E}{d}\,e \tag{17}$$

and therefore

$$v_2 = \frac{E}{v_1}\,\frac{l}{d}\,\frac{e}{m_0}\sqrt{1-\left(\frac{v}{c}\right)^2} \tag{18}$$

From Equations (13), (14), and (18) we now obtain the relation of Equation (15) in a new form:

$$\tan\alpha = \frac{E}{V}\,\frac{l}{d}\,\frac{V + c^2\,\frac{m_0}{e}}{V + 2\,c^2\,\frac{m_0}{e}} \tag{19}$$

Now, the ratio between the charge $e$ and the mass $m_0$ of the electron is

$$\frac{e}{m_0} = 1.765 \times 10^7 \text{ electromagnetic units.}$$

and $\quad c = 3 \times 10^{10}$ cm. sec.$^{-1}$.

If $V$ is measured in volts, the value of $c^2\,\frac{m_0}{e}$ in electromagnetic units must be multiplied by $10^{-8}$. Therefore

$$\tan\alpha = \frac{E}{V}\,\frac{l}{d}\,\frac{V + 5.1 \times 10^5}{V + 10.2 \times 10^5} \tag{20}$$

or for $E$ and $V$ in kilovolts.

$$\tan\alpha = \frac{E}{V}\,\frac{l}{d}\,\frac{V + 510}{V + 1020} \tag{21}$$

For small values of $V$, the term $\frac{V + 510}{V + 1020}$ becomes $\frac{1}{2}$ and so Equation (21) conforms with Equation (1). For a cathode voltage of 60 kv. the above fraction attains the value of $\frac{1}{1.895}$.

This effect can very well be demonstrated with the instrument described in this paper. Thus we are brought in direct contact with the realm of the theory of relativity through an apparatus which, on the other hand, is to serve ordinary engineering purposes.

ACKNOWLEDGMENT

The author wishes to express to Messrs. A. M. Opsahl, Lewis R. Smith, and J. J. Torok his appreciation for their valuable contributions. Through their cooperation and their long experience with cathode ray oscillographs, the work to which Dr. H. Norinder laid the cornerstone, has been advanced greatly.

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17. Fortescue, Atherton, Cox, A. I. E. E. JOURNAL, April 1929.
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## Discussion

**E. S. Lee:** The paper by Mr. Ackermann describes a cathode ray oscillograph with Norinder relay. The oscillograph is of the Dufour type in which a stream of electrons from a cold cathode at high voltage strikes a photographic film to record the phenomenon under observation. For cases where the occurrence of the phenomenon cannot be controlled, such as in measurements

of lightning wherein the lightning flash comes without warning, the Norinder relay may be added to the oscillograph to prevent the electron stream from striking the film until the phenomenon occurs. This scheme was referred to by Dr. Harald Norinder two years ago (see A. I. E. E. TRANS., Vol. 47, p. 446) and was described a year ago by Messrs. Fortescue, Atherton, and Cox (A. I. E. E. TRANS., Vol. 48, p. 451).

While the scheme suggested by Dr. Norinder is most interesting, it is not at all necessary for such measurements, as results can be obtained equally well with a simple oscillograph of the Dufour type using an external circuit for establishing the cathode ray stream. The first surge voltage due to natural lightning recorded in this country, reported from this platform a year ago (A. I. E. E. TRANS., Vol. 48, p. 445), was thus obtained as were more than one hundred other similar records reported at this convention.

The type of oscillogram obtained with the cathode ray oscillograph with Norinder relay is shown in Fig. 9. It is quite generally conceded that records of this form are not as satisfying as those obtained directly in rectangular coordinates. To obtain these with the Norinder relay requires an additional external circuit as shown in Figs. 10 and 11.

It thus appears that since records can be obtained with an oscillograph of the Dufour type with an external circuit to compare with those obtained with an oscillograph of the Dufour type with a Norinder relay and an external circuit, the Norinder relay is not necessary.

**E. J. Wade:** There is one question which Mr. Ackermann did not mention which I think may give some difficulty in the operation of this oscillograph. This is in connection with the cathode. Where the voltage is maintained for a long period it would seem that trouble might be experienced due to liberation of gas in the tube due to bombardment by cathode rays. In our experience in the laboratory we do not excite the cathodes except for brief periods. We are able to take at least 1000 oscillograms before we have to replace the cathodes. But due to the very short time which it is excited the integrated life is only about five seconds. Mr. Ackermann must of course obtain very much longer life than that. Possibly the reason for the much shorter life that we find, is that we apply about 100 kv. to the cathode rays rather than I think 50, as he stated in his paper.

In Fig. 12 of Mr. Ackermann's paper in which he shows the use of the cable for delaying the surge, it seems that it should be 1000 ft. of cable rather than 100 ft.; otherwise the delay is not consistent with the length of cable.

In the three-electrode triple gap scheme which was shown on the slide, the middle electrode was connected to the ground. This scheme would not work correctly for surges of both polarity. It would only work for one polarity. As we used the scheme, this middle electrode was held at one-half of the potential of the cathode.

Incidentally, I might mention that this circuit is covered by a U. S. Patent, 1,738,464.

**E. F. W. Beck:** After Mr. Lee's forceful and critical discussion, I rather hesitate to say very much, but I should like to point out that my colleague, Mr. Cox, and I, have prepared a paper on the cathode ray oscillograph study transmission lines. In this paper we discuss the relative advantages and disadvantages of the oscillatory and the linear time scale, and we have endeavored to show in this paper why we use one or the other. We believe the oscillatory time scale has certain advantages, particularly in the early work with the duration of transient to an arc which we have known.

I should like to point out that with the use of this Norinder relay the record starts immediately when the transit voltage exceeds the linear voltage.

**O. Ackermann:** Mr. Lee asks me to show the advantage of an oscillograph with Norinder relay used in connection with a circuit for automatic starting and unidirectional timing movement as compared with a Dufour oscillograph with external initiating circuit.

It may be difficult to see the advantage unless you have had operating experience with both schemes. We have been using the Dufour oscillograph with external initiating circuit (triple gap scheme) in the laboratory for many years. I refer to a paper by Messrs. Harrington and Opsahl in the *Electric Journal* in 1927. We know that it is difficult to operate an oscillograph with a triple gap scheme. The circuit is very sensitive, if not capricious, because it depends on the operation of a high-voltage spark-gap. You realize this especially if you want to run a number of oscillographs of this type for which you must find suitable operators.

An oscillograph with Norinder relay is much easier to operate. It is therefore much less difficult to find capable operators for this type of instrument. There is a steady cathode ray beam which can be adjusted conveniently to the best concentration. You can try it on 60-cycle recurrent phenomena and so even a less skilled operator is able to do the job. This is a considerable advantage if you have to find the personnel for a larger number of instruments.

As to the building material for cathode ray oscillographs housings, we have built oscillographs out of copper tubes, brass tubes, and castings. Once the housing has left the shop and is pronounced air tight, it is air tight, no matter what kind of a material is used. But if it is necessary to produce a half dozen oscillographs for a lightning season and for laboratory experiments in a short time, then we must rely on the shop force to produce the instruments air tight without much delay. In such a case we naturally choose a method which the shop is familiar with, and that is the air tight arc welding. I do not say that the oscillograph with a steel housing is better in use, but it surely is much easier made. That has been proved by our own experience. In other companies with different shop facilities this may not be true, but in the Westinghouse Company it has worked out best in this way.

The question has been raised as to what accessory apparatus is needed for a cathode ray oscillograph. Mr. Lee mentioned our Fig. 4. There we have a switchboard, an oscillator, a high-voltage rectifier, but the largest part of the room is occupied by a surge generator in the rear.

In connection with Fig. 12 the question has been brought up as to why we use a delaying cable when experimenting with the surge generator.

First of all I want to call to your attention that in these experiments we use the same automatic oscillograph circuit as applied for lightning records,—that is, there is no control connection between oscillograph and surge generator circuit. Work with the surge generator is always done on de-energized lines, and therefore we can conveniently use a resistance potentiometer into which a delaying cable can be inserted without difficulty. The purpose of the delaying cable is to start the voltage deflection a short interval after the timing movement has begun.

Mr. Wade asks how we can keep the cathode tube energized continuously without being troubled with the liberation of gases and burning of the cathode. By means of a leak valve we can regulate the constant flow of a small amount of air into the oscillograph. This has a cleaning effect and the valve can easily be adjusted so that a balance between the liberated gases, the flow of fresh air, and the pump capacity is reached. The burning of the cathode plug is very slight even after a full day's operation. Apparently the cathode current under permanently applied cathode voltage need not be as high as for short time excitation. This is partly due to the fact that a steady beam can easily be adjusted for best efficiency. After all, it is not difficult to exchange the cathode plug about once every second day.

I think this answers the major questions which have been brought up in connection with my paper.

# Submarine Telegraphy
## in the Post-War Decade

BY I. S. COGGESHALL*

Non-member

***Synopsis.***—*The post-war decade, which has given to the technique of the submarine telegraph both the regenerative repeater and the inductively loaded cable, deserves to be chronicled as one of the most significant periods in the history of the cable art. These two major developments and some important corollary inventions and applications are discussed in this paper. Reference is made to articles previously published describing recent developments at length. In addition the paper contains descriptions of:*

*A two-element cable recorder code adapted to land-line transmission.*

*A three-element Wheatstone code adapted to cable transmission.*

*A cable printer system using a two-element code of practically the same time length as three-element recorder code.*

*A typical installation of Pernot superimposed cable carrier apparatus.*

*A brief account of the steps which have been taken to balance an inductively loaded duplex cable.*

*An appendix to the paper comprises a discussion of certain variables which affect the traffic capacity of cables.*

* * * * *

### Historical Notes

PRIOR to the year 1918, transatlantic cables were worked sectionally by manual relay; that is, cablegrams were recorded and re-sent at various cable stations between New York and London, involving transcription by operators in Nova Scotia, Newfoundland, Ireland, or Cornwall, and sometimes at all four points. This procedure was expensive, but not necessarily slow because an operating technique, succinctly described as "sending under the siphon," had cut down the time delay at each transmission point to a few seconds.

The year 1918 saw the first successful American attempts to repeater one long cable section into another, the result having been made possible by improvements in relays, shaping networks, and magnifiers. These early experiments resulted in a decrease of the speed of working the long sections, because of the necessity, under conditions of electrical relay operation, for the mechanically pivoted contacting element to take up a definite position at every change of polarity, whereas in siphon operation the operators had become accustomed to read signals which often did not approach or cross the zero line.[1] A Newfoundland-Ireland cable with capacity-resistance parameter of 2.43 ohm-farads was operated sectionally, duplex, during the latter part of the war, at 9.9 cycles per second, three-element signals, (320 letters per minute, recorder code); the same cable with electrical relay at Newfoundland worked through from Ireland to Nova Scotia at 8.8 cycles per second (285 letters per minute); this remains to-day the letter-capacity of that cable in each direction, but the regenerative repeater has made it possible to secure this speed through from New York to London.

In spite of the relatively high-speed sectional operation maintained during the war and immediately thereafter, the combined facilities of all cable companies were not sufficient adequately to care for the traffic which was offered. There was difficulty in having deep-sea repairs made owing to the necessity of convoying cable ships. Sectional operation and military censorship threw a great burden of service traffic upon the cables, with the result that the congestion was sometimes so great that it could not be cleared overnight. The traffic incident to the war and later to the negotiations for peace overwhelmed the cable plant and served to focus attention upon the military and economic importance of adequate overseas communications.

By way of contrast with the conditions of ten years ago, it is interesting to note that due largely to technical improvements in operation and to an increase of cable facilities, the transatlantic cable plant is now running practically "clear" from 9 p. m., New York time, until the opening of business the following morning, and that prior to 9 p. m. the load handled is about 40 per cent greater than the war time load. Despite the general use by the public of low rate deferred services which have cut the average cost per word from New York to London from $0.25 to $0.152, with a minimum of $0.03, the cable daily load factor has dropped from 100 per cent to 50 per cent. The developments of the last few years have therefore not only met immediate demands for cable traffic capacity but have opened opportunity for future development without additional plant cost.

An analysis of the factors which may be thought of as having given impetus to the unprecedented technical expansion of the decade just ended gives first place to the success with which automatic apparatus was adapted to landline telegraphs in the preceding decade; second, to a wide dissemination among engineers of transmission principles, epitomized in the "telegraph equation" and popularized by writers like Malcom's and third, to an economic urge produced by

*General Traffic Supervisor, Western Union Telegraph Co., New York, N. Y.

1. See Appendix, Section 5.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

2. "Theory of the Submarine Telegraph and Telephone Cable," by H. W. Malcom, Benn Bros., London, 1917.

transoceanic radio competition with its threat to supersede cable telegraphy unless the costs of maintaining the older form of communication were substantially reduced.

To survey the accomplishments of the period under consideration in proper perspective necessitates the selection of the more important developments. These were, in order of importance of results, the regenerative repeater, the inductively loaded cable, the cable printer, and a number of others grouped below as miscellany.

## Regenerative Repeaters

The regenerative repeater is a device for picking up the least distorted portion of successive unit signal impulses as they arrive over a circuit, and for utilizing their respective polarities to control the formation of completely regenerated signals to be passed into another circuit. The application of regenerative repeaters to cable systems is an achievement of the post-war decade.

In practise, tuning forks vibrating in synchronism at the opposite ends of a cable section form the basis of regenerative repeater systems. The frequency of vibration of the forks usually bears some integral ratio to the primary signaling frequency, $f$. ($f$ is the frequency which is produced by an unbroken succession of unit signal impulses of opposite polarities.) Thus, a fork at Penzance, England, vibrating at frequency $5f$, may drive a multipolar synchronous motor at a constant speed such that the transmitter, which is geared to the motor, will send square-topped alternating current into the transatlantic section at frequency $f$. At Bay Roberts, Newfoundland, a fork vibrating at frequency $2f$ may be so phased with respect to the incoming signals that a contact on the tine will, in effect, be applied to the cable in the middle, or best portion, of the received unit impulses. The polarity of the incoming impulse at the instant the tine makes contact will be locked up through suitable circuits for the full duration of a unit impulse, and will determine the polarity of a "regenerated" impulse to be transmitted into the next section of line. The fork repeater[3] is the simplest of the regenerators and during the past few years has found extensive application in cable work.

The design of constant frequency forks has naturally received much attention. Since the modulus of elasticity varies with temperature, constant temperature chambers in which forks are placed[4] have been designed. Practically all forks at the present time are magnetically impelled, some through circuits set up by tine contacts,[3] others by external circuits containing oscillating vacuum tubes.[4] Most forks are weight loaded; fine variations in frequency are secured by adjustable weights[5] or adjustable magnetic loading on the tines.[6] The fork used by the Eastern Telegraph Company has a magnetic loading which is alternately applied and removed, as determined by the relationship of the rotation of a synchronous motor, driven by the fork, to the movement of the pendulum of a fine clock; the fork frequency varies between narrow limits from second to second but integrates over a period of a minute or a week with an accuracy as great as that of the timepiece itself.

To maintain two forks on a 240-letters per minute cable in absolute synchronism for 8 hours would require of each fork a degree of accuracy such that the variation would not exceed one part in 1,500,000. This is not practically attainable at present, so all fork regenerative systems employ some method of correction of fork speed. Several different systems take advantage of the fact that frequency varies slightly with amplitude of fork vibration, and that amplitude is readily controlled by magnetically loading the fork. The instant of reversal of polarity of incoming current forms a convenient datum point to which the action of the receiving fork is referred; if the phase of the receiving fork leads the incoming signal, a circuit is set up which dampens the vibration of the fork; this in turn will result in a lag of the fork behind the incoming signal, causing the setting up of a circuit which will increase speed. The fork is therefore always kept in phase, within narrow limits.

At times it is advantageous to arrange a receiving fork to drive a synchronous motor at constant frequency and to handle the received currents through brushes mounted on the motor shaft, thence through segments forming the "rings" of a distributor.[5] If the motor has a speed of $f/2$ revolutions per second, one unit signal impulse will cover 90 deg. of rotation of the wheel. Such an arrangement is called a rotary regenerative repeater. The pick-up and lock-up principles do not differ radically from those employed with the fork regenerator.[3] Correction usually takes the form of a ratchet[5] or differential-gear[7] mechanism interposed in the discontinuous shaft by means of which the synchronous motor drives the brushes.

The signals which compose the letters of cable recorder code are called three-element signals because they contain impulses of positive, negative, and zero (earthed) potentials. Regenerators repeat three-element signals from cable to cable perfectly, but where landlines are involved the zero potential is not conveniently handled on account of the high level of induced currents encountered. In 1926 the Western Union first joined three-element cables to two-element landlines through a modified rotary repeater, and since then this system has afforded great flexibility in making

3. *Printing Telegraphs on Non-Loaded Ocean Cables*, by Herbert Angel, A. I. E. E. Trans., Vol. XLVI, 1927, p. 884.

4. Western Electric installation of constant temperature fork chambers, thermostatically controlled; tube-driven forks; New York-Emden cable.

5. *Printing Telegraph Systems*, by J. H. Bell, A. I. E. E. Trans., Vol. 39, Part 1, 1920.

6. *A Non-Rotary Regenerative Telegraph Repeater*, by A. F. Connery, A. I. E. E. Trans., Vol. XLVI, 1927, p. 897.

7. "Automatic Printing Equipment for Long Loaded Submarine Telegraph Cables," by A. A. Clokey, *Bell System Tech. Jl.*, Vol. VI, July 1927, p. 402.

up through cable-landline circuits. The modified rotary repeater[8] makes use of the fact that if the limiting frequency of a cable section is $f$, the landline to which it is connected can almost always be worked without difficulty at $2f$. Consequently the three-element signals may be converted after regeneration into two-element signals of half-unit length; the recorder "dot" becomes plus, minus; the dash becomes plus, plus; and the letter-space becomes minus, minus. The cable signal for letter "A," (dot, dash, space), regenerated from the cable at frequency $f$, is thus retransmitted to the landline as plus, minus, plus, plus, minus, minus, at frequency $2f$. This signal can be repeatered through any standard landline repeater. At the terminal the signal is "unscrambled" by means of a fork running at frequency $4f$ and suitable relay circuits, and is read by the operator as ordinary three-element cable recorder code.

A recent adaptation of the above arrangement makes it possible to send Wheatstone code through cables at double the ordinary speed.[9] The Wheatstone two-element code averages 9.27 impulses per letter,[10] compared with recorder code, 3.71. An examination of Wheatstone as punched on a standard perforator shows that successions of center-holes may be divided into pairs containing only the three combinations: plus, plus; minus, minus; plus, minus. This suggests the reversal of the process just described. Wheatstone two-element signals, received from a landline at frequency $f$ are retransmitted after regeneration into a cable as three-element signals of frequency $f/2$. The code on the cable therefore averages only 4.63 impulses per letter, which is more nearly comparable in efficiency with the recorder average of 3.71. At the cable terminal the code may be reconverted into Wheatstone and can be read by ear or recorded by Creed system if desired.

An example of the application of the rotary regenerator to a circuit employing cable recorder code is afforded by the Western Union's present direct New York-Berlin circuit, composed as follows: From Berlin to Emden, aerial landline, earthed, three-element. At Emden, a three-element repeater with no regeneration. From Emden to London, submarine four-conductor cable, earthed three-element circuit. At London, three-element rotary regenerative repeater. From London to Penzance, underground cable, metallic three-element circuit. At Penzance, three-element rotary regenerative repeater. From Penzance, England, to Bay Roberts, Newfoundland, earthed three-element submarine cable. At Bay Roberts, three-element rotary regenerator. From Bay Roberts to Hearts Content, Newfoundland, aerial landline, three-element. At Hearts Content, three-element repeater, no regeneration westward. From Hearts Content to North Sydney, N. S., submarine cable, three-element, superimposed carrier, Pernot system. At North Sydney, three-element to two-element fork regenerator, (variant). From North Sydney to New York, aerial landline, two-element, with repeaters at New Glasgow, N. S., St. John, N. B., Bangor, Me., and Boston, Mass., earthed all the way but operated in conjunction with simplex telephone from North Sydney to Vanceboro, Me.

The regenerator has had several marked effects upon the fortunes of all the cable companies. First, it has resulted in labor savings at repeater stations of the order of 70 per cent of the total staff in attendance. Second, it has met the challenge of the transoceanic radio for "direct" connections. New York is now electrically connected by the cables of various companies with London, Liverpool, Irish Free State, Emden, Berlin, Havre, Paris, the Azores, Havana, Mexico City, Barbados, Pernambuco, Rio de Janeiro, Valparaiso, and Buenos Aires, and several intermediate points. An adaptation of the fork-driven transmitter has made it possible economically to assign direct facilities between important branch offices, as, for instance, between the New York and Liverpool cotton exchanges. A third effect of the regenerator has been to improve the speed of service on the bulk of traffic, as compared with the purely specialized handling of important files that was common in days of manual relay. Fourth, the accuracy of the service has been improved, both by reduction of the hazard incident to the handling of messages by many operators, and by the substitution of a bold, easily read signal for the old-time distorted characters.

## Inductively Loaded Cables

The principles involved in the improvement of transmission of cable signals by inductive loading have been understood for many years, but their application has been the work of the past decade.

Inductive loading may be lumped, continuous, or tapered. The latter two methods have proved to be practical on long cables, continuous loading being optimum for one-way operation and tapered loading for duplex operation. Both methods employ permalloy,[11] an American-made alloy, or mu-metal, a similar foreign product, applied in the form of a continuous helix of tape or wire wound around the cable conductor as an axis, and contiguous to it. The alloys mentioned are composed of nickel, about 80 per cent; iron, about 20 per cent; sometimes cobalt; and certain other metals added to provide mechanical malleability, electrical resistivity, etc., required in practise. Alloys of this character have high permeability in weak magnetic fields. Their general effect upon transmitted signals is to make more abrupt the slope of the "arrival curve" of power at the terminal; at the same time the attenuation of the signals of frequency $f$ is decreased, so that for an irreducible minimum of received power at the

8. C. F. Nelson, U. S. Patent, 1927.
9. C. F. Nelson, U. S. Patent, 1929.
10. See Appendix, Section 6, Table I.
11. *The Loaded Submarine Telegraph Cable*, by Oliver E. Buckley, A. I. E. E. Trans., Vol. XLIV, 1925, p. 882.

terminal, $f$ can be increased. The layman's conception of added inductance "offsetting" the capacity of a cable, while inaccurate in detail, is essentially correct in estimating effect.

There are now four continuously loaded cable sections and one taper-loaded cable in operation in the Atlantic. Two of the four continuously loaded sections are repeatered to form one four-channel uni-directional cable between New York and London, operated by the Western Union; and the other two sections are repeatered to form one five-channel uni-directional cable between New York and Emden, Germany, with one channel dropped at Horta, and operated jointly by Western Union, Commercial Cable Company, and German Atlantic Telegraph Company. The present uni-directional printer operating speeds of these cables are 67.5 and 65.0 cycles per second, respectively, (two-element signals).

Neither of these cables is being operated at its maximum output. Some idea of the magnitude of the capacity of these cables for traffic can be gathered from the discussion in Section 15 of the Appendix. Higher speeds on all permalloy cables are at present limited only by terminal apparatus. New equipment is being designed to make available some of the excess capacity.

While the level of parasitic interference forms the ultimate barrier to further increases of speed on uni-directional cables, the artificial-line balance continues now, as ten years ago, to limit the speed on long sections of cable operated in duplex fashion. It has been pointed out[12] that a cable having a $C\,R$ value of 2.7, utilizing three-element signals, and satisfactorily duplexed at 9 cycles per second, has a uni-directional speed of 22 cycles per second, but that the signal shaping apparatus by means of which the high speed is secured is of little use with the order of unbalance and interference levels usually existing. Nevertheless, the wide disparity between these two figures is a challenge to further work on securing better duplex balances. It has been recorded[13] that the Vancouver-Fanning Island 1902 cable, having a $C\,R$ value of 9.21, is duplexed at 4.3 cycles per second, a utilization twice as effective as that encountered in transatlantic practise; but it is explained that the level of interference is very low at both terminals, and that due to the low signaling speed a sluggish adjustment of the recorder can be made to filter out the high-frequency components of whatever unbalance exists.

The Bay Roberts-Horta cable, laid in 1928, is taper-loaded, the end sections being unloaded. It has a nominal one-way speed of 77.6 cycles per second, (2500 letters per minute, three-element).[14] Western Union engineers have successfully balanced this cable at one end, at 43.4 cycles per second, (1400 letters per minute, three-element); equipment is now being manufactured for the other end. It is to be seen, therefore, that in spite of the difficulties of balancing cables containing inductance as well as resistance and capacity, the duplex speed in each direction is more than half the uni-directional speed.

The balance was obtained, in this case, by the method of wave reflections from points on cable and artificial-line where impedances abruptly change, using the oscillograph[15] as a tool. A single impulse traveling simultaneously along cable and artificial-line is reflected at each point where the surge impedance changes. If there is a lack of correspondence between main and artificial lines at a point reached by the wave at time $t$ after the wave starts, a momentary difference of potential across the cable bridge will exist, due to reflection, at time $2\,t$. The artificial-line is then adjusted until at time $2\,t$ no difference of potential exists. Attention may then be given to conditions at time $2\,(t + d\,t)$, etc., until a straight line is obtained on the oscillograph, denoting "perfect" balance. Many practical difficulties, due to double reflections, effect of sea-earth, etc., had to be overcome in practise to secure a balance.

The artificial-line network used on this cable may be described as a succession of inductance units jointed in series, paralleled by a succession of resistance units joined in series, and the two series cross-connected at their respective joints by condenser units. The values are so chosen that the cable is, as nearly as possible, matched in impedance throughout its length, due regard being given to the relative importance of the portion of line nearest the terminal.

The considerations which result in the decision to lay a duplex loaded cable instead of a uni-directional cable are complicated. Each time the question comes up, the situation must be investigated from many angles, of which the rate of flow of traffic in each direction during different hours of the day is one of the most important, as is also the allocation of paralleling facilities to various uses. Since it is possible to secure an output of 2800 letters per minute from the duplexed cable referred to above, compared with a net uni-directional speed of 2380 letters per minute (deducting 5 per cent lost time for automatic turn-around), the duplex operation of a taper-loaded cable would appear to be optimum. A continuously loaded cable having the same uni-directional speed would require less copper but more miles of loading; the element of cost therefore has to be considered in determining whether to lay a duplexed or uni-directional cable.

At the present state of the art, uni-directional loaded cables are being utilized for handling "bulk" traffic of ordinary and deferred classes, while the old-type cables are being deployed for the fast, specialized services.

12. "The Application of Vacuum Tube Amplifiers to Submarine Telegraph Cables," by Austin M. Curtis, *Bell System Tech. Jl.*, Vol. VI, July, 1927.

13. "Recent Developments in Submarine Cable Design," by R. L. Hughes, *I. E. E. Jl.*, (London), Vol. 66, 1927, p. 140.

14. The conversions of cycles per second to letters per minute are based upon Section 6 of the Appendix.

15. Described by J. J. Gilbert, in an article: "Determination of Electrical Characteristics of Loaded Telegraph Cables," *Bell System Tech. Jl.*, Vol. VI, July, 1927.

## Printers

Printing telegraphs have been well established in landline practise for many years; their application to loaded and non-loaded cables is the product of the post-war decade.

Adaptation of printers to high-speed uni-directional cables has been made practicable by:[7] (a) Utilization of vibrating circuits for fill-in purposes, (b) Brush-driven vibrating circuits, (c) Automatic turn-around, with provision made for stopping and starting transmitters and printers, and short-circuiting amplifiers, stage by stage, (d) Improvement in relays, in distributor prime-movers, and in means for controlling phase relationships of sending and receiving brushes, (e) Provision for sending Morse at low frequencies over the cable without paralyzing the amplifiers.

The application of printing systems to old-type duplex cables[3] has been complicated by balance troubles. While the system of attenuation of single impulses can be carried on successfully at the receiving end of the cable, the application of double frequency at the sending end puts a burden on the balance too great to be taken care of at present. Two remedies have been suggested: (a) improved artificial lines which will handle the higher frequencies, (b) a "tank" circuit designed to attenuate the single impulses before impressing them on the cable apex through a three-element relay. The high speeds handled also introduce problems of variable lag,[3] all of which have not as yet been solved. Up to the present time the use of printers on old-type cables has been successful in so far as they have duplicated the performance of recorders, but purely for traffic reasons their installation in combination with recorder circuits in the same offices has not produced notable gains in operating economy. The factors entering into the application of printers to duplex cables in place of recorders are discussed in the Appendix.

A new type of printer system[16] is now being tried out which avoids some of the troubles encountered previously. It makes use of Murray-Baudot five-unit, two-element, uniform code, reconstructed into a non-uniform, two element code, wherein the letters are from 6 to 9 half-units in length, the average number of full-length impulses per letter being 3.50, comparing with 3.71 for cable recorder code (see Appendix, Section 6). Marking impulses of Baudot are transmitted full length, there being arbitrary reversal of polarity between each two successive marking impulses; spacing impulses are transmitted at half-length, the polarity of any number of them in succession from 1 up, being the same as the marking impulse which preceded them. Thus the letter $W$, which in Baudot is $M, M, S, S, M$,[17] in the Angel modification becomes $+ +, - -, -, -, + +$, each of the units being half the length of those in Baudot. The letter $F$ in Baudot is $M, S, M, M, S$; in Angel code it is $+ +, +, - -, + +, +$. The perforator, transmitter, and printer are the same as used in Baudot operation. The printer has the interesting and valuable feature of "going into pi" whenever a line hit or repeater fault occurs; this is caused by the non-uniform code, which results in the printer's going out of step when one letter is mutilated; but the receiving operator can restore synchronism with a push-button and get a correction by $R\,Q$ and $B\,Q$.[18] It will be noted that the code is so constituted that the half-units never occur singly, hence the code is handled at the same line frequency as Baudot and no undue demands are made of artificial line balances. It is to be observed also that while the double impulses are of length $L$, the same as single impulses in Baudot, the receiving margin must be such that signals of length 1.5 $L$ can be distinguished from those of length $L$.

## Miscellaneous Apparatus

Minor improvements in apparatus are not within the scope of this survey and some major developments can only be itemized. The post-war decade has seen the first practical applications of the vacuum tube amplifier with frequency-differentiating networks to cable operation.[12] A new method of correcting for zero-wander has been made available.[12]

A constant-frequency, impulse-motor-driven transmitter with gear-shifting arrangement for changing speeds has been successfully applied by the Eastern Telegraph Company.

Interpolators and reed-controlled switching of re-perforators, and their adaptation to way-cable operation, have been brought to a high degree of perfection by the All-America Cable system.

A re-perforator has been applied to the Western Union permalloy cable for purposes of picture transmission between London and New York by the Bartlane system, the five-hole tape of Baudot printer code being used to operate light shutters controlling six values of light in the picture reproducing machine.

Storage transmitters have been designed to eliminate the perforated tape between the perforator and transmitter; a printer will now record traffic within three to five letters of the perforator operator's keyboard manipulation.

This decade has seen the first uses made of permalloy and cobalt steel in cable instruments where strong fields are required under various conditions.

The year 1923 saw the laying of a submarine telegraph bi-core cable between Ireland and England; it is operated to give one metallic and one grounded circuit, thus avoiding the induction usually experienced in multi-core cables.

In 1923 the Commercial Cable Company laid the fastest non-loaded transatlantic cable[13] from New York to England via Nova Scotia and the Azores.

16. H. Angel and J. W. Robinson, patent applied for.

17. $M$ stands for *marking*, $S$ for *spacing*. The commas have no significance except to clarify the conversion.

18. $R\,Q\,s$ and $B\,Q\,s$ constitute "service" requests for information and replies thereto.

One development that has created interest among cable men is the Pernot system of superimposed a-c. signals, which has been applied to short sections of cable by several different companies. A short description of some of the constants of the Western Union's North Sydney, N. S.-Hearts Content, Nfld., installation follows.

The cable itself runs from Canso, N. S., to Hearts Content, being looped into North Sydney. On the "d-c. side," it is balanced for duplex working at Canso and Hearts Content, being operated at 8.0 cycles per second, (260 letters per minute, three-element recorder), and joined through rotary regenerative repeaters at Canso with a cable going to New York, and at Hearts Content with a transatlantic section. The operation of this circuit has not been disturbed by the Pernot application, except that it was necessary to compensate on the artificial-line at Canso for the Pernot coupling to ground at North Sydney.

The "a-c. side" is operated duplex on the North Sydney-Hearts Content section, at a speed of 5.0 cycles per second to 7.5 cycles per second, (160 letters per minute to 240 letters per minute, three-element recorder), and joined through a fork repeater at North Sydney with a New York landline, and through a three-element repeater at Hearts Content with a landline going to Bay Roberts, Nfld., rotary repeater, a few miles distant.

The "a-c. side" has a 50 cycles per second carrier for eastward transmission and an 80 cycles per second carrier for westward transmission. Since the primary signaling frequency $f$ of the alternating current may be 5.0 cycles per second to 7.5 cycles per second, the unit signal impulse modulates from 5 to 8 cycles of the carrier.

The required three values of current for three-element operation are provided by exciting the field of the alternator to zero, half, and full value, these values being controlled by the usual cable sending-on relays. At the receiving end the received high-frequency signals are amplified and rectified, and the envelopes of signals are caused to upset an impedance bridge. Currents of zero, half, and full magnitude are thus sent through the mechanically biased coil of a drum relay, the contact of which is adjusted to rest on "No Man's Land" when the modulating current is at half value. Full current modulation gives a "dot" contact and zero modulation a "dash" contact.

Special precautions are taken at North Sydney and Hearts Content by means of resonant acceptance and rejection circuits to keep transmitting carrier frequencies out of the receivers and vice versa. At Canso, high-frequency traps are provided, as North Sydney's transmission in mid-cable, through inductive coupling, goes both east and west.

## Conclusion

Enough has been presented in the foregoing outline of the accomplishments of the post-war decade to indicate that at its close we are dealing with cable transmitting speeds of a different order of magnitude from those characteristic of its beginning. There has been a corresponding satisfactory increase in patronage and consequent prosperity for the cable companies, which may be considered in the light of a guaranty of further technical developments in years to come. It is fairly safe to predict that there will be increasing utilization of electrically repeatered landline feeders to high-speed ocean cable sections, affording a large number of direct connections between the important cabling cities of the American and European continents. There have been recent announcements by the Bell System to the effect that we may expect further increases of cable speed through improvement of cable dielectric and armoring, making it possible to handle voice frequencies as well as those used for telegraphic signaling. The future, therefore, promises much of interest to engineers connected with one of the oldest, and now one of the liveliest, of the electrical arts.

The author desires to express appreciation to his associates in the Western Union organization for permission to describe, in some cases for the first time, the results of their research and experimentation.

## Appendix

### Factors which Affect the Traffic Capacity of a Cable

*1. Electrical parameters of the cable.*[11] These include total length; unit-length inductance, leakance, capacity; and unit-length resistance due to copper, eddy currents, sea return, and hysteresis. The values of some of these vary with frequency, and some are different in different parts of the cable. Since the length of the cable appears as an exponent in the attenuation equation, it is important to keep the length of sections at a minimum. A great deal has been accomplished in recent years by rearranging cable repeater spacing, within the rigorous limits imposed by geographical layouts.

*2. Maximum impressed voltage, sending end.* The hazard of breaking down the insulation of a cable is an effective limitation to the voltage, positive or negative with respect to earth potential, which may be employed. With voltages of 50 + and 50 − from grounded batteries, there is a total potential difference, available for signaling, of 100 volts, which can be used either for two-element or three-element transmission. It is evident that for a given frequency, there is no essential difference between the power transmitted when applied voltages are alternated, in the one case between earth and 50 volts positive, and in the other between 25 volts positive and 25 volts negative. Hence, twice as much power is transmitted with two-element signals as with three-element signals, the allowable maximum voltages to ground being constant.

The attenuation of power, however, increases with

frequency in exponential ratio,[11] and there are also variations introduced into the time-lag of signals on the line as frequency is increased. Hence, while it is possible to raise transmitted power from $W$ to $2\,W$ by sending two-element signals instead of three-element signals, and, keeping frequency $f$ constant, to raise the power at the receiving end of the circuit from $w$ to $2\,w$, it is not possible to apply power $2\,W$ at frequency $2\,f$ and obtain received power $w$. However, if $2\,W$ is applied, and received power $w$ is sufficient to override interference, the cable can be operated at a frequency $f_m$, such that $f < f_m < 2\,f$, where $f$ is the maximum three-element frequency, and $f_m$ is the maximum two-element frequency, the limiting voltages on the cable being the same. Observation has shown that this figure may lie in the region of $f_m = 1.10\,f$ or $1.15\,f$. The determination is usually complicated by the fact that as frequency is raised on a duplex cable, balance troubles come in to offset in part the gain made by doubling the power and increasing the frequency. Again, variations in lag[3] are likely to prove troublesome as the frequency is raised from $f$ to $f_m$, even to the extent of nullifying the entire gain by excessive errors or losses of synchronism.

*3. Method of impressing sending voltage on the cable.* In order to preserve the shape of signals, all essential frequencies must be applied to the cable at correct power levels.[19] The total amount of power transmitted is represented roughly by the area under the voltage curve[20] at point of application to the cable. It is the practise, especially in connection with permalloy cables, to shape the received signals partly by modifying the usual sending wave-form[21] produced by the large "sending block" condenser. It is apparent that the problem is one of getting maximum total power into the signal, properly shaped (that is, containing the correct proportions of harmonics),[19] and yet with a maximum impressed voltage peak not reaching that set by hazard to the cable dielectric.

*4. Degree to which signals may be amplified.* On simplex cables with vacuum tube amplifiers there is no limit to amplification except the level of parasitic interference. This can be reduced by long sea-earths, properly compensated.[15] On duplex cables the level of interference of sent signals with received signals is so high that ordinarily it constitutes the present limit to increased speed through higher amplification. This is quite a different situation from that obtaining ten years ago when the lack of suitable magnifiers made it inadvisable to divert part of the received energy for shaping purposes.

*5. Degree of tolerance in distorted signals.* This is greatest in sectional recorder operation, where the skill of the operator permits the acceptance of badly distorted signals. Next comes the regenerator, which requires that the mid-point of each signal be definitely on one side or the other of zero position. Electrical relay without regeneration is most critical of all in this respect. If $f_m$ represents the maximum frequency which is important to the transmission of properly shaped signals, an approximate line frequency of $f_r = f_m/1.65$ can be secured for relay operation, and a line frequency of $f_k = f_m/1.50$ can be secured with recorder operation.

$$f_k/f_r = 1.10. \quad f_r/f_k = 0.91.$$

*6. Code used.* Codes are of various lengths; obviously those which contain fewer unit signal impulses per letter are the more economical of line time, other things being equal; but the ability to apply various expedients to save transmission time are not to be overlooked. (See Section 10, below.)

A recent study of "run-of-mine" cable traffic forms the basis of Table I. Letters, figures, punctuation, and letter-spaces have been properly weighted for frequency of occurrence. The number of center holes has been counted as punched on standard perforators.

TABLE I
COMPARATIVE LENGTHS OF CODES IN UNIT SIGNAL IMPULSES PER TRANSMITTED CHARACTER

| Code | No. of elements | Average number per character including letter spaces | |
|---|---|---|---|
| | | Impulses | Cycles |
| Wheatstone (Continental) | 2 | 9.27 | 4.63 |
| Cable Recorder | 3 | 3.71 | 1.86 |
| Baudot (Murray) | 2 | 5.00 | 2.50 |
| Baudot (Angel) | 2 | 3.50 | 1.75 |
| Gott (Continental) | 2 | 5.72 | 2.86 |
| Cooke | 3 | 3.00 | 1.50 |
| Barclay | 2 | 11.24 | 5.62 |
| Morkrum (Green Code) | 2 | 8.00 | 4.00 |
| Simplex (Teletype) | 2 | 7.00 | 3.50 |
| 6-Unit Baudot | 2 | 6.00 | 3.00 |
| Nelson Recorder | 2 | 7.42 | 3.71 |
| Nelson Wheatstone | 3 | 4.63 | 2.32 |
| Theoretical Codes | | | |
| Continental (2 impulse dash) | 2 | 7.18 | 3.59 |
| Crehore | 2 | 5.84 | 2.92 |
| Baudot (Angel) Ideal | 2 | 3.38 | 1.69 |
| Ideal, three-element | 3 | 3.38 | 1.69 |
| Ideal, four-element | 4 | 3.00 | 1.50 |

*7. Allowance for handling of short figures.* Owing to the practicability of using Continental code figures in short form, (*e. g.*, *A* for 1, *U* for 2, etc.), a virtual shortening of the code has to be reckoned with. A careful count of actual usage shows that a factor of 0.96 (1/0.96 = 1.04) should be applied to the length of the cable recorder letter to estimate the effect of short figures. The corresponding figure for Wheatstone, transcribed by typewriter, is 0.94; (1/0.94 = 1.06).

*8. Allowance for handling of figure shifts.* Where figures in printer operation are produced by the shifting carriage method, the code must be loaded proportionately. It has been found that the proper factor to use is 1.035 for all printers except three-unit Cooke, (for

19. *Submarine Cable Telegraphy*, by J. Willard Milnor, A. I. E. E. Trans., Vol. XLI, 1922, p. 20.

20. *Certain Factors Affecting Telegraph Speed*, by H. Nyquist, A. I. E. E. Trans., Vol. XLIII, Feb. 1924.

21. "High-Speed Ocean Cable Telegraphy," by O. E. Buckley, *Bell System Tech. Jl.*, April, 1928.

which it is 1.053 on account of shifting for the letters *J* and *V*), and those printers which do not shift for figures. In the case of the latter it is obvious no allowances should be made for figure shifting.

The product, 1.035 (1.06) = 1.10; (1/1.10 = 0.91); is a measurement of the net effect in comparing recorder with printer output, due to the handling of figures. These figures take into consideration the allowances of both Sections 7 and 8.

*9. Short cuts and abbreviations.* Since the product of a printer system has to be delivered to the public, some abbreviations which are quite feasible when transcribed by typewriter cannot be used. A study shows that the gain in length of printer transmission over typewriter due to this cause is represented by a factor of 1.06; (1/1.06 = 0.94).

*10. Applicability of "fill-in" transmission.*[3] It is possible to transmit two-element code over a cable so rapidly that complete attenuation of single unit signal impulses takes place. A regenerative repeater of proper design can be employed to "fill in" the attenuated impulses at the receiving end. If, originally, the single impulses were received with sufficient amplitude at frequency *f*, an increase in frequency from *f* to 2 *f* will result in the double impulses being received at same form and value as the single impulses formerly were. This results in doubling the output of the cable. The system has been applied extensively to Wheatstone transmission over cables, by the Eastern Telegraph Company in London, and to Baudot transmission on the New York-Emden cable.[7]

The effect of suppressing single impulses at source is embodied in the Nelson three-element Wheatstone and the Angel modification of Baudot, described in the body of the paper. Such systems are not exacting upon duplex balance as are those in which attenuation occurs on the line. It would be incorrect to apply a factor of 2.0 to outputs using these last-named systems of suppressed transmission, however, as weight has been given in the shortening of the codes themselves.

*11. Lost circuit time.* Continuity of operation is one of the most strict demands made of any system of cable operation. In uni-directional operation of cables lost time averages 3.5 per cent on account of loss of adjustment and 5 per cent by the automatic reversing of direction of transmission every two minutes.

*12. Collation and confirmation.* Collation, the practise of sending words twice as is often necessary through heavy static on radio circuits, is not a source of lost time in cable work. The same is true of the confirmation of figures following each message.

*13. Re-runs.* The "setting back" of transmitter tape for the purpose of re-running a message which has been errored in transmission is a cause of inefficiency. When circuits are operated by page-printers, and a high standard of perfection of copy is set, losses due to this account may run consistently as high as 10 per cent. With tape-printer operation, "paste-over" corrections being permitted, the figure is 2 per cent. On duplex recorder circuits the losses amount to 5 per cent.

*14.* The figures in Table II are useful in estimating the relative weight to be given to the various components of transatlantic traffic.

TABLE II
RELATIVE AMOUNTS OF REVENUE-BEARING AND NON-REVENUE TRAFFIC

| | Percentage | Ratio to paid characters |
|---|---|---|
| Paid letters and spaces | 73.7 | 1.000 |
| Unpaid letters and spaces in paid traffic | 18.0 | 0.243 |
| Services and deadheads | 4.1 | 0.055 |
| RQs and BQs | 1.3 | 0.017 |
| Operating functions | 2.9 | 0.040 |
| Total characters in transit | 100.0 | 1.355 |

Analysis of revenue-bearing words

| | Characters per word | Words per message |
|---|---|---|
| Preferred rate, code language | 8.33 | 6.76 |
| Preferred rate, plain language | 6.77 | 17.99 |
| Ordinary rate, code language | 9.64 | 11.32 |
| Ordinary rate, plain language | 7.23 | 15.88 |
| Deferred rate, plain language | 6.79 | 20.90 |
| Press | 7.13 | 81.70 |
| Total | 7.88 | 14.81 |

*15. Applications.* An example will serve to show how the figures derived in Sections 1 to 14 of this Appendix may be applied. One method is to set down two series of weight factors which may be multiplied together and the ratio of one series to the other obtained. For example:

The 1924 New York-Horta permalloy cable was successfully tested out at a three-element recorder speed of 1920 letters per minute.[11] The character of the signals produced between zero and either pole of battery was such that a relay could be positively operated with the sending voltages used. It is required to find what the ultimate operating advantage would be of installing a tape-printer system with completely attenuated single impulses, over the recorder system.

See Section 1, above. The length of cable and its electrical parameters are constant under the two sets of conditions. As the frequency is raised, there will be an increase in the losses, but these are taken care of in the attenuation curves upon which the figures in Section 2 were based.

Section 2. Two-element transmission should give a merit factor of 1.10 for printer system against 1.00 for recorder. While in some cases this ratio might be higher, the high speeds encountered in rotating terminal distributors with attendant chances for variable lag and speed-control difficulties makes it advisable to use the more conservative figure.

Section 3. Impressed voltage wave form. Conditions the same for recorder and printer.

Sections 4 and 5. Degrees of amplification and distortion tolerance. Same for both systems.

Section 6. Printer code, length, 5.00 impulses per character. Recorder code, length, 3.71 impulses per character. Factors of merit are therefore: printer, 1.00; recorder, 5.00/3.71 = 1.35.

Sections 7 and 8. Handling of figures. With a printer merit factor of 1.00, the recorder factor is 1.10.

Section 9. Short-cuts and abbreviations. Factors of merit: printer, 1.00; recorder, 1.06.

Section 10. The fill-in system of transmission is not applicable to three-element recorder operation. The merit factors are, therefore, printer, 2.00, recorder 1.00.

Sections 11, 12, and 13. Lost circuit time and lost time due to confirmations and re-runs. Same for both methods of operation, assuming both systems of equal stability.

Section 14. The character of traffic is assumed to be fixed. The $RQ$ and $BQ$ percentages would not vary noticeably between the two systems provided both proved stable at their respective operating speeds.

The factors of merit may now be set down in parallel columns, and products obtained:

| Section | Printer | Recorder |
|---|---|---|
| 1. | 1.00 | 1.00 |
| 2. | 1.10 | 1.00 |
| 3. | 1.00 | 1.00 |
| 4. | 1.00 | 1.00 |
| 5. | 1.00 | 1.00 |
| 6. | 1.00 | 1.35 |
| 7. } 8. } | 1.00 | 1.10 |
| 9. | 1.00 | 1.06 |
| 10. | 2.00 | 1.00 |
| 11. | 1.00 | 1.00 |
| 12. | 1.00 | 1.00 |
| 13. | 1.00 | 1.00 |
| 14. | 1.00 | 1.00 |
| Products | 2.20 | 1.57 |
| Quotients | 2.20/1.57 = 1.40 | 1.57/2.20 = 0.72 |

It is evident, therefore, that in determining to adopt printer operation on the New York-Horta cable, there was a traffic advantage of 40 per cent over cable recorder ultimately to be gained.

## Discussion

**O. E. Buckley:** There is only one fault which I can pick in the excellent summary which Mr. Coggeshall has made in his paper, and that is with regard to the relative importance of the different developments to which he refers. Perhaps I am prejudiced, but I do not feel that the development of the permalloy loaded cable is secondary in importance to any of the developments which he has named.

One feature of the subject on which Mr. Coggeshall has not laid emphasis is that the developments of the post-war decade have come very largely from America. This is a great contrast to the previous history of submarine cable telegraphy. Prior to the initiation of the developments referred to in this paper, most of the technical advances in cable telegraphy came from Great Britain.

One method of cable operation which Mr. Coggeshall has not referred to, because it has not yet come into use, is the simultaneous use of two cables for carrying traffic on a simplex basis in opposite directions. As he has pointed out, the advantage of duplexing is not so great with the loaded cables as with non-loaded cables, and no considerable gain in traffic carrying capacity has been made by changing from simplex to duplex even with loaded cable which was specially designed for duplex operation work. He also points out the great need for simultaneous two-way operation to get high-speed and instantaneous transmission. It seems to me that in many cases this need will best be met by two loaded cables laid parallel to each other over the same route so that each cable can be operated all of the time in one direction. The cables could, of course, be provided with automatic reversing apparatus so that in case one cable should go out traffic could be handled by single cable with automatic reversal.

**Hobart Mason:** As a traffic engineer I don't know that I would subscribe entirely to Dr. Buckley's idea that a loaded cable is of greater advantage than the regenerative repeater. That may depend on circumstances, the necessary lengths of cable sections, and the number of repeaters in circuit. I have no data but I suspect if we figured the over-all cost per word to the communications companies that the regenerative repeater might very likely show as great a saving as does the loaded cable. I incline to the opinion that Mr. Coggeshall's arrangement of the sequential order was justified.

The circumstances surrounding a given case would also govern in considering Dr. Buckley's statement about the duplex cable. The question of frequency and duration of cable interruptions comes into it, as do the kind and volume of traffic and the relative speeds. As Mr. Coggeshall points out, we have duplexed our second Horta cable at more than half the speed of its simplex operation but that conductor, it is true, is taper-loaded and as a simplex it would have been faster had it been full loaded throughout. The question is open to argument and we shouldn't jump at conclusions as to which would be the ultimate thing. The desire that we have for extending channels of cables to different termini as Liverpool, London, Paris, and Berlin, as we are doing now, tends to make two duplex cables more desirable than two simplexes of twice the speed, although I will admit the possibility of working the two simplexes in that form of hook-up.

The point, I think, that a traffic man should stress in this whole paper of Mr. Coggeshall's is the trend of these improvements. They are directed to two and only two things: one, the improvement of the speed of service, and the other the lowering of the costs of giving service. Included in the speed of service, of course, is the question of continuity of service. Sometimes these two elements go together hand in hand, as for instance, the regenerative repeater not only eliminated a very considerable payroll at the repeater stations but eliminated a considerable time drag in the origin-to-destination speed of service of messages. More often, however, the requirements are at odds. This tug of war is one that confronts almost every utility or public service concern. It is the relationship between the volume of plant provided and the peak load to be experienced, the readiness to serve, the length of time that we are going to let a message wait before it gets its turn on the facilities.

One technical aspect of this same general pulling apart of the two requirements is touched on very briefly in Mr. Coggeshall's paper in the matter of the storing transmitter. We find that to keep a cable fully loaded we must feed it automatically. That is, impulses must go into the cable as fast as the cable speed permits, and that is not practical directly from manual operation for no man can have a cadence operation that will not omit any of the beats. When he takes his hand off the keyboard to move a message from the rack and puts another in front of him the cable runs dry. We must have some storage. Particularly is that the case where we channelize the cables and the impulses must correspond to a nicety with the aspect of the apparatus at the receiving end.

With our present tape apparatus we find the tape is an excellent storage device in all but one respect. It is an unfortunate

fact that there are about 100 centerholes between the pins of the perforator and the pins of the transmitter. That means anywhere from 20 seconds to three-quarters of a minute, depending upon the speed of the channel after the end of the message has been perforated before it is put on the cable. There should be an improvement of that situation. In the meantime, this storage transmitter has been developed, a rather expensive and inflexible thing, but necessary to conserve these few seconds of time. The public mind, I suspect, does not realize the ends to which we go to conserve fractions of a minute in the handling of our traffic.

**M. L. D. McFarlane:** Picture transmission is really an extremely simple matter; it is the same thing as transmitting any other form of intelligence. In transmitting a message one starts off with signals indicating the first letter of that message. In transmitting a picture one starts at one part of the picture and transmits signals indicating the shade of that part of the picture.

In the early days of picture transmission when we started to develop the Bartlane system, we determined to find some method of picture transmission which could use existing facilities. We choose telegraph rather than telephone facilities, because at the time telephone facilities were not nearly as universal as telegraph.

We therefore developed the system of translating a picture in a perforated tape, because perforated tape was being used for all high-speed message transmission. This perforated picture tape is transmitted by the communication company, being delivered at the receiving end again in the form of perforated tape.

There are several methods by which we make a tape from a picture. One is a more or less purely photographic method: the picture is taken and analyzed into a number of tones photographically. Normally we use six tones, which are photographically impressed on metal plates, having areas which are conducting and other areas which are insulating. These tones are run under pointers, and an electrical contact is either made or not made, causing a code combination corresponding to the tone value to be set up in relays and perforated in tape.

At the receiving end a black tape is used. The black perforated tape is run in front of a powerful light and in front of shutters, and thus controls the light falling on a photographic film, and a picture is built up from the holes in the tape. As this is entirely a light action, the actual building up of a picture takes about one minute.

We also use the photoelectric method of preparing the tape in which the picture is scanned in the conventional method by reflected light and the amplified photoelectric current is used to operate the relays which perforate the tape.

One thing which is of interest is the fact that in the picture apparatus we have no synchronism troubles. We hand in a certain length of tape to the transmission company and they give us at the receiving end the same length of tape. We use the same gear on our machines for both preparing the tape and preparing the picture from the tape. As a result, if we hand in 50 ft. of tape to the sending office, and are given 50 ft. at the receiving end, the picture is correct.

The tape method of picture transmission has the advantage over direct methods in that it can be interrupted like all messages, without the necessity of starting again at the beginning. This has manifold advantages from the traffic point of view.

The time of transmission of a picture depends entirely on the traffic conditions that exist on the wires, and that is a thing that is entirely in the hands of transmission companies.

I believe that the future of picture transmission lies in the probability that facsimile transmission will be the one recognized method of the communication of intelligence some years hence. The length of time before this comes to pass is uncertain,—it may take fifty years.

**H. H. Haglund:** Mr. Coggeshall's paper was, I believe, prepared before the recent earthquake which caused so much damage to the North Atlantic cables. He could not therefore touch upon any of the interesting phases of cable development brought out by this catastrophe.

One, in particular, I should like to call to your attention.

As brought out in the paper printers have not conclusively demonstrated their superiority to recorder operation on old style, low speed cables. For the loaded cables, however, they have come into favor.

The earthquake proved these printer circuits to have a much greater flexibility than has usually been attributed to this method of operation.

Within a few days following the quake, which took away the Bay Roberts-Hammel connecting link for the Bay Roberts-Penzance loaded cable, a temporary connection had been set up via sections of old cables Bay Roberts to St. Pierre and St. Pierre to North Sydney and 1400 miles of landline from North Sydney to New York. By providing temporary rotary repeaters for St. Pierre, North Sydney, and Bangor, a speed of 1200 letters per min., 50 cycles was obtained over this route.

With high-speed recorder operation this would have been considerably more difficult since, as mentioned by Mr. Coggeshall, three-element signals are difficult to repeater over landlines and if a three-element, two-element rotary had been employed the consequent doubling of the speed would have produced a frequency too great for the available lines to handle.

The importance of the temporary route may be realized when I point out that the traffic capacity so obtained was over half the total capacity of the remaining five North Atlantic cables available to the Western Union after the quake. The temporary route was made available many weeks before the cable was repaired.

# Magnetic Circuit Units

BY ARTHUR E. KENNELLY*

Fellow and Past President, A. I. E. E.

***Synopsis.***—*A proposition to introduce a change in the units of the magnetic circuit was made at the meeting of the International Electrotechnical Commission (I. E. C.) in Bellagio, September 1927. The proposition was referred to an international subcommittee for consideration and report, by the Advisory I. E. C. Committee on Nomenclature. The subcommittee has recently reported, recommending that the matter be placed on the agenda of the next I. E. C. meeting, and that in the meanwhile, the subject should be discussed in all the national committees, more especially in the various electrical engineering societies, so as to pave the way for well considered international action. This paper has been prepared in the hope of presenting the questions definitely, with a view to eliciting discussion and opinions that may be helpful from the international point of view.*

*As an aid to the formulation of views on the subject among those who may not have given special attention to the historical development of the magnetic-circuit units, a short outline of their history is here submitted.*

*Recent International Proposals.* At the meeting of the International Electrotechnical Commission (I. E. C.) at Bellagio in September 1927, the Italian delegation submitted† a proposal to establish a new international unit of magnetic flux $\phi$ in the ‡"practical system," with a magnitude of $10^8$ C. G. S. magnetic units, or corresponding to what is sometimes called a "volt-second," and to assign to this new unit of flux the name "maxwell."

After some discussion, the matter was referred to an international subcommittee of seven, (representing the national I. E. C. committees of France, Germany, Great Britain, Holland, Italy, Russia, and the United States) for consideration and report to the I. E. C. Committee No. 1 on *Nomenclature*.

The subcommittee discussed the matter by correspondence distributed through the General Secretary's office in London, during 1928 and 1929. It presented a report in September 1929 to Dr. Mailloux, the president of the I. E. C. Nomenclature Committee. A copy of the report is appended to this paper.

*Need for General Consideration and Discussion.* From the correspondence among the members of the international subcommittee, it was evident that although no official change has been made in the international status of magnetic-circuit units since the Paris International Electrical Congress of 1900, yet there exists a considerable difference of usage of magnetic units in the various countries, not merely as to the names, but also as to the definitions of the units. It is therefore in the interest of all countries that the whole question of the magnetic units and their names should be considered afresh, with a view to arriving at a sound, simple, and satisfactory international agreement upon the same. While, therefore, the subcommittee could not endorse the proposal to change the value of the *maxwell* from 1 C. G. S. to $10^8$ C. G. S. units of magnetic flux $\phi$, it recommends that the matter be discussed in all the twenty-five countries participating in the I. E. C., particularly among their engineering societies, in order to elicit useful suggestions and to pave the way for well considered international action. This paper aims to present a brief history of the development of the magnetic-circuit units, especially during the last forty years, in so far as may be helpful in visualizing the present status of these units, to indicate the reasons existing for changing that status, and of submitting a few suggestions in that direction by way of starting the discussion in the American Institute of Electrical Engineers.

*Outline History of the Magnetic-Circuit Units.* The first analysis of the behavior of a suspended magnetic needle appears to have been given by Ampère in 1820.* The first analysis referred to absolute measure, *i. e.*, to units of length, mass, and time, is attributed to Gauss† in 1833. In 1840, W. E. Weber, who collaborated with Gauss, showed how to measure the strength of a steady electric current in absolute measure with the aid of a tangent galvanometer, and later, with an electrodynamometer. The magnetic units employed by Gauss and Weber were in the millimeter-milligram-second system (mg-mm-sec.) or M. M. S. system, in direct decimal relation with the international metric system.

In 1861, two electric telegraph engineers, Latimer Clark and Charles Bright, read a paper at the Manchester meeting of the British Association for the Advancement of Science (generally known as the B. A.) calling attention to the needs for scientific electrical units, standards, and measures in telegraph engineering. This led to the formation by the B. A., in that year, of a committee‡ on "Standards of

*Professor of Electrical Engineering, Harvard University, Cambridge, Mass.

†Bibliography 29, pp. 121-123. Report of I. E. C. Meeting at Bellagio.

‡The term "practical system" as here used, refers to the series of international electrical units, substantially as adopted at the Electrical International Congress of Chicago in 1893; *i. e.*, the international volt, ohm, ampere, etc.

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*Ampère, André M., "Sur l'état magnetique des corps qui transmettent un courant d'électricité," *Ann. Chem. Phys.*, XVI, Paris, 1821.

†Gauss, Karl Friedrich, "Intensitas vis magneticae terrestris ad mensuram absolutam revocata," Gottingen, 1833.

‡British Association Reports. "On Electrical Standards," 1861, 1863, 1864, 1865, 1867. (First B. A. Committee.)

Electrical Resistance." Its members were eminent in basic and applied science. This first B. A. committee set to work to establish units and standards of resistance, e. m. f., and current in absolute measure, making reports to the B. A. from 1863 to 1867, when it was reorganized and the second B. A. committee§ was appointed "for the Selection and Nomenclature of Dynamical and Electrical Units." The first B. A. committee issued standard B. A. ohms and microfarads in the meter-gram-second* (M. G. S.) system, the B. A. standard ohm being made to represent $10^7$ absolute M. G. S. units of resistance, and the B. A. standard microfarad to represent $10^{-13}$ M. G. S. units of capacitance. At the present date, these would be taken respectively as representing $10^9$ C. G. S. units of resistance and $10^{-15}$ C. G. S. units of capacitance. The same B. A. standard condenser was originally called a *farad*;* but by common consent its name was changed to *microfarad*, to preserve the unitary relations between the newly adopted practical units. The *volt* of $10^8$ M. G. S. units of electromotive force was also recognized and adopted by the committee, as being not far from the e. m. f. of a Daniell zinc-copper cell, at that time well known in telegraphy; but so greatly did different voltaic cells of the same type vary in e. m. f., that it was not until 1873, that the first Clark zinc-mercury cell was developed as a working standard of e. m. f.

When the second B. A. Committee made its first report in 1873, it recommended changing the basis of the absolute units from the M. G. S. to the C. G. S. system,† mainly for the reason that in the latter, the systematic unit of density was the gram per cubic centimeter and substantially equal to the density of pure water; whereas in the former, the systematic unit of density was the gram per cubic meter or one millionth that of water. Thereafter, the M. G. S. system was superseded by the C. G. S. system, not only in electrical and magnetic units, but also in all branches of science. The change seems, however, to have been made against some opposition, since one member of the second committee went on record† as being opposed to the substitution of the centimeter for the meter.

The first International Congress of Electricians assembled at Paris, in 1881. It adopted the C. G. S. system as the basis of absolute units. It likewise adopted the *ohm, volt, ampere, coulomb,* and *farad* just as they are today, except for minor corrections, and all decimally derived from the C. G. S. system.

The second International Electrical Congress of 1889, also at Paris, adopted three more units in the "practical" system—the *joule, watt,* and *quadrant* (now the *henry*). The Congress also discussed magnetic units in the "practical" system, recommending the *weber* as the name of a practical unit of magnetic flux, defined as $10^8$ C. G. S. units of magnetic flux $\phi$, and also the *gauss* as the name for the practical unit of field intensity*, or $10^8$ C. G. S. units of magnetic flux density $B$. No definite action, however, was taken by the Congress on either of these units.

The rapid development of dynamo-electric machines in the eighties, led to a demand among electrical engineers for magnetic units with corresponding names, to be used in the analysis and description of magnetic circuits.

In 1891, the A. I. E. E. appointed a committee on "Units and Standards" with especial reference to the study of magnetic-circuit units. The committee reported[4] in June 1891, recommending units of magnetomotive force, magnetic flux, magnetic induction density, and magnetic reluctance, all in the "practical" system, except, as was pointed out in the discussion, that the flux density was referred to the square centimeter, and was therefore a departure from the "practical" system. No names were offered for these units, but it was suggested that the A. I. E. E. should seek to have these units adopted at the next following international electrical congress, with names for the same. No action was taken on the report beyond accepting it and printing it in the Proceedings.

The subject of magnetic units was discussed at the third International Congress, held at Frankfort, in September 1891. The names *gauss* and *weber* were recommended, in the "practical" system, for the units of field intensity $H$, and magnetic flux $\phi$, respectively, but no action was taken.

*International Congress of Chicago.* At the fourth International Electrical Congress, held at Chicago in 1893, the subject of magnetic units received attention in the Chamber of Deputies. The recommendation was recorded[5] that the C. G. S. system should be used for magnetic units, and that for the present no names should be given to them.

It is to be remembered that magnetic observatories had come into existence about the year 1850, for measuring and recording the earth's magnetic field in their respective localities. At first, these observatories used M. M. S. (mm-mg-sec.) units, but after about 1875 the records were kept in C. G. S. units. Among magneticians, this practise was regarded as a reason for

§First Report of the B. A. "Committee for the Selection and Nomenclature of Dynamical and Electrical Units," (Second B. A. Committee) 1873.

Second Report of same Committee, 1874. See also Appendix to Everett's "Illustration of the C. G. S. System of Units," 1875-1891.

*Clark, Latimer and Sabine, Robert, "Electrical Tables and Formulae," E. & F. N. Spon, London, 1871, pages 1-5 and Preface.

†Everett, J. D., "Illustrations of the C. G. S. System of Units," Macmillan & Co., 1891, Appendix.

*Although the term "field intensity" suggests magnetizing force $H$, yet the context seems to indicate that the *gauss* was intended for the unit of flux density $B$.

4. For numbered references see Bibliography.

keeping the magnetic units in the C. G. S. system. Many objections appeared in electrotechnical literature, between 1890 and 1894, to the adoption of magnetic units in the "practical" system. Up to that time, however, only the two names *dyne* and *erg* had been adopted for units in the C. G. S. system. All of the names for electric units and standards had been assigned by international congresses in the "practical" system. The retention of magnetic units in the C. G. S. system thus raised difficulties in the way of giving names to them. On the other hand, electrical engineers working with the design and construction of dynamo-electric machines, and with the analysis of their magnetic circuits, were insistent for unit names as well as unit magnitudes for the essential elements of those circuits.

In view of the recommendations of the Chicago Congress for retaining the working units of the magnetic circuit in the C. G. S. system, the Committee on "Units and Standards" of the A. I. E. E. reported to that body in March 1894* in favor of provisionally adopting the working units of the magnetic circuit in the C. G. S. magnetic system with the following names: (1) the *gilbert* as the C. G. S. unit of m. m. f. with the value $10/4\pi$ ampere-turn; (2) the *weber* as the C. G. S. unit of magnetic flux; (3) the *oersted* for the C. G. S. unit of reluctance; and (4) the *gauss* as the C. G. S. unit of flux density, or one *weber* per normal sq. cm. The report was discussed at two meetings of the Institute and provisionally adopted at the second.

In 1895, the Committee of Electrical Standards† of the British Association recommended the tentative adoption of the following units and names:

(1) As the unit of magnetic flux, $10^8$ C. G. S. magnetic units, to be known as the *weber*.

(2) As the unit of magnetomotive force, the C. G. S. magnetic unit of m. m. f., to be known as the *gauss*.

In May 1900,‡ in view of the then approaching International Electrical Congress at Paris in August 1900, the A. I. E. E. Committee on Units and Standards reported to that body in favor of fixing the working units of the magnetic circuit in the C. G. S. system, and also of considering their rationalization (the elimination of the factor $4\pi$ from the unit of m. m. f.). The A. I. E. E. adopted the report and instructed its delegates to recommend accordingly at the Paris Congress.

*Fifth International Electrical Congress, at Paris.* At the Paris Congress, there was much difference of opinion and also some misunderstanding. It was generally agreed that the working units of the magnetic circuit should be retained in the C. G. S. system, but there was considerable opposition to giving them names. The Congress finally voted and printed in its report[7] the adoption of two names, *viz.*, the *gauss* for the C. G. S. unit of field intensity $H$, and the *maxwell* for the C. G. S. unit of magnetic flux $\phi$. These two working magnetic units in the C. G. S. system were adopted at the close of an animated debate. The A. I. E. E. delegates supposed that the name *gauss* had been assigned by the Chamber to the C. G. S. unit of flux density $B$, and so reported to the A. I. E. E.‡ It was not until after the publication of the official Paris Congress report that the discrepancy was discovered.

*International Conditions Subsequent to the Paris Congress of 1900.* There has been no official international action on magnetic units since 1900; but usage in electrotechnical literature has varied considerably as between different countries. Indeed different writers in one and the same country have sometimes differed in their use of magnetic units. In America, the custom has been to use the *gilbert* for the working unit of magnetic potential, the *gilbert per centimeter* for the unit of magnetizing force or field intensity $H$, the *maxwell* for the unit of magnetic flux $\phi$, the *gauss* for the unit of flux density $B$, and the *oersted* for the unit of reluctance; *i. e.*, for the reluctance of 1 cubic centimeter of free space; all in the C. G. S. system.[7] It has been recognized that the *gilbert* and *oersted* had no international status and had never been internationally adopted. In addition, however, to these more or less standardized working C. G. S. magnetic units, American electrotechnical literature contains various other magnetic units; such as the *ampere-turn* for m. m. f., the *line* for the C. G. S. unit of magnetic flux, and the *line per square inch* or *maxwell per square inch* as hybrid units of flux density $B$.

In European literature, the *gauss* has been used by some writers as the C. G. S. unit of magnetizing force or magnetic field $H$, and sometimes as the C. G. S. unit of magnetic flux density $B$. Some writers have also used the *gauss* indifferently for both $H$ and $B$. As regards the *maxwell*, the usage has been more generally standardized, and where it has been employed, it has meant the C. G. S. unit of magnetic flux $\phi$ in nearly all cases. In some countries, however, the *maxwell* has been little used, being sometimes replaced by the *line*. The *gilbert* and the *oersted* have been rarely used outside of the United States.

In addition to the lack of complete international standardization of magnetic-unit terminology, there has also been manifest, in literature, a lack of complete standardization in the definitions of the magnetic quantities to which the units are applied. That is to say, there are differences of opinion as to the "dimensions" of magnetic units, and especially as to the dimensions of magnetic permeability $\mu$. This divergence of opinion exists to some extent in all countries, and to a

*A. I. E. E. Trans., Vol. XI, 1894; Jan. 17, pp. 48-52; Mar. 21, pp. 124-132.

†"Electric Units and Standards" Circular No. 60 of the Bureau of Standards, Washington.

‡A. I. E. E. Trans., 1900, Vol. XVII, pp. 309-318, May 17, 1900.

7. A. I. E. E. Trans., Vol. XVII, pp. 543-547, Nov. 21, 1900 and Bibliography 6.

considerable extent in some countries. The question is rendered more difficult by the fact that, as was pointed out many years ago by Rücker,[3] it is not yet possible to assign dynamical dimensions, (in $L$, $M$, and $T$) to all electromagnetic quantities; so that we are unable at present to assign their precise dimensions. It is customary to express the dimensions of the various electromagnetic quantities either in terms of length, mass, time, and permeability ($L\ M\ T\ \mu$) or in terms of length, mass, time, and electric permittivity ($L\ M\ T\ \kappa$). This is equivalent to the admission that the dimensions of $\mu$ and $\kappa$ are still undetermined, except that their geometrical mean $\sqrt{\mu\ \kappa}$ is the reciprocal of a propagation velocity, or $1/v$. If, however, the dimensions of $\mu$ are zero, so that $\mu$ is a mere numeric, it must follow that in the ordinary formula connecting magnetic force with magnetic flux density; *i. e.*, $B = \mu\ H$, the unit for $B$ must have the same nature as the unit of $H$, and the same name will be applicable to both. If one of these quantities is expressed in *gausses*, the other must likewise be expressible in *gausses*. If, on the contrary, $\mu$ has physical dimensions, and is not a mere number, then $B$ and $H$ cannot properly be expressed in terms of the same unit. The question turns upon the definitions that are used for $H$ and $B$. It is generally admitted that under certain definitions of $B$ and $H$, their ratio $\mu$ will be a mere numeric, while under other definitions, their ratio will have physical dimensions. In order, therefore, to secure satisfactory international standardization of the C. G. S. magnetic units, it seems first necessary to reach international agreement on the underlying definitions of the quantities involved.

In 1911,* the A. I. E. E. recommended the use of the following magnetic units, all in the C. G. S. magnetic system: the *gilbert-per-cm.* for magnetic force $H$, the *maxwell* for magnetic flux $\phi$, and the *gauss* for magnetic density $B$. In the A. I. E. E. Standardization Rules for 1914† following the vote of the Paris 1900 Congress, the *gauss* is inserted as an alternative C. G. S. unit of magnetic intensity $H$, without withdrawing the same name from the unit of flux density. A footnote states "The *gauss* is provisionally accepted for the present, as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric."

*Magnetic Units in "Practical" Systems.* It was pointed out by Maxwell that‡ the "practical" system of units forms an absolute system in which the unit of length is a quadrant of the earth, or $10^7$ meters, the unit of mass an eleventh-gram or $10^{-11}$ g., and the unit of time the mean solar second. The discovery of this relation theoretically placed the "practical" units upon an independent basis, quite detached from the C. G. S. units. Unfortunately, the underlying unit of mass was so small and that of length so large, that the systematic use of the independent "practical" system became very inconvenient. Thus, with the *ampere* as unit of current, the logical and systematic unit of current density becomes in the Q. E. S. (*quadrant, eleventh-gram, second*) system the *ampere per square quadrant*, or $10^{-14}$ *amperes* per square meter. If the practical unit of density were arbitrarily taken as the *ampere per sq. m.*, or the *ampere per sq. cm.*, this would be adopting a hybrid unit outside of the Q. E. S. system, and the simplicity inherent in a logical absolute system would be lost, through the necessity of introducing numerical coefficients like $10^{-14}$ into computations involving current density. Consequently, although the Q. E. S. system of independent absolute units including the "practical" units, has been recognized as a "comprehensive" system for nearly fifty years, no writer has espoused the cause of magnetic units in the Q. E. S. system. The unit of magnetic field intensity $H$ would presumably be the ampere-turn per quadrant, and the unit of flux density $B$ would be referred to unit flux per square quadrant.

*Giorgi System of M K S Ω Units.* Commencing in 1901,* Giorgi pointed out that a rationalized absolute system of units could be used, including all the practical or volt-ampere-ohm series, by taking the meter as the unit of length, the kilogram as the unit of mass, the second as the unit of time, and the international ohm. Whereas the C. G. S. system was essentially dual, with a magnetic series and an electric series, interconnected by awkward coefficients of $v$ or $v^2$ or their reciprocals, the M. K. S. Ω system was essentially single, or had only one series. Such a system may be described as a "unified" system. The M. K. S. Ω system has been favorably commented upon† by specialists in various countries. It takes the permeability of free space $\mu_0$ as $4\ \pi \times 10^{-7}$, instead of unity as in the C. G. S. magnetic system, and it takes the specific permeability of steel or other magnetic medium $\mu$, as a simple numeric. It is open to the objection that whereas the density of pure water in the C. G. S. system is 1 g. per cu. cm. and therefore unity, under proper specifications, the density of water in the M. K. S. Ω system is one thousand kilograms per cubic meter, or unit density is one thousandth that of water. So far as is known, no electrotechnical book has yet been written in the M. K. S. Ω system.

*The "International" or C. G. S. S. System.*[22, 23, 24] In 1916, Dellinger and Bennett suggested the "International" comprehensive unified system, including all the "practical" units, based on the centimeter as unit of length, the gram-seven or $10^7$ gm., as unit of mass and the second as unit of time. This is sometimes called the centimeter-gram-seven-second or C. G. S. S. system. Like the Giorgi system, it is rationalized, and the ampere-turn becomes the rational and practical unit of

*A. I. E. E. Trans., 1911. Part III, Vol. XXX, Standardization Rules, p. 2564.

‡Bibliography 1. Chapter X. Dimensions of Units.

†A. I. E. E. Trans., 1914. Part II, Vol. XXXIII, Standardization Rules, p. 1798.

*Bibliography 8, 9, 10, 12, 13, 14, 17.

†Bibliography 11, 15, 16, 19, 21, 23, 25.

m. m. f. in both. It takes the permeability of free space $\mu_0$ as $4\pi \times 10^{-9}$. The unit of reluctance in the Giorgi system would be based on the reluctance of a cubic meter of free space, whereas in the C. G. S. S. system, it would be based on the cu. cm. Except in regard to the fundamental units of length and mass, there seems to be little to choose between the two systems. On the one hand, the Giorgi system has the meter and kilogram, while the C. G. S. S. has the cm. and the gram-seven or ten metric tons. The meter is preferable to the centimeter as a fundamental unit of length, on account of having no *centi* prefix to start with; but of course electrical workers are very familiar with the cm. by long habit. Again, the *kilogram* although encumbered with the prefix *kilo*, is preferable as a fundamental unit to the *gram-seven*. In fact Dellinger[22] has considered that in view of this awkward magnitude of unit mass, the C. G. S. S. system was not adapted for use in general scientific measures outside of electromagnetics. The unit of density in the C. G. S. S. system is of course $10^7$ g. per cu. cm., or ten million times that of water. A book,* pamphlets,[20,24,26,28] and papers have appeared, written in the C. G. S. S. system; so that the C. G. S. S. system may claim to be a competitor of the M. K. S: Ω system, as a unified, rationalized, and comprehensive absolute system, embracing all the "practical" units, and quite independent of the original parent C. G. S. tree. The choice between them, if one or other should finally be adopted, probably lies as much with non-electrical as with electrical workers.

Moreover, in addition to the M. K. S. Ω and C. G. S. S., there are two other possible absolute systems embracing the "practical" units; namely, one based on the decimeter and $10^8$ grams, the other based on the dekameter and dekagram. It was pointed out by Ascoli,* that since the kinetic energy of a mass $M$ moving with a velocity $V$, is $M V^2/2$ units of dynamical energy, and since we desire to retain the fundamental time unit constant, in all these systems, as the mean solar second, then because the joule as a "practical" unit of dynamical energy has to be conserved at the magnitude of $10^7$ ergs, we may vary the unit magnitudes of $M$ and $L$ so long as the product $M L^2$, expressed in C. G. S. values, remains constant at $10^7$. Hence if $M$, the mass unit, is $10^m$ grams, and $L$, the length unit, is $10^n$ cm., we must keep $m + 2n = 7$. Restricting ourselves to positive values of $m$ and $n$, *i. e.*, keeping within the range 1 cm. to 1000 cm. in $L$ and from 1 g. to $10^7$ g. in $M$, we have the C. G. S. S. Dellinger-Bennett system for $n = 0$ and $m = 7$; while we have the M. K. S. Ω Giorgi system for $n = 2$ and $m = 3$, the meter and the kilogram; but two other possible combinations are $n = 1$, $m = 5$ and $n = 3$, $m = 1$. Incidentally, it may be noticed that if we make $n = 9$ and $m = -11$, we obtain the Q. E. S. or quadrant-eleventh-gram-second system of Maxwell.

A comparative table of C. G. S., Giorgi, and C. G. S. S. units is appended (Table II).

*Contribution to the Discussion on Future Desirable Action of the I. E. C.* In what has preceded, the writer has endeavored to present the historical background of the magnetic-unit situation without prejudice or partiality. The following remarks are, however, submitted from the standpoint of an advocate for a particular course of I. E. C. action in the matter, as a contribution to the general discussion.

*First.* Before any definite new action is taken, it is desirable to standardize internationally the definitions of magnetomotive force, magnetizing force, magnetic reluctance, magnetic flux, and especially permeability, so as to reach international agreement upon the dimensions of permeability.

In the Giorgi and C. G. S. S. systems, it appears that permeability is a product $\mu_0 \mu$ of space permeability $\mu_0$, or the permeability of a vacuum, and specific permeability $\mu$, that of the magnetic circuit with respect to free space. Space permeability $\mu_0$ will probably be generally admitted to have dimensions; while specific permeability $\mu$ is probably a mere numeric. Perhaps on such a basis, definitions may be drawn which will secure universal endorsement.[30]

*Second.* It seems desirable to revise internationally the assignment of names to a few magnetic units in the C. G. S. system. With the dimensions of permeability established, the question whether the *gauss* can apply to both $H$ and $B$ can be decided. Concerning the *maxwell*, as adopted at Paris in 1900, there has been neither dispute nor confusion. It is true that in some countries the *maxwell* has been little used, but it has been considerably used in other countries. Its proper use should not be interdicted. Whatever new action may be taken in the near future, we must expect to see C. G. S. magnetic units continue to be used for a long time.

*Third.* It would be desirable to accept part of the Italian delegation's proposal at Bellagio in 1927, and adopt a "practical" unit of magnetic flux at the value of $10^8$ C. G. S. units; but not to call it the *maxwell* which name has been reserved for the C. G. S. unit since 1900. Giorgi suggested the name *weber* for this "practical" unit, in his papers of 1901-1904, and Bennett also suggested the name *weber* for the same C. G. S. S. "practical" unit in 1917. The name would have to be agreed upon internationally. For the present, we may call this unit the *volt-second*.

It does not seem likely that the adoption of the *volt-second*, with its appropriate new name, would seriously conflict with the *maxwell* in practical use. Their magnitudes are so remote. The advantage would be that the path would be opened for electrical workers to employ either the Giorgi or the C. G. S. S. comprehensive practical system, without reference to the C. G. S.

*Karapetoff's "The Magnetic Circuit" N. Y. 1911, although referring in its preface to the Giorgi system, appears to be written in the C. G. S. S. system and may perhaps be the first publication in that system.

*Ascoli M., Bibliography 16, p. 134.

units, if they desire to do so. The ampere-turn as a rationalized unit of m. m. f. in both these systems, already exists and probably needs no other name. The difficulty comes when an attempt is made to adopt the corresponding "practical" unit of flux density, whether with or without a special name. If the unit of flux density be chosen as the volt-second per square meter, it fits into the Giorgi M. K. S. Ω system, and virtually fixes upon that system exclusively. If, on the other hand, the unit of flux density is chosen as the volt-second per sq. cm., it fits in with the Karapetoff-Dellinger-Bennett "International" C. G. S. S. system, and logically would fix upon that system. It would seem to be sufficient at this time, to leave the path open for the use of a comprehensive system, without fixing upon the system, or on its series of units. If, however, a choice should be made at once, then in the opinion of the writer, the meter and kilogram are to be preferred over the centimeter and gram-seven.

If a comprehensive system such as the M. K. S. Ω system developed and found favor with electrical workers, it would greatly simplify electromagnetic theory, for teachers, students, readers, and writers, since we should all be able to abandon the existing duality of the C. G. S. and the derived "practical" units. It might well happen that the new comprehensive system would carry all before it, and relegate the C. G. S. system to history and the shelves, so far as electrical workers are concerned. In that case, the comprehensive system, being also adapted for use in mechanics, chemistry, optics, and all other branches of science, might readily invade those branches, and ultimately replace the C. G. S. units they use with M. K. S. Ω units. The numerical changes thus effected in tables and formulas, would be decimal changes, or a shift of the decimal point, in nearly all cases. Such a change, if it occurred, would probably come very slowly, and take many years to effect. Nevertheless, when it is remembered that all science is so closely interlaced through its units, that what happens to the units in one branch may readily react upon the unitology of other branches, it seems desirable not to take final steps of change in any region, without giving ample notice to the workers in others. All are interested, in all countries.

At present, no comprehensive system of units can make headway in the magnetic circuit, so long as the magnetic-circuit units are by international agreement wholly in the C. G. S. system. If a new unit of flux is created, with a name, in the "practical" series, that obstacle would be removed. If the comprehensive system utilizes this, and develops useful service to the world in the next few years, then subsequent I. E. C. action can adopt the comprehensive system, and set the C. G. S. system aside. If, however, for any reason the comprehensive system fails to find favor, the volt-second unit will probably not come into use, and might later be withdrawn. The C. G. S. system might then continue.

*Remarks upon the Tables and their Contents. Table I* gives a brief summary of the proposals made by the different members of the I. E. C. International Subcommittee on Magnetic Units, in their exchange of correspondence. It is evident that their opinions differed widely as to what recommendation should be reported to the I. E. C. It is, however, needless to say that it is impossible to do adequate justice to a series of fairly long and carefully considered written documents in a simple skeleton chart of this kind. If it had been possible to hold meetings and discussions, it might have been possible to come to a closer range of proposals. The subcommittee report, however, as appended, met with general agreement.

TABLE I

SUMMARY IN BRIEF TABULAR FORM OF PROPOSALS MADE BY THE VARIOUS MEMBERS OF THE I. E. C. INTERNATIONAL SUBCOMMITTEE ON MAGNETIC UNITS

| | Quantity | | 1900 Paris Congress | British Delegate | French Delegate | German Delegate | Holland Delegate | Italian Delegate | U. S. A. Delegate |
|---|---|---|---|---|---|---|---|---|---|
| C. G. S. System (Magnetic) | Field Intensity | $H$ | gauss | abolish all names and start afresh | mascart | weber | gauss | gauss | |
| | Magnetomotive Force | $\mathfrak{F}$ | | | | | | | |
| | Flux | $\phi$ | maxwell | | | maxwell | | | maxwell |
| | Flux Density | $B$ | | | | gauss | maxwell/cm.$^2$ | | gauss |
| | Reluctance | $\mathfrak{R}$ | | | | | | | |
| "Practical" System | Field Intensity | $H$ | | | no name | (Amp./cm.) no special names proposed | gilbert ← A. I. E. E. unrationalized system as proposed in 1893 | maxwell | |
| | Magnetomotive Force | $\mathfrak{F}$ | | | | | | | |
| | Flux | $\phi$ | | | | (volt-second) | weber or maxwell | | |
| | Flux Density | $B$ | | | | (volt-sec./cm.$^2$) | | | |
| | Reluctance | $\mathfrak{R}$ | | | | | oersted | | |

*Table II* offers a comparison, in parallel columns, of corresponding units in the fundamental C. G. S. magnetic system and three "practical" systems, *i. e.*, the Q. E. S. system of Maxwell, the Giorgi system, and the more recent "International" system of Dellinger, Bennett, and Karapetoff. The C. G. S. electrostatic system has been omitted to save space.

All three "practical" systems are represented as being

TABLE II

TABLE OF FUNDAMENTAL C. G. S. UNITS AND OF THREE DERIVED "PRACTICAL" SYSTEMS

| No. I | Quantity II | Symbol III | Fundamental C. G. S. IV | Practical: Q. E. S Maxwell, 1881 V | In C.G.S.U. VI | M. K. S. Ω Giorgi, 1901 VII | In C.G.S.U. VIII | C. G. S. S. Dellinger-Bennett IX | In C.G.S.U. X |
|---|---|---|---|---|---|---|---|---|---|
| | *Mechanic* | | | | | | | | |
| 1 | Length | $L$ | *cm.* | quadrant | $10^9$ | *meter* | $10^8$ | *cm.* | 1 |
| 2 | Mass | $M$ | *g.* | eleventh-g. | $10^{-11}$ | *kilogram* | $10^3$ | g.-seven | $10^7$ |
| 3 | Time | $T$ | *second* | second | 1 | *second* | 1 | *second* | 1 |
| 4 | Area | $S$ | *cm.*$^2$ | sq. quad. | $10^{18}$ | *m.*$^2$ | $10^4$ | *cm.*$^2$ | 1 |
| 5 | Volume | $V$ | *cm.*$^3$ | cubic quad. | $10^{27}$ | *m.*$^3$ | $10^6$ | *cm.*$^3$ | 1 |
| 6 | Density | $d$ or $\rho$ | *gm./cm.*$^3$ | eleventh g/quad.$^3$ | $10^{-38}$ | *kg/m.*$^3$ | $10^{-3}$ | *g-seven/cm.*$^3$ | $10^7$ |
| 7 | Velocity | $v$ | *cm./sec.* | quad./sec. | $10^9$ | *m/sec.* | $10^2$ | *cm/sec.* | 1 |
| 8 | Acceleration | $a$ | *cm./sec.*$^2$ | quad./sec.$^2$ | $10^9$ | *m/sec.*$^2$ | $10^2$ | *cm/sec.*$^2$ | 1 |
| 9 | Force | $F$ | *dyne* | centidyne | $10^{-5}$ | dyne-five | $10^5$ | dyne-seven | $10^7$ |
| 10 | Pressure | $p$ | *dyne/sq. cm.* | cntdyne/sq. quad. | $10^{-20}$ | dyne-5/sq. *m.* | 10 | dyne-7/sq. cm. | $10^7$ |
| 11 | Torque | $Q$ | *dyne* ⊥ *cm.* | cntdyne ⊥ quad. | $10^5$ | dyne-5 ⊥ *m.* | $10^5$ | dyne-7 ⊥ cm. | $10^7$ |
| 12 | Moment of Inertia | $J$ | *g.-cm.*$^2$ | 11th-g-quad.$^2$ | $10^7$ | *kg-m.*$^2$ | $10^7$ | *g-cm.*$^2$ | 1 |
| | *Energetic* | | | | | | | | |
| 13 | Work | $W$ | *erg* | *joule* | $10^7$ | *joule* | $10^7$ | *joule* | $10^7$ |
| 14 | Power | $P$ | *erg/sec.* | *watt* | $10^7$ | *watt* | $10^7$ | *watt* | $10^7$ |
| | *Thermal* | | | | | | | | |
| 15 | Heat | $H$ | *g-calorie* | 11th-g-cal. | $10^{-11}$ | *kg-calorie* | $10^3$ | *g-calorie* | 1 |
| 16 | Temperature | $t$ or $T$ | *Deg. C. or Abs.* | *Deg. C. or Abs* | 1 | *Deg. C. or Abs.* | 1 | *Deg. C. or Abs.* | 1 |
| | *Luminous* | | | | | | | | |
| 17 | Flux | $F$ | *lumen* | *lumen* | 1 | *lumen* | 1 | *lumen* | 1 |
| 18 | Illumination | $E$ | *phot* | lumen/quad.$^2$ | $10^{-18}$ | *lux*, lumen/m.$^2$ | $10^{-4}$ | *phot* | 1 |
| 19 | Intensity | $I$ | *int. candle* | *int. candle* | 1 | *int. candle* | 1 | *int. candle* | 1 |
| 20 | Brightness | $B$ | candles/cm.$^2$ | candles/quad.$^2$ | $10^{-18}$ | candles/m.$^2$ | $10^{-4}$ | candles/cm.$^2$ | 1 |
| 21 | Focal Power | | cm.$^{-1}$ | quad.$^{-1}$ | $10^{-9}$ | *diopter* | $10^{-2}$ | cm.$^{-1}$ | 1 |
| | *Electric* | | | | | | | | |
| 22 | Electromotive Force | $E$ | abvolt | *volt* | $10^8$ | *volt* | $10^8$ | *volt* | $10^8$ |
| 23 | El: field intensity | $e$ or $V$ | abvolt/cm. | volt/quad. | $10^{-1}$ | volt/m. | $10^{-3}$ | volt/cm. | $10^8$ |
| 24 | Resistance | $R$ | abohm | *ohm* | $10^9$ | *ohm* | $10^9$ | *ohm* | $10^9$ |
| 25 | Resistivity | $\rho$ | abohm-cm. | ohm-quad. | $10^{18}$ | ohm-m. | $10^{11}$ | ohm-cm. | $10^9$ |
| 26 | Current | $I$ | abampere | *ampere* | $10^{-1}$ | *ampere* | $10^{-1}$ | *ampere* | $10^{-1}$ |
| 27 | Current density | $i$ | abamp/cm.$^2$ | amp./sq. quad. | $10^{-19}$ | amp./sq. m. | $10^{-5}$ | amp./sq. cm. | $10^{-1}$ |
| 28 | Conductance | $G$ | abmho | mho | $10^{-9}$ | mho | $10^{-9}$ | mho | $10^{-9}$ |
| 29 | Conductivity | $\gamma$ | abmho/cm. | mho/quad. | $10^{-18}$ | mho/m. | $10^{-11}$ | mho/cm. | $10^{-9}$ |
| 30 | El: Quantity | $Q$ | abcoulomb | *coulomb* | $10^{-1}$ | *coulomb* | $10^{-1}$ | *coulomb* | $10^{-1}$ |
| 31 | El: Displacement | $D$ | abcoulomb/cm.$^2$ | coulomb/quad.$^2$ | $10^{-19}$ | coulomb/m.$^2$ | $10^{-5}$ | coulomb/cm.$^2$ | $10^{-1}$ |
| 32 | Capacitance | $C$ | abfarad | *farad* | $10^{-9}$ | *farad* | $10^{-9}$ | *farad* | $10^{-9}$ |
| 33 | Permittivity | $\kappa_0$ | (abfarad/cm.) = 1 | farad/quad. | $= \frac{1}{4\pi v^2}$ | farad/m. | $= \frac{10^7}{4\pi v^2}$ | farad/cm. | $= \frac{10^9}{4\pi v^2}$ |
| 34 | Frequency | $f$ | cycle/sec. | cycle/sec. | 1 | cycle/sec. | 1 | cycle/sec. | 1 |
| | *Magnetic* | | | | | | | | |
| 35 | Magnetomotive Force | $\mathfrak{F}$ | gilbert | *amp.-turn* | $\frac{4\pi}{10}$ | *amp.-turn* | $\frac{4\pi}{10}$ | *amp.-turn* | $\frac{4\pi}{10}$ |
| 36 | Mag: field intensity | $H$ | gilbert/cm. | amp-turn/quad. | $4\pi/10^{10}$ | amp-turn/m. | $4\pi/10^4$ | amp-turn/cm. | $4\pi/10$ |
| 37 | Space Permeability | $\mu_0$ | abhenry/cm. | henry/quad. | $1/4\pi$ | henry/m. | $10^7/4\pi$ | henry/cm. | $10^9/4\pi$ |
| 38 | Magnetic Flux | $\Phi$ | *maxwell* | volt-second | $10^8$ | volt-second | $10^8$ | volt-second | $10^8$ |
| 39 | Mag. Flux Density | $B$ | maxwell/cm.$^2$ | volt-sec./quad.$^2$ | $10^{-10}$ | volt-sec./m.$^2$ | $10^4$ | volt-sec./cm.$^2$ | $10^8$ |
| 40 | Permeance | $\mathcal{P}$ | (oersted)$^{-1}$ | henry | $10^9/4\pi$ | henry | $10^9/4\pi$ | henry | $10^9/4\pi$ |
| 41 | Reluctance | $\mathcal{R}$ | oersted | yrneh | $4\pi/10^9$ | yrneh | $4\pi/10^9$ | yrneh | $4\pi/10^9$ |
| 42 | Inductance | $L$ | abhenry | *henry* | $10^9$ | *henry* | $10^9$ | *henry* | $10^9$ |
| 43 | Magnetization | $I$ | | volt-sec./quad.$^2$ | $10^{-10}/4\pi$ | volt-sec./m.$^2$ | $10^4/4\pi$ | volt-sec./cm.$^2$ | $10^8/4\pi$ |
| 44 | Magnetic Pole | $m$ | maxwell/$4\pi$ | volt-sec. | $10^8 \times 4\pi$ | volt-sec. | $10^8 \times 4\pi$ | volt-sec. | $10^8 \times 4\pi$ |
| | *Chemical* | | | | | | | | |
| 45 | Electrochemical Equivalent | | g/abcoulomb | 11th-g/coulomb | $10^{10}$ | Kg/coulomb | $10^{-4}$ | g-seven/coulomb | $10^{-3}$ |

rationalized by the removal of the $4\pi$ factor from magnetomotive force and inserting it into reluctance, so as to keep the unit of flux correct. This method of rationalization did not become available until about 1893, and did not appear in the original scheme of Maxwell; but the comparative relations of the three systems are best presented by applying the same rationalization to all alike. Likewise, all three are presented as unified systems through the Giorgi device of adopting suitable values for the space coefficients $\kappa_0$ and $\mu_0$.

The units appearing in italics in the table have names that have been internationally adopted, or may claim to have met with international recognition. The names in Roman type, on the contrary, have not been adopted internationally, or are descriptive only.

The numerical values appearing in Columns VI, VIII, and X indicate the number of C. G. S. units contained in the practical unit considered, except in the case of $\kappa_0$, No. 33, which gives the values of that coefficient in the three different "practical" systems.

It will be observed that all three "practical" systems have the following electric, magnetic, and energetic units in common: the *joule, watt, volt, ohm, ampere, coulomb, henry, and ampere-turn*, if the last named may be properly regarded as an international unit. In many of the other units, however, characteristic differences of magnitude appear. Since it is unlikely that anyone will recommend the Q. E. S. system for practical use throughout, owing to the very awkward values of its length and mass units, we may confine attention to the

TABLE III

NUMERICAL VALUES OF SPACE PERMITTIVITY $\kappa_0$ AND OF SPACE PERMEABILITY $\mu_0$ IN THE Q. E. S., M. K. S. Ω AND C. G. S. S. "PRACTICAL" SYSTEMS

| | * $n = 9$ $m = -11$ Q. E. S. Maxwell, 1881 | $n = 2$ $m = 3$ M. K. S. Ω Giorgi, 1901 | $n = 0$ $m = 7$ C. G. S. S. or "International" Dellinger-Bennett |
|---|---|---|---|
| Space Permittivity $\kappa_0$ | $\frac{1}{4\pi v^2}$ with $v = 29.98$ $8.85 \times 10^{-2}$ | $\frac{10^7}{4\pi v^2}$ with $v = 2.998 \times 10^8$ $8.85 \times 10^{-12}$ | $\frac{10^9}{4\pi v^2}$ with $v = 2.998 \times 10^{10}$ $8.85 \times 10^{-14}$ |
| Space Permeability $\mu_0$ | $4\pi$ 12.566 | $4\pi \times 10^{-7}$ $1.2566 \times 10^{-6}$ | $4\pi \times 10^{-9}$ $1.2566 \times 10^{-8}$ |

*All of the "practical" units thus far (1929) adopted internationally conform to any one of a theoretically infinite series of $L\ M\ (T = 1$ sec.) systems, in which $L = 10^n$ cm., and $M = 10^m$ g.; such that $2n + m = 7$. The adoption of the "volt-second" practical unit of flux does not affect this generalization. It seems, however, that the international adoption of a corresponding "practical" unit for either $H$ or $B$ will logically select the particular "practical" system, as M. K. S. Ω or C. G. S. S. for the entire series of Table II, according as the meter or centimeter is taken for length and cross-section.

M. K. S. Ω and C. G. S. S. systems, in Columns VII and IX.

Among the electric and magnetic units, 22 to 44, inclusive, there is not much to choose between the two systems of Columns VII and IX. Indeed, electrical workers may prefer the centimetric values of Col. IX to the metric values of Col. VII, because by long familiarity with the fundamental C. G. S. system, the centimetric operations are familiar. There is likewise little advantage on either side in the thermal and luminous lists. The principal differences are found in the mechanic series, particularly in Mass and in Density, Nos. 2 and 6. Here the M. K. S. Ω system has distinct advantages. The unit mass of ten metric tons, or $10^7$ grams, is a serious handicap to the C. G. S. S. system. Consequently, if the "practical" system were restricted entirely to the use of electrical workers, with problems involving mass seldom presenting themselves, either of the two systems might be adopted, to the ultimate exclusion of the fundamental C. G. S. system. There might then be two remaining systems in scientific work, one the "practical" system for electrical workers, and the other the C. G. S. system for non-electrical workers, or all other scientists. It seems more likely that the M. K. S. Ω system would gain the favor of all the non-electrical workers, than the C. G. S. S. system with its large unitary mass. In other words, the greater hope for a final single scientific system of units in the distant future, seems to lie on the side of the M. K. S. Ω system. At all events, this question deserves careful consideration before a "practical" unit of magnetic intensity $H$, or flux density $B$ is internationally adopted.

*Table III* presents the numerical values of $\kappa_0$ and $\mu_0$ in the three "practical" systems.

## Appendix

### Report of International Subcommittee on Magnetic Units

To Dr. C. O. Mailloux, President, I. E. C. Committee on Nomenclature—

The Subcommittee on Magnetic Units has considered the questions proposed to it at the Bellagio meeting of 1927, as follows:

(1) In view of certain differences of usage of the magnetic unit *gauss* in different countries, can we recommend any action directed towards unification of usage in the future?

(2) In view of the communication of the Comité Electrotechnique Italien [1 (Italy) 27], presented at Bellagio, what recommendations are we able to make?

The subcommittee has discussed these questions by correspondence only.

The subcommittee recommends (1) that steps should be taken towards unification of the definitions of the magnetic units and of their names. The subcommittee has not yet been able to arrive at an agreement on the specific steps that should be thus taken. It recommends that the Committee on Nomenclature of the I. E. C. should place this important question on the agenda for its next international meeting, and should seek to elicit discussion upon the question in the various national committees, in advance of the meeting, so as to pave the way for well considered international action.

(2) The subcommittee is unable to recommend the suggestion in the proposal of the Italian Committee [1 (Italy) 27], to change the name *maxwell* from the C. G. S. U. of magnetic flux $\phi$ to the "practical" or volt-ampere-ohm unit of magnetic flux $\phi$, in view of the dislocation in understanding of electromagnetic literature that might thereby be brought about.

Signed
W. H. Eccles
P. Janet
A. E. Kennelly, Chairman,
L. Lombardi
Mitkievitch
K. Strecker
G. J. Van de Well

24th September, 1929.

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## Discussion

**W. J. Shackelton:** The American Society for Testing Materials has a standing committee whose responsibility it is to formulate specifications describing approved methods of testing materials for such magnetic properties as are of mutual concern to the two major classes of its members, that is to say, to suppliers and consumers. The use of such uniform methods in the inspection of material supplied under a specification of magnetic quality is a matter of practical necessity. In its work this committee, of course, has had to use magnetic units and for many years has recognized that the situation with respect to definitions and names has not been a very happy one. This is well brought out by the historical outline contained in Dr. Kennelly's paper.

Some three years ago the committee, in view of its special needs, undertook a compilation of a glossary of the commonly used magnetic terms with their definitions. The result of this undertaking has been:

1. The publication in 1927 of a preliminary list of terms and definitions on which criticism and comment were requested.

2. The publication in 1928 of a revised and enlarged list, also as a matter of information and comment.

3. The publication in 1929 of the list again slightly revised as a tentative standard of the society.

Quite recently this list has been submitted to the newly formed Sectional Committee on Electrical Definitions of which Dr. Kennelly is the chairman.

The A. S. T. M. Committee throughout its study of the subject has approached the problem from the standpoint of selecting wherever possible that which is most nearly representative of good general practise now prevailing. In the matter of units it found that there was a sufficiently well defined usage to indicate which should be formally recognized. These, of course, do not include the "ampere-turn" or the "volt-second," although the committee recognizes that these units have some distinctive merits. On the question of definitions, however, no substantial agreement could be found in the literature; a situation which is also pointed out by Dr. Kennelly. It was necessary, therefore, for the committee to strike out to a certain extent for itself, and after a considerable amount of discussion among those evidencing an interest in the subject, the definitions as published were set up.

In the light of our experience in this connection I can definitely second Dr. Kennelly's conclusion as to the desirability, in fact I should say the necessity, of obtaining agreement on definitions, at least of magnetomotive force and magnetic flux, before much lasting progress can be made toward a uniform system of units and names. Comparing the tentative definitions of the A. S. T. M. with the specific proposals made by Dr. Kennelly, I do not find any conflict in substance. It may be that all will not wish to subscribe to these definitions exactly as now worded, but it would seem that they might well serve as a starting point for the general agreement which it is so desirable to have.

**M. G. Lloyd:** Dr. Kennelly has pointed out the different views with respect to the unit in which $H$ should be measured, and it seems to me those different views are perhaps rooted in a difference in the idea which is represented by this symbol $H$. I think there are two distinct things represented by that symbol in different cases, and because they have the same numerical value they have been confused.

In Table II, on the seventh page of the paper, Item No. 36 is listed as magnetic field intensity and the symbol $H$ is given and the unit is given as gilbert/cm. If $H$ represents the resulting flux in air it seems to me it has the same dimensions as $B$ and should be measured in the same unit. They are both flux densities. One is in air, or in a vacuum perhaps, which has a permeability *one* which we have assigned to it. The other is in a medium of different permeability, but in each case there is a resultant flux, which has a flux density. Because the permeability happens to be unity in one does not make it disappear in terms of dimensions. The magnetic flux density in air has the same dimensions and can be measured in the same unit as magnetic flux density in iron.

However, gilberts per cm. is a different quantity, if permeability has dimensions. Different people have called them both $H$. Perhaps the same person has called them both $H$. Possibly we need to distinguish between our gilbert/cm., the magnetomotive force per unit length, and the resultant flux from it in

the medium which has permeability unity. I think perhaps that difficulty is at the root of the confusion.

I want to endorse the recommendation of the committee, that if a different unit is wanted for the magnetic flux we should not attempt to carry the term now well known over to a new magnitude, but we should find a new name for that new unit, and let the maxwell either be continued as it is at present, or forgotten if we all come to another unit.

**C. L. Dawes:** During the last fifteen years immense progress has been made in the matter of international standardization, and it comes, I believe, as a distinct surprise to a number of us to learn that no international agreement has as yet been reached in the definitions of such very fundamental scientific quantities as magnetic units. It appears that the first attempts to define electrical quantities were made as far back as 1861, and the first specific attempts to define magnetic quantities were made in 1889. Although various conferences for standardizing units have been held over a period of forty years, such fundamental quantities as magnetic units have not as yet been standardized internationally.

The purpose of this paper, as is stated by Dr. Kennelly, is to obtain individual opinions from members of the Institute on three specific recommendations which he proposes. With any substantial support by Institute members and other scientific organizations, he may be able to effect an agreement with the other members of the International Subcommittee, on certain definitions, and hence make a beginning, at least, toward international accord on magnetic definitions. I personally am in hearty agreement with all three recommendations.

Referring to the first suggestion, dimension, I believe, should be assigned to the quantity $\mu$. The fact that the dimensions of a quantity cannot be expressed immediately in the fundamental units of length, mass, and time does not mean necessarily that the quantity has no dimension, but rather that our present knowledge is too inadequate to assign dimensions. For example, many believe that temperature has dimensions, but so far, dimensions in units of length, mass, and time cannot be assigned to it. We also know that $\sqrt{\mu\kappa}$, where $\kappa$ is dielectric constant, is equal to the reciprocal of a velocity which has dimensions. This implies that $\mu$ is dimensional. Hence, in view of the present limits of our knowledge, I believe that it would be safer to consider $\mu$ a dimensional quantity, and if at some future time it is found to have no dimensions, the quantity could then be considered a numeric, without any harm having been done. If then, $\mu$ is considered as a dimensional quantity, $B$ and $H$ cannot have the same dimensions. I agree absolutely with Dr. Lloyd that most of the confusion in considering $B = H$ comes from the fact that the gilberts per cm. are equal numerically to the flux density in air. If the fact that these quantities are only equal numerically, were clarified, I believe that most of this confusion would disappear. This may be done very readily by adopting the suggestion of Dr. Kennelly in assigning to free space a permeability $\mu_o$, a dimensional quantity, and considering $\mu$, relative permeability, a mere numeric. In the second suggestion Dr. Kennelly asks merely that the name *maxwell* be applied to the unit of flux and he feels that the other members of the committee would concur in this. In view of accepted usage in this country, I do not believe that any objection can be raised to this. Moreover, I believe that the further recommendation should be made that the unit of flux density be called the *gauss*.

The third suggestion refers to a proposal by the Italian delegate that the name volt-second ($= 10^8$ c. g. s. lines) be applied to the practical unit of magnetic flux.

In international conferences of any character, it is usually necessary that everyone make some concessions. We are asking that names of units which have acquired usage in this country be applied to some of the magnetic units, and delegates from other countries are asking consideration of their recommendations. Hence, I not only see no harm in accepting this terminology proposed by the Italian delegate, but feel that this country should welcome such a practical unit. Moreover, if agreeable to the committee I should be in favor of calling this unit the *weber*. This unit is advantageous in that it eliminates the factor $10^8$ which enters so many engineering calculations.

The opinion has been expressed that if such a practical unit were adopted, the fundamental c. g. s. system would thereby be eliminated. From its very nature, it is almost impossible to eliminate any fundamental system of units. As Dr. Kennelly has said, if this ever should happen, it would be at a remote period and I do not believe at this time that we need be concerned with it.

This paper, by outlining so concisely the history of the development of magnetic units and by focusing attention on their present status, should give a much needed impetus to a final standardization of magnetic units internationally.

**F. W. Gay:** The use of units to be employed in any given instance has often been considered as merely the matter of placing a decimal or the question of whether the multiplier between units should be 10, 12, or some other number.

There are far greater basic factors affecting the choice of units. These factors may perhaps be arranged in two great groups.

*1. Psychological.* It is undoubtedly a fact that for any particular class of work there is a particular dimension for the basic unit which will give the best result in aiding the engineer or practical man in his calculating work. A smaller unit would give too large a figure for ready mental calculation while a larger unit would often drive him to the use of decimals.

*2. Practical.* It is quite possible that an entirely different unit may be desirable from the standpoint of the workman who performs actual mechanical work, since he does little figuring and is only interested in the meeting of dimensions within the required tolerance.

As an example of the first instance it might be stated that the centimeter has not proved the equal of the inch in ordinary magnetic calculations involving design work. The unit appears to be so small that the figures which must be mentally multiplied and divided are too large for the mental arithmetic of the ordinary engineer. The inch appears to be a much better unit.

As an example of the second sort it might be wise to consider the industrial prosperity of the United States. The unit of measurement which has given the United States its present industrial position is the mil, the one thousandth part of an inch. The fact that years ago the American workmen set up the mil as a tolerance standard to work to and the industrial manager has determined to obtain a high output accurate to one mil, has resulted in the interchangeability of parts and all that such interchangeability means.

If we look abroad we will find that the metric system either has a logical tolerance value approximately four times as great or only four-tenths as great as our mil. It is well known that the Swiss workman works to the smaller tolerance unit, that is, he works to a much greater accuracy than that used in the United States. His workmanship is very fine but his output is so small that it will not compete with the output of the United States in the same line of work. In some other foreign countries the tolerance standard is four times as great as in the United States, that is, it is approximately four mils and this degree of tolerance is so liberal that interchangeability of parts is not possible. In consequence it is necessary to fit articles by hand and costs are correspondingly increased.

Of course it can be argued that even tolerances are not necessary. The fact nevertheless remains that they are convenient tolerances, which are automatically set up as standards once a system is chosen.

It is altogether possible that the standards of workmanship obtainable in the United States will be pushed up so high that

a tolerance of four-tenths as great as at present can be used without a great increase in cost per unit. However, it would seem that we are a long way from such a desirable condition and hence we are a long way from the time when the metric system should be adopted as our standard.

In conclusion we should like to point out that it is more important for foreign countries to change to a commercially sound and practical system of measurements than for the United States to change. It is undoubtedly desirable that an international system should be adopted; but the possibilities for good or evil both upon the engineers who must think in the system and upon the morale of the workman who must work in the system are so great that the prosperity of a nation may be seriously affected by an unwise choice.

When the electromagnetic fundamental units have once been standardized it might be wise to carry forward time studies looking towards picking a practical system of magnetic units based perhaps on the ampere turn and the reluctance of a cubic inch of air.

**V. Karapetoff:** I most heartily second Dr. Kennelly's wish that a new unit of flux be introduced to agree with the practical ampere-ohm system of units in general use. The question whether it should be called the weber or the volt-second is not so important, although I have used the term weber in my "Magnetic Circuit" (McGraw-Hill) since 1911.

I should like to go a step further and ask that the ampere-turn be recognized as the practical unit of magnetomotive force, because this would automatically fix the magnitude and the physical dimension of permeability. The fundamental equation of the magnetic circuit, corresponding to Ohm's law in the electric circuit, is

$$\Phi = M P \tag{1}$$

where $\Phi$ is the flux, $M$ the magnetomotive force, and $P$ the permeance of the circuit. For a circuit of uniform cross-section

$$P = \mu A/l \tag{2}$$

where $l$ is the length, $A$ the cross-section of the circuit, and $\mu$ its absolute permeability. Substituting this value of $P$ from Equation (2) in Equation (1) and dividing both sides by $A$, gives

$$\Phi/A = \mu M/l \tag{3}$$

or simply

$$\mu = B/H \tag{4}$$

Thus, the dimension of $\mu$ is the ratio of those of $B$ and $H$. If $B$ is expressed in volt-seconds per sq. cm., its dimension is $R\ I\ T\ L^{-2}$, where $I$ is the dimension of the current and $R$ that of the electrical resistance; $L$ and $T$ are length and time respectively, and with their units we are not here concerned. The dimension of $H$ in ampere-turns is $I\ L^{-1}$. Therefore, the dimension of $\mu$ in the practical ampere-ohm system is

$$\mu = R\ T\ L^{-1} \tag{5}$$

and not a numeric ("The Magnetic Circuit," p. 263). We may now put

$$\mu = \mu_r\ \mu_v \tag{6}$$

where $\mu_r$ is the relative permeability of a material and $\mu_v$ is the absolute permeability of vacuum. In this manner, the usual values of $\mu$ can be retained, only they become values of relative permeabilities whose dimension is a numeric.

Professor McKeehan's argument that the physical dimensions of $B$ and $H$ are the same, because of the formula

$$B = H + 4\pi J \tag{7}$$

is not convincing. This formula was originally deduced on the supposition that $\mu = 1$. In any other system of units the formula would read

$$B = \mu_v H + k J \tag{8}$$

I was surprised to learn from Dr. Kennelly's computations that the unit of mass in the system of magnetic units which I have been advocating and using for over twenty years is ten metric tons. To me this simply shows that in framing a convenient system of electric or magnetic units, a convenient unit of mass or length is not essential, because it is so seldom used in conjunction with electric units. It is better to have a convenient system of electric and magnetic units, and to use a decimal factor for the mass when it comes in on rare occasions, than to be forced to a system of inconvenient electric units for the sake of basing them on the centimeter and the gram.

No one deplores the existing multiplicity of magnetic units more than I do, yet looking back upon the progress of our art and of the adjacent branches of physics, it does not seem to me that the progress has been materially impeded by a lack of agreement about units, nor that serious misunderstandings have ever arisen in this respect. I am not trying to belittle the praiseworthy efforts of Dr. Kennelly and his colleagues on the I. E. C., but partly to re-assure outsiders that no critical (or near-critical) situation exists, and partly as a possible explanation of the exceedingly slow progress made by the Commission with respect to magnetic units. Had an urgent need existed for an agreement in regard to magnetic units, I am sure that speedier progress would have been made.

The real situation is that each group of workers using magnetic quantities employs a few units which it finds convenient, and is not troubled by the fact that the corresponding unit of length in that system is one-quarter of the terrestrial meridian, nor that the density of water comes out to be quite an unusual figure. Much work is done in algebraic symbols, without even specifying the system of units used, and the results are usually correct in any consistent system of units.

It seems to me that the problem of units could be considerably simplified if we agreed beforehand to accept a unit with all its multiples and submultiples in powers of ten as belonging to the same system. For example, I see no particular reason for arguing whether the meter or the centimeter is preferable as the fundamental unit of length. In applications we have to use lengths from billionths of a millimeter to billions of kilometers, and yet no confusion arises because all these lengths are connected by simple factors equal to ten to some integral power. The same applies to the electric and magnetic units, and I see no valid reason for arguing whether the maxwell or the weber should be the fundamental unit of flux, as the two are connected by the factor equal to ten to the eighth power. No matter which one is decided upon, both will be used in applications, as well as kilo-maxwells, mega-maxwells, milli-webers, etc. I may be missing an essential factor from the point of view of the general philosophy of units, but from the standpoint of a user I am only mildly interested as to which of the two is decided upon. Of course, re-naming the bigger unit the maxwell is like re-christening the Washington Monument the Lincoln Monument, and the proposal will never be approved by a judicious and conservative body like the I. E. C.

When, however, it comes to units whose ratio is $3 \times 10^9$ or $4\pi$, the situation is more troublesome, and I heartily support Dr. Kennelly's recommendation that the whole question of the theory of the magnetic circuit be first gone over, especially with regard to the physical dimensions of permeability, which is really the crux of the whole situation. The commission should state that $B$ is to be measured in flux units per unit area and $H$ in current-turns per unit length; this will at once give physical dimensions to the absolute permeability, and will permit differentiation between the absolute permeability of a medium and its relative permeability with respect to that of the air, as I showed above. The numerical value of the absolute permeability of the air (or vacuum) will still depend upon the system of units used.

Dr. Kennelly dismisses the c. g. s. electrostatic system from his considerations, and perhaps he is right in so far as its use in power engineering is concerned. However, it is also of importance to consider the needs of physicists. At least I, for one, have always considered that the functions of the government delegates to the I. E. C. included the needs of pure science as well. Moreover, the progress of the engineering art is essentially

determined by advances in physics and chemistry, and it would be quite unfortunate if the final definitions and units adopted by the I. E. C. were not acceptable to research physicists. I hope that in the final draft of his paper Dr. Kennelly will include the history of the two other systems of units now largely used in books and articles on theoretical physics, namely the Gauss system[1] and the Heaviside-Lorentz system.[2] The first system permits the use of the electric quantities in an electrostatic system of units and the magnetic quantities in an electromagnetic system of units, in the same equation. The second system accomplishes the same purpose and also enables us to avoid an "eruption of 4 $\pi$'s."

With the advent of the electronic theory and with a growing interest in electromagnetic waves in space, equations are used more and more in which electrostatic quantities, such as the charge on an ion and the electric field intensity, are combined with magnetic quantities, $H$ and $B$. Therefore, in considering various systems of magnetic units it is essential, for the sake of future workers, to provide convenient relations with electrostatic quantities. The Gauss system is largely used by mathematical physicists; therefore, it is only a question of time when research engineers will also be using it in continuing and applying the work of physicists to their problems. As a rule, it does not do to anticipate a system of units ahead of its actual use, but here we undoubtedly are facing an inevitable invasion and it may be wise to be prepared for it.

I sincerely hope that the I. E. C. will adopt the policy of "decimal families of units," not insisting on a particular unit, but including all its multiples and sub-multiples in powers of ten as well. I also hope that the status of the absolute permeability and absolute permittivity will be settled at least in so far as recognizing them to be dimensional quantities and not pure numerics.

**Edward Bennett:** (communicated after adjournment) The status and the historical background, not only of the magnetic circuit units, but also of the proposals looking to an agreement as to the units of length, mass, and force in the system of international units are so clearly and fairly presented in Dr. Kennelly's paper that his plea for full discussion to pave the way for well considered international action should meet with the heartiest response. My discussion will be confined to the principles which should be applied in passing upon the merits of alternative proposals and to some comparisons in the light of these principles.

The aim in devising a *comprehensive system* of units is to *reduce mental effort* in the fields of thought which have been explored, in order that men may be free and fresh for adventures in virgin fields.

*Importance of Unencumbered Formulas.* In the devising of a system of units, the process is to adopt the smallest possible number of *arbitrarily defined independent* units to serve as the *fundamental* units of the system, and to define the units for all other physical quantities in the simplest and most comprehensible manner by means of these fundamental units. The scores of units which in this manner are defined by reference to the fundamental units are called the *derived* units of the system.

Now the unit for one physical quantity can be defined in terms of other physical quantities only by means of known relations between the quantities. Accordingly, the use of a *system* of derived units makes it possible to reduce mental effort, *provided* these known relations are properly utilized in defining the *derived* units. Proper utilization means that the derived units must be so defined that the important equations, or formulas, used in predicting the values of unknown quantities are not *encumbered* by needless or perplexing factors which are burdensome to the memory.

The difference between thinking in terms of the haphazard *set* of arbitrarily defined units of a primitive culture and in terms of a *system* of derived units is this: In the former case, every quantitative relation or formula is the expression of an empirically or experimentally determined relation, and consequently every formula is *encumbered* with a non-significant numerical factor. In the latter case, the experimentally determined relations are so used in defining the quantities and in defining the units as to leave many of the important formulas free of encumbering factors. In other words, those relations which are *matters of definition* are made to play a simplifying role. The difference between the two situations, thinking in terms of encumbered and unencumbered formulas, may seem slight. But it may be recalled that the Scriptures portray the prophet of old as smiting with his rod to cause the life-giving water to flow from the rock. Well, the prophet of today is the scientist, the formulas constitute his rod, and encumbered formulas make an ineffective rod,—at least for the minor prophets.

Any system of units falls short of the ideal to the extent to which it is encumbered by the presence of needless numerical factors in the formulas expressing the relations between quantities.

*Importance of Units of Convenient Size.* If the first desideratum in a system of units is that the formulas of the system shall be unencumbered, certainly the second is that the units for which the formulas have been written shall be of such a size as to lead to *convenient numerical expressions* for the quantities dealt with in the shop, the laboratory, and the market. It is particularly desirable that the *formula units* of the quantities dealt with in the every-day affairs of the common life of the community shall be of *convenient and readily comprehensible size.*

In this discussion, it is important to have a clear understanding of the term *formula unit.* In the formulas of a comprehensive and completely consistent system, any physical quantity such as length,—no matter in what formula it appears, whether in a formula for area, velocity, force, energy, temperature gradient, electric intensity, or what not,—*will always be expressed in the same unit,* say the meter. This unit is termed the *formula unit* of length in that system.

If past experience with systems of units teaches any lesson it is that the *formula units* of any comprehensive system cannot all be of convenient magnitude for the varied needs of the shop, laboratory, and market. For example, if the *formula unit* of length is the *meter,* men may be expected to measure cloth and town lots in meters but they can not be expected to dimension machine shop drawings or talk about the thickness of paper, or automobile speeds, or city to city distances in meters. As further illustrations:

The *joule* or the *watt-second* is not a convenient unit for use in billing energy and so energy is measured and billed in *kilowatt-hours.*

Transformers are rated and sold in terms of *kilowatts* or *kilovolt-amperes.*

Condensers are rated and sold in terms of *microfarads.*

Machine shop drawings are dimensioned in *millimeters.*

Insulation resistances are stated in megohms and metallic resistivities in *microhms.*

And so it happens that no matter how comprehensible the formula units may be, a great number of shop, laboratory, and market (s. l. a. m.) units will come into use. There is not the slightest possibility of preventing these s. l. a. m. units from springing into use. Nor should there be any desire to suppress or to discourage their use, *provided,*

1. That these s. l. a. m. units are decimal multiples or sub-multiples of the formula units,

2. That the ratio of each s. l. a. m. unit to its corresponding formula unit is unambiguously shown by a consistent use of the system of decimal prefixes in forming the name of the s. l. a. m. unit from that of the formula unit.

1. Geiger und Scheel, *Handbuch der Physik,* Vol. 16, 1927, pp. 4 to 13.
2. Leigh Page, "Introduction to Theoretical Physics," 1928, pp. 424 and 432.

The lesson from these illustrations is that the use of decimal multiples and submultiples of those units which are of inconvenient size for the transactions of commerce is readily accepted, or is an easy thing to bring about. The appearance of the prefix micro, milli, or kilo in the name of a s. l. a. m. unit does not militate against the use of the unit by the uninformed man in the shop, laboratory, and market. To the uninformed man, the prefix "kilo" is a part of the name, and the two syllables mean no more to him than do two syllables in any polysyllabic name. But to the informed man, the prefix "kilo" should not be a part of the name of the unit. The use of the decimal prefixes should be so consistent, that the informed man may always treat the prefix as a part of the *numeric*, and may always regard the name following the prefix as the name of the *formula unit* of the system.

Since there are gaps in the list of decimal prefixes, I venture to propose that these gaps be filled by the prefixes which are printed in italics in Table I.

TABLE I
DECIMAL PREFIXES FOR FORMING THE NAMES OF THE S. L. A. M. UNITS FROM THE FORMULA UNITS

| Subdivisions | | | Multiples | | |
|---|---|---|---|---|---|
| Prefix | Symbol | Multiple | Prefix | Symbol | Multiple |
| deci | dc | $10^{-1}$ | deka | dk | 10 |
| centi | c | $10^{-2}$ | hekto | hk | $10^2$ |
| milli | m or ml | $10^{-3}$ | kilo | k | $10^3$ |
| *demil** | dml | $10^{-4}$ | myria | my | $10^4$ |
| *cemil*† | cml | $10^{-5}$ | *penta*¶ | p | $10^5$ |
| micro | $\mu$ or mc | $10^{-6}$ | mega | mg | $10^6$ |
| *billi*‡ | bl | $10^{-9}$ | *kilomega* | kmg | $10^9$ |
| Micro micro§ | $\mu\mu$ or mcmc | $10^{-12}$ | *mega mega* | mgmg | $10^{12}$ |

*from decimilli.

†from centimilli.

‡billi from billionth, the alternative is the Latin-Greek hybrid "milli-micro" mlmc.

§trilli (tr) from trillionth, may be considered as an alternative to micro micro.

¶the Greek "penta" suggesting the exponent 5. A. E. Kennelly has suggested the prefix "lakh" from the Sanskrit for 100,000.

*The Importance of Unencumbered Names for the Formula Units.* Unvarying adherence to the principle that, "In forming the name of a s. l. a. m. unit from the name of the formula unit, a given decimal prefix, as "kilo," shall always signify the same multiple of the formula unit," means that it is not permissible to *encumber the names of formula units* with misleading decimal prefixes. To comply with this principle, new names will have to be coined and applied to four or perhaps five of the formula units which appear in the comprehensive systems which have been proposed for universal use. For example, in the c. g. s. systems, the name of the unit of length is encumbered with the prefix "centi;" in the m. k. s. system, the name of the unit of mass is encumbered with the prefix "kilo;" in the c. g. s. system, the name of the unit of mass is encumbered with the suffix "seven."

The formula units which must be disencumbered by renaming them, and the new names which I venture to suggest are shown in Table II.

*Basis of Comparison of Systems of Units.* To summarize, the desiderata in a comprehensive system of units for universal use are:

1. The formulas expressing the relations between quantities should not be *encumbered* with needless or perplexing numerical factors.

2. The *formula units* of the system should have names which are not encumbered with misleading decimal prefixes. The decimal prefix in a name should always signify that the unit is a s. l. a. m. multiple of the formula unit.

3. The *formula units* of the few quantities dealt with in the every-day affairs of community life should be readily comprehensible. In addition it is desirable that in the case of all the formula units of the system, their s. l. a. m. units lying between the micro and the mega unit shall be of convenient size to meet the needs of the shop, laboratory, and market.

TABLE II
PROPOSED DISENCUMBERED NAMES FOR THE FORMULA UNITS

| | M. K. S. system | | C. G. S. S. system | |
|---|---|---|---|---|
| Quantity | old name | new name | old name | new name |
| length | meter | meter | centimeter | tyc* |
| mass | kilogram | newt | gram-seven | newt† |
| force | dyne-five | galileo or galeo | dyne-seven | galileo‡ or galeo |
| area | sq. meter or centare | derm | sq. cm. | derm§ |
| volume | cu. meter or stere | stere | cu. cm. or milliliter | cuba¶ |

*To commemorate the industry, the skill, and the vision of Tycho Brahe, the measurer preeminent, who, before the inventions of the telescope, made the precise astronomical measurements from which Kepler was able to deduce the laws of planetary motion.

†To commemorate Newton's invention of the concept of "the mass of a body."

‡To commemorate Galileo's keen observations of the circumstances attending the motions of bodies.

§From the Greek "derma"—skin.

¶From the Greek "kybos"—cube.

*Deficiences of the International System of Electric and Magnetic Units.* In the light of this discussion of the basis for comparing the relative merits of different systems of units, let us first consider the *deficiencies* of the hybrid system which has been legalized throughout the civilized world by governmental actions, namely the centimeter, gram, second absolute system for the mechanical units and the international system of electric and magnetic units.

The fundamental formula units of this hybrid system are:

a. The unit of time is the second of the mean solar day; this unit is common to both the absolute and the international sets of units.

b. In the absolute set, the centimeter and the gram, as represented by the platinum-iridium prototype meter and prototype kilogram Standards, in the custody of the International Bureau of Weights and Measures, are the remaining two fundamental units.

c. In the international system, the two fundamental units, other than the second, are the ohm and the ampere as represented by the mercury ohm standard and the silver nitrate coulombmeter set up in accordance with the legal specifications for the international ohm and the international ampere.

This hybrid system of units is deficient in the following respects.

1. The international unit of energy, the joule, as represented by the energy expended per second when a current of 1 international ampere flows in a resistance of 1 international ohm is not equal to 1 absolute unit of energy, it is not even equal to $10^7$ absolute units, or $10^7$ ergs, but

$$1 \text{ International joule} = 1.00034 \times 10^7 \text{ ergs}$$
$$= 1.00034 \text{ "practical" absolute joules.}$$

This means that formulas for obtaining the mechanical forces and the accelerations in electrical systems are encumbered with the needless numerical factor, $10^7$. For example,

$$f \text{ (dynes)} = 10^7 I_1 I_2 \frac{d M}{d x} \quad \begin{matrix}\text{(amperes, henries)} \\ \text{(cm.)}\end{matrix}$$

$$a \text{ (cm. per sec. per sec.)} = 10^7 \frac{F q}{m} \quad \begin{matrix}\text{(volts per cm., coulombs)} \\ \text{(grams)}\end{matrix}$$

2. The last international actions on the magnetic units are

the action of the International Electric Congress in Chicago in 1893 recommending the use of the unrationalized magnetic units of the electromagnetic system of c. g. s. absolute units and the action of the Fifth International Electrical Congress of Paris in 1900 recommending the use of the following names.

"*maxwell*" for the e. m. unit of magnetic flux.

"*gauss*" for the e. m. unit of field intensity.

The use of the "maxwell" for the unit of flux means that many formulas involving flux are encumbered with the needless numerical factor $10^{-8}$. For example,

$$e \text{ (volts)} = 10^{-8} \frac{d\,\varphi}{d\,t} \quad \begin{matrix}\text{(maxwells)}\\ \text{(seconds)}\end{matrix}$$

$$L \text{ (henries)} = 10^{-8} \frac{\varphi\, N}{I} \quad \begin{matrix}\text{(maxwells, turns)}\\ \text{(amperes)}\end{matrix}$$

$$W \text{ (joules)} = 10^{-8}\, I\, N\, \Delta\, \varphi \text{ (amperes, turns, maxwells)}$$

but note the exception,

$$f_x \text{ (dynes)} = I\, N \frac{d\,\varphi}{d\,x} \quad \begin{matrix}\text{(amperes, turns, maxwells)}\\ \text{(cm.)}\end{matrix}$$

The use of the "gauss" rather than the "ampere-turn per cm." as the unit of field intensity means that the formulas must be written in the unrationalyzed forms, thus

$$\text{M. M. F. (gauss-cm.)} = 0.4\,\pi\, N\, I \text{ (turns, amperes)}$$

$$\varphi \text{ long-solenoid (maxwells)} = \frac{0.4\,\pi\,\mu\, N\, I\, a}{l} \text{ (amperes, cm.)}$$

*A Common Feature of the Proposals to Modify the Existing Hybrid System of Units.* The proposals to improve upon this internationally sanctioned hybrid system of units have one feature in common. This feature is the proposal to "rationalize" the formulas of the system, by shifting the irrational $4\,\pi$ factors from the more frequently used equations to the less frequently used equations.

But there are two radically different proposals as to the method of bringing about this rationalization. The first proposal is that of those physicists who still persist in writing in Heaviside units. Now the ratios of the Heaviside practical units to the corresponding units in the International system which is in universal use throughout the world are shown in Table III.

TABLE III
RATIO OF THE HEAVISIDE PRACTICAL UNITS TO THE CORRESPONDING INTERNATIONAL UNITS

| Unit of | Ratio $H$/Int |
|---|---|
| Charge and current | $1/\sqrt{4\,\pi}$ |
| E.m.f. and electric intensity | $\sqrt{4\,\pi}$ |
| Capacitance | $1/4\,\pi$ |
| Resistance | $4\,\pi$ |
| Magnetic intensity | $1/\sqrt{4\,\pi}$ |
| Magnetic flux | $\sqrt{4\,\pi}$ |
| Dielectric constant | 1 |
| Permeability | 1 |

In other words, writers who continue to write texts in Heaviside units must virtually be advocating that some future international congress shall take an action which will require that the scales of all ammeters in the world be regraduated for full scale readings equal to $\sqrt{4\,\pi}$ times their present indications, that all voltmeters scales be regraduated to read $1/\sqrt{4\,\pi}$ their present values, that all condensers be restamped with ratings equal to $4\,\pi$ times their present ratings, and that all resistance coils be restamped with $1/4\,\pi$ their present ratings.

Furthermore, this action will mean that all tables showing the dielectric strengths, the resistivities, and the hysteresis losses of materials must be revised, and that all $B/H$ curves must be redrawn. And for what purpose? The answer is to be found in the last two lines of Table III. It is as follows: This stupendous job of recalibrating instruments and of revising tables is to be done in order that in the process of rationalizing the equations of the dielectric and the magnetic circuits, the tables of dielectric constants and of permeabilities may not be disturbed. And yet existing tables of these constants almost invariably give the *relative* dielectric constants and *relative* permeabilities of the materials, (relative to free space). Now tables of relative dielectric constants and of relative permeabilities will remain unaltered no matter what changes are made in the fundamental units. And so it transpires that the proposal to rationalize the formulas by changing to Heaviside units amounts to a proposal to change the current, voltage, capacitance, and resistance ratings of every ammeter, voltmeter, wattmeter, lamp, generator, transformer, condenser, and resistor in existence, for the sake of rationalizing the formulas by a process which will leave undisturbed the very tables which will remain unaffected by any change in the units.

The improbability of such an action by any standardization committee is so overwhelming that we may dismiss the proposal to rationalize the formulas by using Heaviside units without a moment's consideration.

In the second method the rationalization of the equations is brought about by two simple expedients.

1. By using as the units of magnetomotive force and magnetic intensity, the *ampere-turn* and the *ampere-turn per centimeter*, instead of the gilbert and the gilbert per cm. (gauss).

2. By drawing a distinction between the *dielectric constant* $k$ and the *permittivity* $p$ of a dielectric. The permittivity is related to the dielectric constant by the defining equation $k = 4\,\pi\, p$, and the permittivity is used in all equations.

By these simple expedients, the substance of all that Heaviside sought to accomplish by his so-called Rational System of Units is attained. This result is attained by submerging the objectionable $4\,\pi$ factors in the empirical constants (of materials) which the equations contain. The change does not require the rerating of any electrical device, it does not require the change of a single table or curve except $B/H$ tables and curves, and tables which give the absolute values of the permeabilities and dielectric constants of materials in unrationalized practical units. The writer has yet to encounter such a table. The existing tables giving the relative permeabilities and the relative dielectric constants in the unrationalized system correctly express the relative permeabilities and the relative permittivities in the rationalized system. The $B/H$ curves will have to be replotted, with $H$ expressed in ampere-turns per cm. instead of gilberts per cm. The constants of free space in the unrationalized and rationalized international units are:

| | | |
|---|---|---|
| Unrationalized units | $k_o = \dfrac{1}{9 \times 10^{11}}$ | $\mu_o = \dfrac{1}{10^9}$ |
| Rationalized units | $p_o = \dfrac{1}{4\,\pi\, 9 \times 10^{11}}$ | $\mu_o = 4\,\pi/10^9$ |

*Comparison of the Merits of the Alternative Systems of Practical Units.* Dismissing from consideration the revolutionary and unwarranted proposal to supplant the International units with Heaviside units and postulating that the equations of the dielectric and magnetic circuit will be rationalized by the simple expedients sketched above, it remains to compare the merits for universal use of the alternative systems of practical units.

The term "practical system" designates (among other things) a system in which the unit of energy (the joule) is defined to be equal to $10^7$ ergs and in which the unit of time is the second, but in which nothing has been said about the units of length and mass, except that with the units of time and energy fixed upon, the units of length, mass, and force must be selected from metric combinations like the following.

| System | Units | | |
|---|---|---|---|
| | Length | Mass | Force |
| ..... | millimeter | gram-nine | dyne-eight |
| C. G. S. S. | centimeter | gram-seven | dyne-seven |
| ..... | decimeter | gram-five | dyne-six |
| M. K. S. | meter | kilogram | dyne-five |
| ..... | dekameter | dekagram | dyne-four |
| | etc. | etc. | |

One of these combinations must be used if such formulas as the following are to be kept free of needless numerical coefficients.

$$\text{energy} = 1/2 \text{ mass} \times \text{velocity}^2$$
$$\text{work} = \text{force} \times \text{distance}$$

Of the possible practical systems shown above only two have been advocated for universal use, namely the centimeter, gram-seven, second (c. g. s. s.) system and the meter, kilogram, second (m. k. s.) system. If the names of the formula units in these systems are to be unencumbered, it will be necessary to coin new names for the units of length, mass, and force in the c. g. s. s. system, and for the units of mass and force in the m. k. s. system. Names for these units are suggested in Table II.

Any judgment as to the relative merits of the c. g. s. s. and the m. k. s. systems must be based upon a comparison of the expressions for the values of the quantities of frequent use when stated in the c. g. s. s. and m. k. s. units respectively. To furnish material for such a comparison, the following statements are offered.

EXPRESSIONS FOR THE SAME QUANTITY IN THE C. G. S. S. AND M. K. S. SYSTEMS

| Expressions involving length | C. G. S. S. | M. K. S. |
|---|---|---|
| Unit | tyc | meter |
| Dimensions on machine drawings are in | decityc | millimeters |
| The thickness of the paper is | 6 millityc | 0.006 centimeters |
| The dimensions of the planks are | 4 x 24 x 480 tyc | 4 x 24 x 480 cm. |
| Cloth is measured in | hektotyc | meters |
| The width of the street is | 15 hektotyc | 15 meters |
| The distance between towns is | 5 pentatyc | 5 kilometers |
| The New York-Chicago distance is | 1150 pentatyc | 1150 kilometers |
| The train speed was | 80 pentatyc per hr. | 80 kilometers per hr. |
| The speed of light is | $3 \times 10^{10}$ tyc per sec. | $3 \times 10^8$ meters per sec. |
| The mean spacing air molecules is | 0.33 microtyc | $3.3 \times 10^{-9}$ meters |
| The diameter of the oxygen molecule is | $3 \times 10^{-8}$ tyc | $3 \times 10^{-10}$ meters |
| Expressions involving area | | |
| Unit | derm or sq. tyc | derm or sq. meter |
| The sectional area of No. 10 B & S wire is | 5.26 centiderms | 5.26 microderms |
| The sectional area of the beam is | 20 sq. tyc or 20 derms | 20 sq. centimeters or 20 demiderms |
| The area of the 20 x 50 lot is | 1000 sq. hekto tyc | 1000 sq. meters or 1000 derms |
| 1 acre equals | 0.405 sq. myria tyc | 0.405 sq. hekto meters |
| Expressions involving volume | | |
| Unit | cuba or 1 cu tyc | stere or 1 cu. meter |
| The milk bottle capacity is | 1 kilo cuba | milli stere |
| The truck capacity is | 2 mega cubas | 2 steres |
| The reservoir capacity is | 50 million mega cubas | 50 million steres |
| Expressions involving mass | | |
| Unit | newt = gram-seven | newt = kilogram |
| Butter packages contain | 0.5 demil newts | 0.5 newts |
| The man's weight is | 70 demil newts | 70 newts |
| The coal costs $5.00 a | decinewt | kilonewt |
| The allowable truck load is | 5 decinewts | 5 kilonewts |
| The mass of an electron is | $9 \times 10^{-28}$ newts | $9 \times 10^{-31}$ newts |
| Expressions involving density | | |
| The density of water is | 0.1 micronewts per cubic tyc | 1. kilo newt per cubic meter |

EXPRESSIONS FOR THE SAME QUANTITY IN THE C. G. S. S. AND M. K. S. SYSTEMS—*Continued*

| Expressions involving length | C. G. S. S. | M. K. S. |
|---|---|---|
| Expressions involving force | | |
| Unit | galeo = $\text{dyne}^7$ | galeo = $\text{dyne}^5$ |
| The pull of the earth on an apple is | 1 centi galeo | 1 galeo |
| The pull of the earth on a newt is | 980 galeos | 9.8 galeos |
| A man can exert a lifting pull of | 700 centigaleos | 700 galeos |
| Normal atmospheric pressure is | 10.132 centigaleos per sq. tyc | 0.10133 mega galeos per sq. meter |
| 300 lbs. boiler pressure is | 200 centi galeos per sq. tyc | 200 galeos per sq. cm. |
| The tensile strength of steel is | 500 galeos per sq. tyc | 500 mega galeos per sq. meter |
| The modulus of elasticity of steel is | 207,000 | $2.07 \times 10^{11}$ |
| Gravitational constant | 0.666 | $6.66 \times 10^{-11}$ |
| Coefficient of viscosity of water, 20 deg. cent | $10^{-6}$ galeos, tycs | $10^{-5}$ galeos, meters |
| Gas constant $R$ in $pv = Rt$ | 3.718 x $10^{-4}$ galeos, tyc, deg. cent. | 3.718 x $10^2$ galeos meter deg. cent. |
| Expressions involving heat | | |
| 1 newt deg. cent | $4.187 \times 10^7$ joules | $4.187 \times 10^3$ joules |
| Tables of specific heat will not be affected | | |
| Thermal conductivity of copper in watts per unit area per degree per unit length | 3.88 | 388. |
| Ditto for wood | 0.0004 | 0.04 |
| Electric and magnetic expressions | | |
| Permittivity of space | $8.85 \times 10^{-14}$ | $8.85 \times 10^{-12}$ |
| Permeability of space | $4\pi \times 10^{-9}$ | $4\pi \times 10^{-11}$ |
| Resistivity of copper | 1.724 x $10^{-6}$ ohm, tyc | 1.724 x $10^{-8}$ ohm, cm. |
| Dielectric strength of air | 30,000 volts per tyc | 3 megavolts per meter |
| Flux density in transformers | 120 micro webers per sq. tyc | 1.2 webers per sq. m. |

**S. L. Gokhale:** The paper under review gives a concise and very clear history of the problem of magnetic nomenclature which has inspired so much discussion during many decades in the past. This historic sketch gives a good perspective view of the whole situation, and is helpful for a clearer understanding of the true nature of the controversy. It has certainly helped me, or at least I believe it has, for which I am very thankful.

There are some points not clear to me until now; for example, I could not see why magnetic induction is expressed by the symbol $B$. In my college days, I was taught to look on magnetic flux as something analogous to emanation of light from a lamp. I had found that analogy very helpful in that it gave me a clear conception of the equations of Gauss, Poisson, and La Place, but it did not occur to me until I read Dr. Kennelly's paper, that magnetic induction ($B$) is analogous to optical brightness at a point, the latter being also expressed by the symbol $B$. I should like to be informed, however, if that is the true explanation.

The problem of nomenclature resolves itself into three separate but closely related problems:

(a) the relation of the several units to each other and their logical sequence.

(b) Size of the units.

(c) Names of the units.

The question of name is obviously the simplest and may be taken up first.

The greatest amount of controversy ranges itself around an appropriate name for the unit of magnetic force intensity (magnetizing force, or magnetic field intensity) expressed by the symbol $H$. Three names have been used in the past, and four more are under consideration namely:

$A$; names in usage

$A$—1, Gilbert per centimeter

$A$—2, Gauss per unit permeability (briefly gauss)

$A$—3, Dyne per unit pole.

$B$; names proposed

$B$—1, Gauss (Paris Congress; Delegation for Holland and Italy)

$B$—2, Mascart (French delegate)

$B$—3, Weber (German delegate)

$B$—4, Gilbert (Holland delegate), for practical unit only.

The four "proposals" have all the merit of being simple names instead of the three complex names in "usage." Among these three, the weight of usage seems to be greatly in favor of the term "gilbert per centimeter."

While popularity of the name may well be conceded, it must also be conceded that it lacks the simplicity and the convenience of a short single worded name, justifying the use of an abbreviated substitute. In view of this fact I had decided to use in the records and reports of my work the single letter "g" as an alternative name of this unit, and have consistently done so for the last six years. (A. I. E. E. 1926, *Law of Magnetization*; 1928, *Saturation Permeameter*). It is necessary to add however, that although the use of the name "g" was technically a mere abbreviation of the term "gilbert per centimeter," the change was guided in my mind by a more important consideration, that goes to the root of the problem.

The paper under discussion together with the discussion which followed the reading of it at the convention, brings out very clearly the indisputable fact, that there are among the scientists of the world, two different conceptions as to the nature of magnetic flux. For convenience of discussion, I shall refer to them as the static and the dynamic conceptions.

According to the static conception of flux, magnetic induction, or flux density as it is sometimes called, is a magnetic force of exactly the same kind as the magnetizing force $H$, and differs from it only in the location of the sources from which it emanates. The total or resultant magnetic force at a point in a magnetic body in general, is made of two parts:

(a) Resultant of forces emanating from distance sources, such as magnetism on the free surface of the body, magnetism on surfaces of neighboring bodies, and electric currents magnetically associated with these bodies. This is called the magnetizing force $H$.

(b) Resultant of forces emanating from sources infinitely near the point, such as the magnetic poles of molecular magnets (Weber's theory), or molecular electric circuit (Ampère's theory) or the microcosmic electronic orbits, (Langevin's theory) in the neighborhood of the point. This force is called intrinsic force or intrinsic induction $\beta$.

According to this definition $\beta = 4\pi J$, where $J$ is the intensity of magnetization. The total magnetic force at the point is called total induction or briefly the induction $B$. Thus we have the relation $B = \beta + H = 4\pi J + H$. The method of computing analytically the forces from the near and distant sources, by the use of an auxiliary imaginary cavity of proper size, shape, and orientation, is described in all leading text books and need not be repeated here. (J. J. Thomson: "Electricity and Magnetism," Art. 153) According to this conception $B$ and $H$ have identical dimensions and therefore, permeability ($\mu$) must have zero dimensions, with the value $\mu_o = 1$ for free space.

According to the dynamic conception of flux, magnetic flux is analogous to electric current, while the magnetizing force corresponds to electromotive force (Karapetoff, "The Magnetic Circuit," p. 5). The analogy is best expressed by the equations.

$$\frac{B}{H} = \mu \text{ (Permeability)}\ ;\ \frac{I}{E} = \gamma \text{ (conductivity)}$$

The dimensions of $\mu$ are supposed to be unknown but not zero; its value for space may be taken as unity. According to this conception, induction and magnetizing force are dissimilar quantities, which call for different units for their respective measurements. The static conception is generally favored by physicists (J. J. Thomson: *Ibid.*, Art. 256 footnote), and the dynamic conception by the electrical engineers, (Karapetoff, *Ibid.*, p. 257) perhaps because each group finds his favorite system better adapted for his special work. Theoretically there is nothing to guide us in our choice at present, and the situation is not likely to be changed in any way for some years to come.

In view of the facts, I suggest, that:

(a) There should be two systems of nomenclature.

(b) One of these should be based on the dynamic conception of flux having separate units for magnetizing force and flux; the terms "gilbert per centimeter" and "gauss" might be accepted as their most convenient names.

(c) The other system should be based on the static conception, and should have one single unit for both force and flux, and of course with a single name.

(d) It should be recognized that eventually one of the two systems will have to be discarded, but we do not know which one it is to be. The names of the units should be so selected that either system could be easily discarded at any time if necessary, without inconvenience to the readers and users of magnetic literature and data in which the discarded system will have been used.

(e) The unit "g" meets all these requirements. As an abbreviation for "gilbert per centimeter" and also for "gauss" if necessary, it is capable of replacing both of them, if the dynamic system is ever discarded. On the contrary if the static system is discarded the letter "g" may still retain its usefulness as a mere abbreviation of "gilbert per centimeter" only.

The unit magnetic pole, is another quantity that deserves a name. If, as some scientists advocate, we decide in favor of discarding the conception of poles altogether, there will be of course no need for a name; but if we intend to use it in the future, as much as we have been using it in the past, it certainly ought to have a unit with a name worthy of its position. I suggest the name "ewing."

The need of a convenient name for the practical unit $10^8$ maxwell, has long been felt, but no acceptable name has yet been suggested. The name "line" as a synonym for maxwell has long been in use and is very popular; the names "kilo-line" and "mega-line" as convenient names for $10^3$ maxwell and $10^6$ maxwell respectively, have also become quite popular. In view of these facts I suggest the name "arb-line" as a synonym for $10^8$ maxwell, (the prefix "ARB-" being a part of the Sanskrit numeral "arbuda" which means "hundred-million") with a confession of my ignorance of Latin and Greek as an apology for the suggestion; the convenient form of the word is its own defense.

The name "electromagnetic" as applied to that well known system of units seems to be a misnomer. In contra-distinction to the "electrostatic," the name "magnetostatic" seems to be more appropriate; I have used it in my own records and reports even without the formality of an explicit statement to that effect, and have had no protest. The following are formal definitions of some of the terms, as I use them in my analysis of systems of units:

An *electromagnetic system* of units, is a system of both the electric and the magnetic units; it includes the "electrostatic" system.

An *electrostatic system* is a complete "electromagnetic" system involving the dual assumption $K_e = 1, \mu_o = 1/V^2$ with or without any factors of convenience.

A *magnetostatic system* (popularly called electromagnetic) is a complete electromagnetic system involving the assumption $K_e = 1/V^2, \mu_o = 1$, with or without any factors of convenience.

A *comprehensive system* is a system in two parts, with electrostatic units for the electric part and with magnetostatic units for the magnetic part, the two parts being connected by the equation $\mathfrak{F} = I/V$, with or without any factors of convenience.

(Note: Dr. Kennelly has used the word "comprehensive" in another sense.)

A *composite system* is a system involving the dual assumption that $K_o = 1/V$, and $\mu_o = 1/V$ with or without factors of convenience.

The "factors of convenience" referred to in the above definitions, are usually factors of the form $(4\pi)^m 10^n$, where $m$ and $n$ have any convenient values.

For tabular classification of these systems see Table II of this review. Referring to Dr. Kennelly's paper, (Table II, units No. 33 and 37), it should be obvious, that all the four systems are magnetostatic, and unified. None of them is comprehensive in either sense. The only difference between them is the sizes of the units, due to differences in sizes of the fundamental units to start with. Leaving aside for a time the whole question of $4\pi$, and limiting the discussion to the question of the factor $10^n$, the difference between the C. G. S. system (magnetostatic) and the three new systems (also magnetostatic) now submitted for consideration, can be reduced to this, namely, that until now it has been our practise to call a "volt" a practical unit and a "gram" an absolute unit, but if we adopt any of the three proposed systems we shall from now on, call a "volt" an absolute unit, and a "gram" a practical unit. This is about all that can be said of the nature of the differences between the old and the new systems. So far as practical use is concerned, we shall use the volt and the gram in the future exactly as we have been doing in the past, irrespective of their being classified as "absolute" or "practical." Concerning this war of the units, one might paraphrase the famous Battle of Blenheim:

It is indeed a glorious war,
But what are they fighting each other for?

Let us now take up the question of $4\pi$ in the equation $F = 4\pi N I/10$. This factor has been challenged on grounds of theoretical invalidity, and of practical inconvenience. The theoretical aspect of the question takes several forms, of which two are most important.

(a) The presence of $4\pi$ in the equation $\mathfrak{F} = 4\pi N I/10$ is due to the mode of derivation of the equation from the polar conception of magnetism, through the intermediate conception of magnetic shells. The polar conception of magnetism is a pure scientific fiction; it is now abandoned by the modern scientific world. The equation has therefore lost its theoretical foundation. It has now no other foundation except the experimental fact that $\mathfrak{F}$ is proportional to $N I$; there is no reason for assuming any constant in particular. The simplest legitimate assumption is $\mathfrak{F} = N I$, which now becomes an equation for defining $\mathfrak{F}$ in terms of $I$.

(b) The equation $\mathfrak{F} = 4\pi N I/10$ is mathematically related to the equation $B = H + 4\pi J$. The latter equation is also based on the polar conception of magnetism, and moreover it involves the twofold assumption that permeability of space is $\mu_o = 1$, and has no dimensions. This assumption is unwarranted and contrary to the probability of the case, which makes the $4\pi$ in both the above equations invalid.

The contention, that "magnet poles are purely fictitious," is itself a fiction which is best refuted by the authors of that contention. For example, according to Professor Karapetoff (*Ibid.*, p. 263)

> "The concept of pole strength is of no use in electrical engineering, and in the author's opinion, its usefulness in physics is more than doubtful. The whole theory of electromagnetic phenomena can and ought to be built up on the two laws of circuitation. . . ."

A reference to pages 2 and 3 of the same book will show that he finds an important use of magnet, pole, *viz.*, to demonstrate the existence of the lines of magnetic force; nor is this merely a case of professorial license, because as far as I know there is no other way of proving the existence of these lines. If magnetic poles be consigned to the realm of fiction, the lines of magnetic force go there also, and lines of magnetic flux also follow, in their turn. One important reason for doubting the existence of poles is, that we sometimes meet with pole-less lines, that is, closed magnetic lines circling round a wire carrying current. But if the existence of such pole-less magnetic lines is an evidence of non-existence of any magnetic poles, the existence of similar endless lines of electrostatic force should also prove the fictitious character of electric charges. Another reason for assuming that the magnetic poles are fictitious is, that every kind of magnetic field can be construed as the result of certain hypothetical, well designed electric current circuits, that magnet poles are therefore not necessary for production of magnetic fields and equipotential surfaces, and that they should be therefore looked upon as mere scientific fiction. The argument is far from convincing. First, even if every function of a magnetic pole were fulfilled by a system of electric currents, that could not prove the poles to be non-existent; and secondly every theoretical function of a magnet pole cannot be fulfilled by electric current. It can be shown that every magnetic or electromagnetic system can be represented in theory by a series of harmonic magnets, the first member of the series being a single magnet pole, which gives rise to a potential function of the form of simple spherical harmonic of zero order (*Magnetic Shielding*, A. I. E. E. Trans., Oct. 1929). Theoretically, no conceivable single electric circuit can take the place of this pole or produce the corresponding spherical harmonic. Practically, I know of no electric device to demonstrate the existence of magnetic lines of force circulating round a wire carrying a current. See Fig. 1.

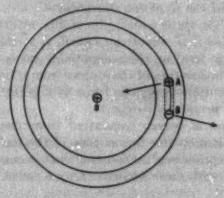


Fig. 1

Let $o$ be a wire perpendicular to the plane of the paper, carrying a current from the front to the back side, and producing the circular lines of force whose existence is challenged. $A\ B$ is a projection of a small electric circuit parallel to the wire $o$, and parallel also to the magnetic field produced by $o$. According to Ampère's law relating to action of a current on a current, the part $A$ approaches $o$ and the part $B$ recedes from it. These forces are radial. There is no tangential force; there is therefore neither a magnetic field nor a magnetic flux. This is the conclusion we reach when we ignore magnetic poles and try to interpret magnetic phenomena in terms of electric currents. Since it is not possible to ignore magnetic poles without ignoring electromagnetic fields, any argument against the use of $4\pi$ (in the basic formula $F = 4\pi N I$) based on the alleged fictitious character of magnet poles, falls to the ground.

The argument based on the theory of dimensions of permeability is equally fallacious. First, the assumption that permeability of space is $\mu_o = 1$, has nothing to do with dimensions of $\mu$. The dimensions of density are $M/L^3$, but that does not prevent us from assuming $D = 1$ for water in physical measurements or for hydrogen in chemical measurements; second, the equation $B = H + 4\pi J$, may or may not be valid; it depends on the purpose of the equation. Dr. Karapetoff's argument, "that we cannot have sheep on one side and apples on the other side of an equation" is sometimes valid and sometimes not. Suppose that I kill by accident one of Professor Karapetoff's sheep, and send him by way of compensation one barrel of apples and in addition a check for \$12-57/100; in my memoranda I write, one sheep

= one barrel apples + 4 $\pi$ dollars. What is wrong with the equation? Thirdly, the contention that $\mu$ must have some dimensions other than zero, is far from proved. If $B$ and $H$ be defined in accordance with the static-conception, their dimensions must necessarily be identical, leading to zero dimensions for $\mu$ as a necessary logical consequence. If on the contrary $B$ and $H$ be regarded as analogous to $I$ and $E$, and defined in accordance with the dynamic conception, then $\mu$ becomes analogous to $R$ and must have some dimensions other than zero. The question of dimensions of $\mu$ is not yet settled and is not likely to be settled in the near future, because the question involves three physical characteristics of space, *viz.*, $K$, $\mu$, and $P$ with only one physical equation connecting them. (See Table I, Equation 5.)

This brings us to the question of physical characteristics of space-medium involved in electric, magnetic, electromagnetic, and magnetoelectric phenomena. These phenomena can be expressed by the five fundamental equations.

TABLE I

FUNDAMENTAL EQUATIONS OF ELECTRIC AND MAGNETIC PHENOMENA

| | | |
|---|---|---|
| (1) | $e^2/K L^2 = f M L/K T^2$ | Electrostatic relation (Coulomb's Law:electric) |
| (2) | $m^2/\mu L^2 = f = M L/\mu T^2$ | Magnetostatic relation (Coulomb's Law:magnetic) |
| (3) | $F = H L = I \,.\, a/P$ $= e/T \,.\, a/P$ | Electromagnetic relation (Ampère's Law) |
| (4) | $E = \phi/T \,.\, b/P$ | Magnetoelectric relation (Faraday's Law) |
| (5) | $P^2/K \mu = V^2 = L^2/T^2$ | Electromagnetic propulsion (Maxwell's Law) |

Notes: (1) $a$ and $b$ in Equations 3 and 4 are factors of convenience; according to the prevailing practise at present we have $a = 4\pi$, and $b = 1$. In some of the recently proposed systems, we shall have $a = 1$, and $b = 1$; these assumptions are merely matters of convenience.

(2) The symbol $P$ in Equations 3, 4, and 5, is the same as $\lambda$ of Ascoli (*Elec. World*, Vol. 67, p. 877) or as $c$ of Heaviside (*Bul. B. of S.*, Vol. XIII, p. 613). No name for this characteristic has yet been suggested. I suggest the name "propulsivity." The symbol $P$ was introduced by J. J. Thomson.

These laws involve three physical characteristics of the medium which in three ways contributes towards the electromagnetic phenomena, *viz.*:

$K$, or dielectric character of the medium; it determines the magnitude of the electrostatic force between two electric charges at rest.

$\mu$, or permeability of the medium; it determines the magnitude of the magnetostatic force between two magnet poles at rest.

$P$, or propulsivity of the medium; it determines in the first place the magnitude of the kineto-static force produced by a moving electric charge on a magnet pole at rest, or by a moving magnet pole on an electric-charge at rest. As a further consequence it contributes to the determination of the velocity of propulsion of electromagnetic impulses in space. When $P$ is assumed to be equal to unity (with or without other factors of convenience) the equation of propulsion takes the form $V^2 = 1/K\mu$, and it then appears as if $K$ and $\mu$ are the only factors involved in the process. This is also the reason why the probability that "the dimension of $\mu$ is not zero" appears to be so high. (Dellinger, *Bul. B. of. S.*, Vol. XIII, p. 610-611). The root of the whole difficulty lies in the fact generally unrecognized that $\mu$ and $K$ are both similar and dissimilar. Their dimensions if they have any, must be therefore complementary. This is the only way in which they could be both similar and dissimilar. But in that case, they would be incapable of yielding a product such as $V = L/T$. In the Heaviside system, it is assumed that $\mu_o = 1$, $K_o = 1$, and $P = V = L/T$. This seems to be the most reasonable assumption. Anyway, the dogma that $\mu$ has dimensions other than zero, has nothing to support it except another dogma that $P$ is not a physical characteristic, and that the velocity $V$ is dependent on $\mu$ and $K$ only. (Dellinger, *Bul. B. of S.*, Vol. XIII, p. 620.)

Since the three quantities $K$, $\mu$, and $P$ are related by only one known equation, there is ample room for speculation and arbitrary assumption, which leads to various systems of units, differing fundamentally, from each other, without going into the question of 4 $\pi$ or of $10^n$. See Table II.

TABLE II

SYSTEMS OF ELECTROMAGNETIC UNIT

| System | Defining assumption |
|---|---|
| Electrostatic | $K = 1$; $P = 1$; $\mu = 1/V^2$ |
| Magnetostatic (popularly called electromagnetic) | $\mu = 1$; $P = 1$; $K = 1/V^2$ |
| Comprehensive (Heaviside) | $\mu = 1$; $K = 1$; $P = V$ |
| Composite-general | $\mu = 1/V$; $K = 1/V$; $P = 1$ |
| Composite-particular type (*e. g.*, Karapetoff) | $\mu = R/V$; $K = 1/RV$; $P = 1$ |

We are now in a position to classify the various systems under discussion in accordance with the above definitions.

TABLE III

CLASSIFICATION OF THE SEVERAL SYSTEMS (OMITTING 4 $\pi$, $10^n$, $R$, etc.

| Name of system | Class | Defining conditions $\mu$ | $K$ | $P$ |
|---|---|---|---|---|
| (1) C. G. S. (Electromagnetic) | Magnetostatic | 1 | $1/V^2$ | 1 |
| (2) Q. E. S. Maxwell (Kennelly, Table III) | Magnetostatic | 1 | $1/V^2$ | 1 |
| (3) Giorgi (Kennelly, Table III) | Magnetostatic | 1 | $1/V^2$ | 1 |
| (4) Giorgi (*B. of S.*, Vol. XIII, p.619) | Composite | $1/V$ | $1/V$ | 2 |
| (5) International (Dellinger & Bennet) (Kennelly, Table III) | Magnetostatic | 1 | $1/V^2$ | 1 |
| (6) International (Dellinger) *B of S.*, Vol. XIII, 603) | Composite | $1/V$ | $1/V$ | 1 |
| (7) Bennett & Crothers ("Electrodynamics," p. 639) | Magnetostatic | 1 | $1/V^2$ | 1 |
| (8) Karapetoff ("The Magnetic Circuit," p. 263) | Composite | $1/V$ | $1/V$ | 1 |

It should be obvious from the above, that all of the systems now under discussion (*viz.*, 1, 2, 3, and 5) involve the assumption that $\mu = 1$ irrespective of dimensions. Therefore the case for the removal of 4 $\pi$, based on the consideration of possible dimensions of $\mu$, falls to the ground, in so far as Dr. Kennelly's paper is concerned.

Another theoretical argument for elimination or rather for dislocation of the 4 $\pi$ from the equation $\mathfrak{F} = 4\pi N I/L$, is that it is irrational "by reason of the occurrence of 4 $\pi$ as a factor in the specification of quantities which have no obvious relation to circles or spheres." This rational principle when applied to the equation in question, leads to the conclusion that the 4 $\pi$ should be just where it is. For we have, first, the experimental fact that the force at a point at distance $r$ from a straight wire is $H = \int I\,d\,l \sin\theta/r^2 = 2\,I/r$. Second, we have the inferential fact that the line integral of $H \,.\, d\,l$ round the wire is $4\pi\,I$, the factor $r$ being eliminated in the process of this second integration. The factor $\pi$ enters into the equation for the obvious reason that the magnetomotive force is a line integral round a circular path. The elimination of the distance $r$ is due to the fact that it ($r$) acts in two opposite ways and cancels itself; it tends to diminish the intensity of the force, but it also tends to increase the length of the path in the same proportion. On account of the simplifications of the formula thus obtained, and also on account of the generalization it stands for, there has grown up a belief that the equation $\mathfrak{F} = c \,.\, I$ is a fundamental experimental fact, and that

the equation $H = d\mathfrak{F}/dl = c \,.\, I/L$ is merely a mathematical inference as a secondary consequence. The fact is just the reverse; the second equation is the one experimentally determined, from which the first is obtained by integration (Bennett and Crothers: "Electrodynamics," Sect. 245).

The c. g. s. magnetostatic system of units is based on the legitimate assumption, that $dH = c'dl \sin \,.\, \theta \,.\, I$ is the fundamental equation and that its simplest form as obtained by assuming $c' = 1$, should be made the basis of the definition of $I$ in terms of $H$ or vice versa. From this equation we get by integration firstly, $H = \dfrac{2I}{r}$ for single straight wire, and secondly $\mathfrak{F} = 4\pi I$ for the complete path round the wire. The $4\pi$ in this equation is not irrational; it comes in for the simple and obvious reason, that it concerns a law of circuitation; this is exactly in accordance with the principle implied in the dictum of Oliver Lodge which disapproves of the "$4\pi$ as a factor in the specification of quantities which have no obvious relation with circles or spheres." (Heaviside, "Electrical Papers," Vol. II, art. 53, p. 575.)

TABLE IV
CHART SHOWING EVOLUTION OF MAGNETOSTATIC SYSTEM OF UNITS, WITH C. G. S. UNITS FOR $L$, $M$ AND $T$

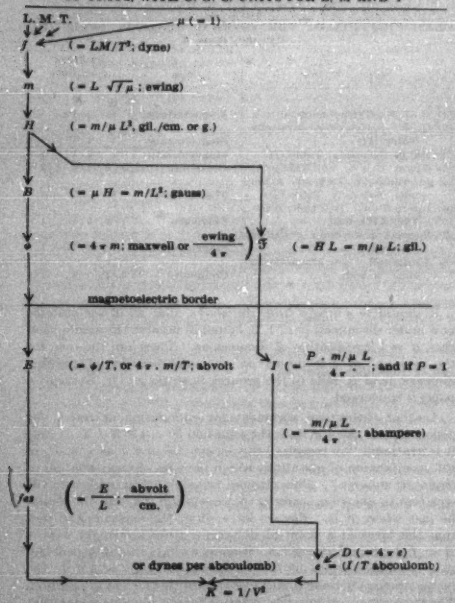


Table IV is a chart showing the evolution of the derived units of the magnetostatic system in their logical sequence. It shows that between the points $m$ and $e$, there are only two equations involving circuitation, and therefore offering legitimate room for $4\pi$. Of these two, only one involves actual mathematical computation, and therefore brings in the $4\pi$ in manifest form. The other equation $E = \phi/T$ is derived directly by experiment, not indirectly by circuitous computation from an experiment. Therefore there is only one place for the rational appearance of $4\pi$ in the whole system between $m$ and $e$. Of course there must be a $4\pi$ in the equation for $E$ also; it is merely suppressed and can be made manifest by substituting $\phi = 4\pi m$. The true form of the equation is $E = \phi/T = 4\pi m/T$ where $m/T$ is the magnetic current. The proposal to omit the $4\pi$ from the equation for $\mathfrak{F}$ is merely an irrational effort to ignore the indisputable fact, that the laws of circuitation involve a real circuitation. It may be suppressed by expressing $I$ in terms of the polarization $D$, so that $\mathfrak{F} = D/T$, is analogous to $E = \phi/T$. This mode of eliminating $4\pi$, is rational but it is not likely to be popular.

From the purely practical point of view, it must be conceded that the presence of the factor $4\pi$ in the equation $\mathfrak{F} = 4\pi N I/10$ is a great inconvenience for the electrical engineer, and a very unnecessary one, because he is mostly concerned with ampere turns. He has absolutely no use for the hypothetical force of so many dynes per unit pole located hypothetically in an imaginary cavity within his magnetic material. This is, however, just the thing the physicist has to deal with. He is not satisfied with average value of $H$ for the whole circuit,—he wants to know the local value of this force at any point. He is like a pupil in a swimming class who wants to know the local depth at the spot he is interested in; he refuses to trust his life to data on the average depth of the whole lake. The best solution of this conflict between the engineer and the physicist would be the use of a supplementary practical unit "the ampere turn," for the use of the practical engineers with or without a new name as they choose. The unit "gilbert per centimeter" briefly "g" should be left unchanged for the use of the physicist. The equation $B = H + 4\pi J$, (or $B = H + \beta$ as I prefer to express it) has done a tremendous service in the past; it has facilitated the work of Ewing, Kennelly, Steinmetz, and many others, and the possibility of its further usefulness in future cannot be discounted dogmatically. If the physicist appreciates the equation so highly and is willing to pay for the service by tolerating the $4\pi$ in all his computation of $H$ let him do so.

In concluding, may I quote the words of Dr. Kennelly, "My personal opinion would be, that we had better leave well enough alone at the present time, and not upheave all our standards, our ohms, volts, and amperes for the sake of $4\pi$" (International Congress, St. Louis 1904, Trans., Vol. I, p. 179).

It is true that this opinion was expressed 26 years ago, but it is equally true, that science has made no new contribution during this interval to change the status of the $4\pi$. His reasons for the change are not clear from his presentation of the case. I must therefore hold to my conclusion, that in the equation $\mathfrak{F} = 4\pi N I$, the factor $4\pi$ should be allowed to stay just as it is, but that in response to the need of the electrical engineers, the unit "ampere turn" should be formally recognized as a supplementary practical unit.

**G. W. O. Howe:** (communicated after adjournment) After a careful reading of this paper, I have found nothing to dissent from, with the exception of one small matter concerning magnetic potential. The various alternative systems of units with their respective advantages and disadvantages are very clearly set forth. The British Association's Committee appointed at Oxford has not been able to make much headway, because we find ourselves divided into two camps—one containing those that regard $H$ and $B$ as of the same nature, and the other those who, like myself, regard $H$ as the m. m. f. per unit length producing $B$. If one writes $B = H + 4\pi I$, then one must belong to the first camp ($I$ = intensity of magnetization). This, however, is a waste of a good symbol to no purpose and it would be better to write $B = B_o + 4\pi I$ and leave $H$ to designate the magnetizing force which, in the opinion of many, is required to produce a flux density $B_o$ in air and $B$ in any other medium such as iron. Those who do not believe in the existence of such a force need not then use $H$ at all. This is really the crux of the whole question. Those responsible for the relevant section of

the Glossary of Terms and Definitions issued by the B. E. S. A. do not regard $H$ as a magnetizing force equal to a m. m. f. per unit length, but maintain that such a force is an unnecessary figment of the imagination, and that all we are justified in assuming is the magnetic flux density $H$ in air, increased to $B$ in iron, which exists, not as the result of any force acting at a point, but as the result of a current somewhere. I should not object to this point of view if those who favor it would agree that, as $H$ and $B$ are of the same nature and only differ in magnitude, it is unnecessary and confusing to use two different symbols for them when a simple suffix would suffice to distinguish them. It is confusing because most electrical engineers use $H$ for a different conception; *viz.*, m. m. f. per cm.; whether this has any real existence as a magnetizing force acting at a point or is merely a convenient aid to magnetic calculation is immaterial to the point at issue.

I note that on the third page of the paper, column 2, it is said that "In America the custom has been to use the *gilbert* for the working unit of magnetic potential." I am sorry to see magnetic potential introduced as I have always found it a very troublesome conception. It is not a fundamental concept but a mathematical derivative. I regard the gilbert as the working unit of m. m. f. To illustrate my point, consider a uniformly wound toroid carrying a steady current. There is a m. m. f. of $(4\pi/10)\ I\ T$ acting around the magnetic circuit, producing at every point in it a

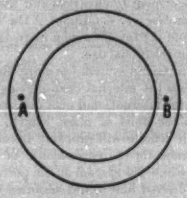


Fig. 2

magnetizing force $H$ equal to the m. m. f. per cm.,—whether as a reality or as a mathematical abstraction is immaterial—but can any one say that there is any difference of magnetic state between any two points in the ring? Can anyone say of the two points $A$ and $B$ in the accompanying sketch that one is at a higher or lower magnetic potential than the other? I think not. Whatever reasoning leads to the conclusion that $A$ is at a higher potential than $B$ also leads to the conclusion that $B$ is at a higher potential than $A$. I am forced to the conclusion that all points of the ring are at the same potential, however many gilberts are acting around it. I think it would be more nearly correct to say that the potential theory which was based on electrostatics and magnetostatics is inapplicable to the magnetic circuit.

**B. Hague:** (communicated after adjournment) I desire to express my appreciation of Professor Kennelly's very interesting paper, which focuses our attention upon the far from satisfactory condition of our magnetic units. I am very much interested in Dr. Kennelly's clear analysis of the various systems of units and his discussion of the question of nomenclature, but I wish to confine my remarks to what appears to me to be of even greater importance, the matter of definitions. I agree that before any international agreement on systems of units and nomenclature is attempted it is of primary importance to secure internationally acceptable definitions of magnetic quantities. It is surprising to discover the extent to which physicists and engineers disagree in regard to such fundamental things as the definition of $H$, $B$, and particularly $\mu$; this disagreement is usually founded in misunderstanding. I would suggest that the time is now ripe for a thorough discussion of these matters by an international congress of engineers and physicists, and I think it would be possible to establish the basis for a set of definitions that would be rational, founded upon experimental fact and dependent upon hypotheses to the minimum extent. Much interest in this subject has already been shown in England, France, and Germany, where recent discussion of the main points of difference would be found, I believe, to have cleared the way already for the profitable international exchange of opinions and perhaps for some useful recommendations.

In framing a set of magnetic definitions I think it is essential to avoid all reference to "unit poles" and "cavities," left over from the old magnetostatics, and to realize that we are really concerned with electromagnetism,—a curl field phenomenon. Everything entering into the definitions should be of a measurable character; they should not be dependent upon conceptions, such as isolated unit poles situated in variously shaped cavities, which have no physical reality. Thus magnetic flux density ($B$) should be based upon a search-coil experiment and Faraday's laws; unit current should be defined from Ampère's laws for the mechanical force experienced by two circuits when carrying the current in series. Magnetic flux should be regarded to exist in a magnetic circuit when current-turns are applied to the circuit; induction or flux density at any point of the path of a magnetic circuit may be regarded, in the way usual to engineers, as due to the application at the point of a certain number of current-turns per unit length of the path. It would be a necessary consequence of a system of definitions of this kind to require the specification of the permeability of vacuous space $\mu_o$, expressing the quantity with dimensions by which a certain number of current-turns per unit length must be multiplied to give the value of the induction $B_o$ (often wrongly called $H$) in vacuo and the additional statement of specific permeability—a numeric—denoting the number of times $B_o$ is augmented to $B$ when vacuous space is replaced by a given material.

If we can decide how we shall define our magnetic quantities, and I desire to make a strong plea for some such experimental basis as I have indicated, the decision should go far to settle the best system of units and the problem of nomenclature. In the interest of uniformity and clarity of thought I would respectfully suggest that the I. E. C. invite discussion and agreement upon the major question of definition before taking up the choice of units and their names.

**G. S. Gibbs:** (communicated after adjournment) In my opinion the names maxwell, gauss, oersted, etc., are superfluous when applied to these units. No names for them are needed. As a rule an author need not even indicate whether he is using the C. G. S. or the practical unit. Misunderstanding will seldom, if ever, arise if no such indication is made. However, if an author considered it necessary it would complicate matters less to designate the unit as C. G. S. or practical than to attempt the use of any system of names.

**Cecil L. Fortescue:** (communicated after adjournment) This characteristically fair and unbiased statement of a complicated matter brings out the two essentials that have to be dealt with before any question of nomenclature can be settled, *viz.*:

a. To decide upon the definitions of the quantities themselves.

b. To determine whether there are, in fact, any grounds for departing from the C. G. S. system and its practical decimal multiples and submultiples.

The first of these two essentials involves the dimensions of permeability. This seems to be purely a matter of convention. Many of us, by sheer force of habit and association with text books of thirty years ago, pay lip service to the idea of entirely unknown dimensions for both permittivity and permeability. But a careful examination of our actual mental process never seems to be quite in keeping with this idea. None of our everyday practical measurements makes either quantity other than a numeric and in the light of present day views of the constitution

of matter there is equally no justification for the adoption of a convention leaving the dimensions of $\mu$ and $\kappa$ uncertain. That being so, $H$ and $B$ are only alternative names for the same thing, *viz.*, the state of space giving rise to a mechanical force on the pole of a magnet. This attitude will certainly be objected to on the grounds that magnetizing force and flux density are manifestly different things. The answer to this objection, however, is that there is a very general confusion between magnetizing force and magnetic field strength, arising from the fact that often they are the same and generally they are denoted by the same letter, $H$. The confusion vanishes if magnetizing force is defined as that component of the magnetic field attributable to current-carrying coils or magnets external to the medium under discussion. Another objection to this attitude is that $\sqrt{\mu\kappa}$ is commonly regarded as having the dimensions of the reciprocal of a velocity. But according to the electromagnetic theory it is $\sqrt{\mu\kappa}/c$, where $c$ is the ratio of the units, that has the dimensions of the reciprocal of a velocity, and it is at least as logical and far more reasonable to attribute the dimensions of velocity to $c$. For, though at first sight $c$ is merely the ratio of two magnitudes it is in reality more than that, *viz.*, a relation between two different observable properties of the ether of space which in different ways may be used to measure a quantity of electricity. It is one of the peculiarities of the medium that the two states should lead to simply self-consistent measures of quantity and there is no difficulty in adopting a convention requiring that this relationship should have dimensions.

For these reasons, and mainly because they seem on examination to be the nearest approach to the actual views held by most physicists and engineers, the writer has for many years advocated the convention of $B$ and $H$, both denoting field strength and $\mu$ being a numeric.

With regard to the second essential upon which a decision is required, the only reason for departing from the c. g. s. system seems to be that the practical and theoretical units should be made to coincide. But is not this advantage very much overrated? The practical units of today are not those of tomorrow, *e. g.*, volt and kilovolt. Moreover the range of magnitude over which electrical measurements are made is so wide that decimal multiples and sub-multiples for practical working are always inevitable. The advantage to be gained is therefore very slight and in view of the general adoption of the c. g. s. system for all theoretical work it seems almost impossible that the great inconvenience (not to say cost) of the change could ever be justified. Anyone who has had experience of the slow progress of the introduction of a decimal system of units into Great Britain will realize the colossal effort and powerful arguments that would be necessary to bring about a departure from the c. g. s. system. And so far as the writer can see, these arguments do not exist.

"The Future is greater than the Past," and this is not to say that no change will ever be made. As knowledge advances some stage may well be reached where a stock-taking and reorganization of the units is unavoidable. It is merely the writer's contention that this stage has not yet been reached. But in expressing this view he does not wish to suggest any failure to appreciate the great value of Dr. Kennelly's description of the various new systems that have been proposed up to date. A frequent examination of all these proposals is one of the essential necessities for the progress of science.

**D. P. Savant:** It is my opinion that the c. g. s. system should be left as it is at present. If a "practical" system is desired, then it seems to me that the m.-k.-s.-ohm would be preferable.

**H. H. Race:** There is one change in nomenclature which I believe would result in a simplification of present practise. We now use the terms:

resistance and resistivity
conductance and conductivity
reluctance and reluctivity
permeance and permeability
elastance and elastivity
capacitance and permittivity

In each case except the last the name of the quantity per unit volume has the same root as the quantity from which it is derived. The reason for the difference in the last case is that historically two names, capacitance and permittance, have both been used for the same quantity.

For simplicity we should use *either* "capacitance," "capacitor," and "capacitivity" *or* "permittance," "permittor," and "permittivity" and we *should not* use words from both sets.

It seems to me that the first set should be retained and the second set discarded for the following reasons:

1. The words capacitance and capacitor are being used generally in the literature and therefore the word capacitivity should find favor and ready adoption.

2. The word permittance is not used and therefore the word permittivity should be dropped in favor of the word capacitivity.

3. Both roots should not be used because of the confusion caused to students, teachers, and readers of technical literature who are not extremely well acquainted with the present nomenclature. This is especially true of foreigners who look for a different meaning in the two words and may confuse dielectric with magnetic phenomena because of the similarity between the words permeability and permittivity.

**H. L. Curtis:** This paper gives a very excellent résumé of the historical development of electrical and magnetic units. It points out the unsatisfactory conditions of the magnetic units at the present time and invites discussion as to the best system of units to adopt for international use.

In my opinion the Giorgi system has more disadvantages than advantages. It uses the international ohm as one of the basic units. However, the international ohm does not have the same definiteness as do the units of mass, length, and time. Any attempt to make it definite will probably involve the establishment of a denite value for the permeability of space. It therefore seems better to base the system on the permeability of space rather than on a derived unit which assumes the constancy of this quantity.

I agree with Professor Kennelly that the first step in establishing the units is to agree on the definitions of the magnetic quantities. The present stumbling block seems to be in determining whether magnetizing force and magnetic induction are the same physical entity and hence should be defined in terms of the same unit. That they are different theoretical entities seems to me to be shown by the fact that in a crystalline material the two vector fields which represent these quantities may not have the same direction. Hence it seems to me essential to distinguish between these two quantities in establishing a system of units.

It does not seem unnatural to me that the magnetic units which are derived from the practical electrical units are not of convenient magnitude for general use. It does not seem possible to establish any extensive system of units which are based on fundamental physical laws in which all of these units will be equally convenient for practical use. This condition exists in the strictly mechanical units where the fundamental units centimeter, gram, and second are of convenient size but the derived unit of work, the erg, is too small to be of practical use so that a multiple, the joule, is commonly employed.

I note several inconsistencies in the abbreviations for square centimeter and cubic centimeter in Table II.

**Leigh Page:** (communicated after adjournment) The subject of electromagnetic units presents a situation which has become more and more complicated the further science has developed. At the present time three systems of c. g. s. units are in common use: the electrostatic system (e. s. u.), the electromagnetic system (e. m. u.) and the Heaviside-Lorentz system (h. l. u.). The first two are used generally by the experi-

menter, e. s. u. being employed if his problem is one involving electrostatic phenomena, or e. m. u. if he is working with magnetic substances, currents, or induced electromotive forces. On the other hand the h. l. u. system is employed in nearly all recent papers and text-books on electromagnetic theory both in the United States and abroad. Finally the electrical engineer uses a system of practical units (q. e. s.) obtained from the electromagnetic system by employing the *earth-quadrant* $\{(10)^8$ em.$\}$ as unit of length and the *eleventh-gram* $\{(10)^{-11}$ gm.$\}$ as unit of mass, the *second* being retained as the unit of time. Nearly all electrical instruments are calibrated in q. e. s.

The seriousness of the situation lies in the fact that the fundamental equations of the science are in many cases different according as one or another system of c. g. s. units is employed. Thus the student has to learn that the force in dynes between two charges $q$ and $q'$ at a distance $r$ apart is

$$F = \frac{q\,q'}{r^2} \text{ in e. s. u.}$$

$$F = c^2 \frac{q\,q'}{r^2} \text{ in e. m. u.}$$

$$F = \frac{q\,q'}{4\,\pi\,r^2} \text{ in h. l. u.}$$

Fortunately the practical system (q. e. s.) as given by Maxwell[3] does not introduce a new set of equations, the equations used being identical in all cases with those expressed in e. m. u. The practical units differ from the electromagnetic units solely in the choice of a larger unit of distance and a smaller unit of mass. The practical units which have received international approval are the *joule*, *watt*, *volt*, *ohm*, *ampere*, *coulomb*, *farad*, and *henry*. I shall refer to these eight as the *recognized* practical units.

Recently Giorgi, and Dellinger and Bennett[4] have proposed new systems of units which preserve the eight recognized practical units mentioned above but which differ from the q. e. s. system in that they change the form of many of the fundamental equations. If either of these systems should be adopted by the electrical engineer the student would have to memorize *four* sets of fundamental equations instead of *three* as at present. Again the Giorgi and Dellinger-Bennett systems make the specific inductive capacity and the permeability of empty space dimensional constants differing greatly in magnitude from unity. For this there is absolutely no warrant in our present theory, which leads unambiguously to such expressions as $B = H + 4\,\pi\,I$ (e. m. u.), showing at once that $B$, $H$, and $I$ are all to be expressed in the same units and that $\mu$ is a pure number having the value unity for empty space. To attribute magnitude and physical dimensions to the permeability of empty space replaces "economy of thought" by profligacy of thought. It is about as reasonable as to write the fundamental equation of dynamics in the form

$$F = k\,m\,a$$

where $k$ is some mysterious dimensional constant of magnitude $(10)^9/4\,\pi$ (or any other value you choose) which makes force a quite different thing from the product of mass by acceleration. Furthermore it is important in this connection not to lose sight of the fact that $B$ inside a permeable medium is the mean $H$, and that the quantity generally known as the magnetic field intensity or magnetizing force is really not the $H$ actually existing in the medium at all, but the purely fictitious field which would exist if each amperian circuit were replaced by an equivalent magnetic shell.

The adoption of either the Giorgi or Dellinger-Bennett system of units would make a bad situation much worse for anyone whose interest covered the whole field of electromagnetism. Even for those whose attention is limited to the field of circuit-theory alone, such small advantages as the inclusion of the commonly used volt/cm. as a unit in the Dellinger-Bennett system are acquired at the expense of a meaningless dimensional constant for the permeability of empty space. It is a simple matter to show that Maxwell's (q. e. s.) system is the only one which can preserve the eight recognized practical units and at the same time preserve the form of *all* the equations of electromagnetism as deduced in electromagnetic units.

The object of this contribution is to propose two systems of units, one c. g. s. and the other practical, which are free from the objections mentioned above and which should satisfy the requirements of theorist, experimenter, and engineer. The proposed systems are based on the following criteria:

1. A *single* set of equations shall suffice for both proposed systems of units. If an equation is deduced in c. g. s. units the same equation shall hold in practical units and *vice versa*. Thus the student need learn only a single set of equations instead of three sets as at present, or four sets as would be required if the Dellinger-Bennett system of units should be adopted in place of Maxwell's q. e. s. system.

2. The eight recognized practical units shall be retained in the proposed practical system. This requirement is essential on account of the general use of these units and the fact that nearly all electrical instruments are calibrated in terms of them.

3. The set of equations chosen shall exhibit the symmetry existing between electrical quantities on the one hand and magnetic quantities on the other.

The only system of units in general use at the present time which satisfies condition (3) is the h. l. u. system. Therefore we shall write our fundamental equations in the form:

$$F = \frac{q\,q'}{4\,\pi\,r^2} \tag{1}$$

$$F = \frac{m\,m'}{4\,\pi\,r^2} \tag{2}$$

$$\nabla \times \mathbf{H} = \frac{1}{c}\,(\dot{\mathbf{D}} + \mathbf{j}) \tag{3}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\,\dot{\mathbf{B}} \tag{4}$$

$$\mathbf{D} = \mathbf{E} + \mathbf{P} = k\,\mathbf{E} \tag{5}$$

$$\mathbf{B} = \mathbf{H} + \mathbf{I} = \mu\,\mathbf{H} \tag{6}$$

$$\mathbf{F} = q\left[\mathbf{E} + \frac{1}{c}\,\mathbf{v} \times \mathbf{B}\right] \tag{7}$$

$$V = \int \mathbf{E} \cdot d\,\mathbf{l} \tag{8}$$

$$i = j\,A = \frac{q}{t} \tag{9}$$

$$R = \frac{V}{i} \tag{10}$$

$$C = \frac{q}{V} \tag{11}$$

$$L = -\frac{V}{\dfrac{d\,i}{d\,t}}, \tag{12}$$

choosing as the system of c. g. s. units to be employed the h. l. u. units advocated by Heaviside and Lorentz and generally used by writers on electromagnetic theory. The symbols appearing in these equations have their usual significance, $c$ being the velocity of light, $V$ potential or e. m. f., $j$ current density, and $A$ cross-section.

3. "Electricity and Magnetism," Vol. II, p. 268.
4. A. E. Kennelly, *Magnetic Circuit Units*, A. I. E. E. Proc., Jan. 1930.

The problem remaining consists in investigating the possibility of choosing new units of time, length, and mass so as to obtain a practical system employing the *same fundamental equations* in which the units of energy, power, e. m. f., resistance, current, charge, capacitance, and inductance shall be the eight internationally recognized units. Evidently it is necessary in so far as the pairs energy-power and charge-current are concerned that we preserve the *second* as the unit of time. Therefore we may introduce new units of length and mass only. Denoting h. l. u. by letters without subscripts and units in the proposed practical system by the same letters with the subscript $p$, we have

$[t_p] = [t] = 1$ sec., $[l_p] = \alpha\,[l] = \alpha$ cm., $[M_p] = \beta\,[M] = \beta$ gm.

We shall use a similar notation for the numerics associated with each physical quantity, using a letter without subscript in the case of h. l. u. and with the subscript $p$ in the case of the proposed practical units. To determine the two constants $\alpha$ and $\beta$ we need two equations. Let us consider energy and charge. Then

$$U\left[\frac{M\,l^2}{t^2}\right] = U_p\left[\frac{M_p\,l_p^2}{t_p^2}\right] = \alpha^2\beta\,U_p\left[\frac{M\,l^2}{t^2}\right],$$

$$U_p = \frac{1}{\alpha^2\,\beta}\,U.$$

But $$U_p = (10)^{-7}\,U$$

in order that the *joule* shall be the unit of energy in the practical system. Therefore

$$\alpha^2\beta = (10)^7. \tag{1}$$

Similarly for charge

$$q\left[\frac{M^{1/2}l^{3/2}}{t}\right] = q_p\left[\frac{M_p^{1/2}l_p^{3/2}}{t_p}\right] = \alpha^{3/2}\beta^{1/2}q_p\left[\frac{M^{1/2}\,l^{3/2}}{t}\right]$$

$$q_p = \frac{1}{\alpha^{3/2}\;\beta^{1/2}}\,q,$$

and if the *coulomb* is to be the practical unit of charge

$$q_p = \frac{1}{\epsilon}\,(10)^{-10}\,q$$

where $\epsilon$ is the number

$$\epsilon = 0.299796\,\sqrt{4\,\pi} = 1.06275$$

Hence

$$\alpha^3\,\beta = \epsilon^2\,(10)^{20}. \tag{2}$$

Solving (1) and (2) for $\alpha$ and $\beta$

$$\alpha = \epsilon^3\,(10)^{13}, \qquad \beta = \frac{1}{\epsilon^4}\,(10)^{-19}. \tag{3}$$

The numbers $\alpha$ and $\beta$ being known, the six remaining practical units may be determined. Evidently the units of power and current are the *watt* and the *ampere* respectively, since the *second* has been retained as the unit of time. Employing the method used above for the other units, the units of e. m. f., resistance, capacitance, and inductance are found to be the *volt*, *ohm*, *farad*, and *henry* respectively. Therefore requirement (2) is satisfied. In this connection it should be noted that inductance is defined as the e. m. f. per unit time rate of decrease of current and not as the flux of induction per unit current. The two are not equivalent in the system of fundamental equations which have been chosen, e. m. f. being the $(1/c)$th part of the time rate of decrease of flux.

We conclude with a table of the more important equivalents in h. l. u. and the proposed practical units, giving the unit in parentheses in cases where it has received a name. The quantities listed are the numerics in each case. The ratio of the units is the reciprocal of the ratio of the numerics.

| | Proposed practical | | H. L. U. |
|---|---|---|---|
| Time | $t_p$ | (sec) | $= t$ (sec) |
| Length | $l_p$ | | $= \epsilon^{-2}\,(10)^{-13}\,l$ (cm.) |
| Mass | $M_p$ | | $= \epsilon^4\,(10)^{19}\,M$ (gm.) |
| Force | $F_p$ | | $= \epsilon^3\,(10)^6\,F$ (dyne) |
| Energy | $U_p$ | (joule) | $= (10)^{-7}\,U$ (erg) |
| Power | $P_p$ | (watt) | $= (10)^{-7}\,P$ (erg/sec.) |
| Charge | $q_p$ | (coulomb) | $= \epsilon^{-1}\,(10)^{-10}\,q$ |
| Elect. Pot. or e. m. f. | $V_p$ | (volt) | $= \epsilon\;(10)^2\,V$ |
| Elect. Int., Elect. Disp. and polarization | $E_p$ | | $= \epsilon^3\;(10)^{10}\,E$ |
| Capacitance | $C_p$ | (farad) | $= \epsilon^{-3}\,(10)^{-13}\,C$ (cm.) |
| Current | $i_p$ | (ampere) | $= \epsilon^{-1}\,(10)^{-10}\,i$ |
| Resistance | $R_p$ | (ohm) | $= \epsilon^2\;(10)^{13}\,R$ (sec./cm.) |
| Pole strength | $m_p$ | | $= \epsilon^{-1}\,(10)^{-10}\,m$ |
| Mag. pot. or m. m. f. | $\mathfrak{U}_p$ | | $= \epsilon\;(10)^2\,\Omega$ |
| Mag. Int., Mag. Ind. and Int. of of Mag. | $H_p$ | | $= \epsilon^3\;(10)^{16}\,H$ |
| Inductance | $L_p$ | (henry) | $= \epsilon^3\;(10)^{13}\,L$ (sec.$^2$/cm.) |

The velocity of light in the proposed practical units is

$$c_p = \epsilon^{-2}(10)^{-13}\,c = 0.00265438 = \frac{1}{376.735}$$

and the powers of $\epsilon$ appearing in the electrical quantities in the table are

$$\epsilon = 1.06275 = \frac{1}{0.940955}$$

$$\epsilon^2 = 1.12944 = \frac{1}{0.885396}$$

$$\epsilon^3 = 1.20031 = \frac{1}{0.833118}$$

The specific inductive capacity $k$ and the permeability $\mu$, being pure numbers, have the same values in the proposed practical units as in h. l. u. The first is the same as in e. s. u. and the second is the same as in e. m. u.

We shall consider now some of the objections which may be raised to the scheme proposed. The most serious of these is that some of the fundamental equations as well as many of the ratios of the c. g. s. to the proposed practical units demand a knowledge of the velocity of light. This, however, is a characteristic of any *complete* set of equations, whether we use e. m. u. or any other system of units. Furthermore, in view of Michelson's extremely accurate determination of the velocity of light this objection is not likely to lead to changes in the ratios comparable with the errors of even the most precise electrical measurements for a great many years to come.

Next Ampère's law and Faraday's law in the proposed units involve the constant factor $(1/c)$. This factor, however, is no more troublesome in numerical calculation than the factors $4\,\pi$ and $(10)^{-8}$ which the engineer is accustomed to use at the present time. In fact, the proposed equations have the advantage that only *one* factor need be learned, instead of *two* as at present. On the other hand the proposed scheme does not alter the form of the Equations (10), (11), (12) which are the ones perhaps most used by the engineer.

The plan proposed, then, has the following very vital advantages over present usage. (1) The equations are in symmetrical form. This results in halving the number of relations between practical and c. g. s. units. Thus the ratio of $E$ to $E_p$ is the same as that of $H$ to $H_p$, and so on. (2) Only *one* set of equations need be learned, instead of *three* as at present or *four* if the Giorgi or Dellinger-Bennett system were adopted. The quantities $k$ and $\mu$ are pure ratios having the same values in c. g. s. and practical units, and the indefensible introduction of dimensional constants of magnitude far from unity for $k$ and $\mu$ of empty space is avoided. (3) The eight internationally recognized practical units are retained unaltered in the proposed scheme.

**L. W. McKeehan:** Professor Kennelly points out that a decision regarding the likeness or unlikeness of the quantities $H$ and $B$ is necessary before any detailed recommendation regarding a system of magnetic units can be made. I wish to show that there is no physical basis for supposing $H$ and $B$ to be different in kind. If, then, as a matter of convenience it is still desired to retain both symbols, the quantities they represent should, it seems clear, be measured in terms of the same unit. The least disturbance of existing practise will probably result if this unit is called the *gauss*.[5]

Ideas regarding the constitution of matter have changed a good deal since the time of Maxwell, when the subject under discussion first arose in its present form. Even as late as 1900 it was still allowable to regard matter as essentially continuous, and to speak without apology about many spatial properties of matter, such as density, electrical resistivity, and magnetic permeability. It was even allowable to attribute such properties to space itself (then called the luminiferous ether). When we use these terms nowadays we are ignoring the whole of modern physics. The present physical hypothesis regarding matter is that it consists of continuous distributions of positive and negative electricity in relative motion. The elementary electrical charges, electrons and protons, of which matter is still imagined to be built, have, to be sure, lost the definite boundaries it was, until recently, customary to imagine about them, but the electric charge density within the space which matter "occupies" is still supposed to vary enormously from point to point. Different kinds of matter differ, on this hypothesis, only in the arrangement, amount, and relative velocity of these distributed electric charges.

Now if we knew completely the motion of electricity everywhere in space we could, at least formally, calculate a value of $H$ at every point, whether the point was, as we have been accustomed to say, in "empty space" or in "matter." We should notice at once that in "empty space" the values of $H$ would not vary rapidly as we changed the place, or the time, for which the calculation was made. In "matter" on the other hand it would make a great difference in $H$ to change the place considered by as little as $10^{-9}$ centimeter, or to change the time considered by as little as $10^{-18}$ second, to take reasonably large changes, on atomic scales, in both cases.

If we decide, in view of this fine-grained structure of $H$, to consider only its average value over such large spaces and such long times as may be necessary to get nearly constant values in "matter" as well as in "empty space," we will find that this average value is precisely the value of $B$ which a believer in continuous matter would have to postulate to explain the results of ordinary (*i. e.*, large-scale and slow) measurements.

In order to support this statement, which may be very surprising to many engineers, let us conduct an imaginary experiment, as follows. Select a region in which $H$ has the constant value $H_o$, and in which, therefore, there is no matter already present to interfere with further operations. Into this region introduce, one at a time, iron atoms, each consisting of electricity of both signs in relative motion, and each capable of producing a non-uniform magnetic field of consequence in the space it occupies and in the immediate neighborhood. The average value of $H$ in a small volume including our first iron atom is different from what it was before, because an atom of iron has that special kind of motion of its electrical charges which we mean when we say an atom is paramagnetic.[6] The average value will be greater than $H_o$ if we place the iron atom so that the intense part of its local magnetic field agrees in direction with $H_o$, and will be less than $H_o$ if we reverse the orientation of the atom with respect to $H_o$. The average value of $H$ in the whole volume at our disposal is affected in the same sense as in the small volume by the introduction of the first atom, but, of course, to a smaller degree.

Let us now arbitrarily decide to put all the atoms into places iron atoms might occupy in a bar of iron of any convenient size, and to place them all in the right way to raise the average value of $H$ in the space thus filled. Let the average value so attained, when all are in place, be $H'$. The bar of iron thus created is easily seen to be magnetically saturated in the original direction of $H_o$.

Let us repeat the experiment from the beginning, first changing external conditions in such a way that the original field has the value $-H_o$, and taking care to put in every atom in such a way as to make the average $H$ within our new bar of iron more and more negative, finally attaining the value, $-H'$, corresponding to negative saturation.

Let us now repeat both the processes just described, but let us do at one stroke the unbuilding of bar number one, the reversal of $H_o$ and the building of bar number two, and watch what happens in a search coil, surrounding the middle of the space where the bars are to be annihilated and created, and connected to a ballistic galvanometer. This measuring device records, of course, just what it would if the search coil surrounded a vacuum of the dimensions of the bar, in which we reversed a magnetic field of intensity $H'$. (The throw of the ballistic galvanometer is proportional to the surface integral of the normal component of $H'$ over the area bounded by the search coil.) But we have done exactly the same thing in our imaginary processes as can actually be done with a single bar of iron by reversing $H_o$, if $H_o$ is chosen high enough to keep the real iron bar magnetically saturated. In this more feasible experiment the quantity we would expect to measure with search coil and galvanometer would be what we usually call the magnetic induction, *i. e.*, $B$. (The throw of the ballistic galvanometer is proportional to the surface integral of the normal component of $B$ over the area bounded by the search coil.) We have therefore proved that $B = H'$, and $H'$ by hypothesis was the average value of $H$ within the bar, including the effects of the atoms present within its boundaries.

I have pointed out in another place (*Optical Society of America Jl.* and *Rev. of Scientific Instruments 19*, 1929, 213-242) that whether we make measurements by artificial electric circuits or by those natural electric circuits which are found in ferromagnetic metals, we measure the average magnetic condition in a relatively extensive space and for a relatively long time, *i. e.*, we measure $B$ or its changes. If I am right in thinking that sub-microscopic $H$ and average $H$, or $B$, only need to be distinguished because our senses or instruments are not acute enough to perceive their common origin, I am, of course, also right in advocating a single unit for both and in denying dimensions to the factor $\mu$ in the equation $B = \mu H$.

The equation $B = \mu H$, by the way, is an extremely awkward equation in some respects. The factor $\mu$ assumes all values between $+\infty$ and $-\infty$ for one and the same specimen of any ferromagnetic material as we traverse a hysteresis loop. The effort to restrict what we may be allowed to do to $H$ (and $B$), so as to limit this erratic behavior of $\mu$, and make it useful in the description of materials, is interesting but would carry us too far into the subject of magnetic testing. The equation $B = H + 4\pi I$ upon which $B = \mu H$ may be considered to depend, has the advantage, by comparison, that $I$ has a limited range of values and that the maximum value of $I$ seems to depend more simply upon the nature of the magnetic material than does any other magnetic vector. The disadvantage of the equation $B = H + 4\pi I$ is that $H$ appearing in it is a fictitious magnetic field due partly to completely external electric currents and partly to the motion of electricity in the non-adjacent regions of the piece of matter under investigation.

The magnetization, $I$, is of course an average quantity just as much as $B$ is, so I am not defending its use as necessary on

5. The plural of *gauss* may be either *gausses* or *gauss*. I prefer the latter as more euphonious.

6. This is a deliberate circumlocution for the statement: "An atom of iron has a magnetic moment different from zero."

physical grounds. Pole strength and magnetic moment are other average quantities that are only useful if we know when to abandon them. Regardless of how carefully we may define and name such properties and suitable units for expressing their values, we need not be surprised if they quietly drop out of use in due time. Meanwhile I suggest caution in sponsoring too many of these temporary concepts.

Much of the confusion that now exists regarding magnetic units arises from forcing the analogy, pointed out by Du Bois, between electric and magnetic circuits. That the analogy is imperfect is plain from the fact that the maintenance of a steady electric current, in a circuit composed of imperfect conductors of electricity, requires a continuous expenditure of energy, whereas the maintenance of a steady magnetic current, in a circuit composed of imperfect conductors of magnetism, does not.

Another word of caution may be in order on devising names for the reciprocals of useful units. The physicists and chemists have long been using the phrase "per gram" as part of the names of many compound units but I have never heard it proposed to substitute for this phrase the word "marg." Too much consistency in nomenclature may be as bad as too little, if we merely succeed in adding items to the long list of things that everyone must succeed in forgetting as soon as he hears them. Similarly, it does not do to be too particular about having a fundamental unit of a "convenient" size, as convenience is not an absolute property. The student of atomic properties has more reason than the electrical engineer to criticize the c. g. s. system for not furnishing him with convenient units of mass, length, or time. Nevertheless, he continues without complaint to use the c. g. s. system for theoretical work and to accept in his results as many powers of ten as may be necessary ($10^{24}$ appears in a recent paper). The units used in expressing the results of routine work need not, of course, be basic units in any system. Finally, if anybody is much confused by the factor $4\pi$ which crops up here and there in the c. g. s. system and in the various substitutes mentioned in this paper, he may adopt Heaviside-Lorentz units, as many theoretical physicists have already done.

**A. E. Kennelly:** The interesting discussion with which the paper has been favored has clearly revealed how serious are the differences of opinion among us as to the definitions and interrelations of the terms used to describe the magnetic circuit, and how great is the need for standardization in this field, both nationally and internationally. It is evident that before we can hope to accomplish any useful constructive work on magnetic-unit terminology, we must first seek agreement on the definitions of certain fundamental terms, especially as to magnetizing force $H$, magnetomotive force $\mathfrak{F}$, magnetic flux $\phi$, permeance $\mathcal{P}$, and specific permeability $\mu$.

It has been shown in the discussion that the symbol $H$ is used with two meanings, namely:

1. Gradient of m. m. f. as expressible in gilberts per cm., or ampere-turns/cm.
2. The magnetic field produced in free space or nonmagnetic material by the gradient of m. m. f. or gilberts cm.

Here No. 1 is the cause, and No. 2 is the effect. No. 1 can be determined, in simple cases, from a knowledge of the ampere-turns linked with the magnetic circuit and the mean length of the same; whereas No. 2 is associated with a resulting state of stress in the magnetic circuit, detectable by iron filings, compass needles, or a twistable search coil. If we can secure agreement upon limiting the use of $H$ to gradient of m. m. f., under the name of *magnetizing force*, and requiring that all fields shall be designated by $B$ with suitable subscripts, such as $B_o$ for the field in free space, it would seem that agreement may be facilitated. We then have in circuits of nonmagnetic material:

$$B_o = \mu_o H \qquad \text{(maxwells per cm.}^2\text{)}$$

where $\mu_o$ is *space permeability*. In the c. g. s. magnetic system, the numerical value of $\mu_o$ is taken as unity. The question is however, whether $\mu_o$ is a mere unity number, or whether it has physical dimensions. If it is a mere number, then $B_o$ is physically identical with $H$, and both may be expressed in *gilberts per cm.* In that case, the *maxwell*, as a unit of flux $\phi$, becomes identical with a *gilbert-cm.*, and it becomes proper to express magnetic fluxes in *gilbert-cm.* The name *maxwell* for the unit of flux $\phi$ becomes not erroneous but superfluous. We thus have the alternative of taking $\mu_o$ as dimensionless, with flux density $B_o$ expressible in *gilberts per cm.*, and flux $\phi$ expressible in *gilbert-cm.*, or of taking $\mu_o$ as having dimensions, and keeping the *maxwell* as a necessary name for flux, together with the *maxwell per cm.*$^2$ a necessary name for flux density $B$.

There seems to be more likelihood of securing agreement on dimensions of some kind for $\mu_o$, with necessary retention of the *maxwell*, than for a purely numerical value for $\mu_o$ and no need for the *maxwell*.

It seems to be generally admitted, however, that *relative permeability* or *specific permeability*, *i. e.*, the ratio of flux density $B$ in a magnetic material, such as iron, to the flux density $B_o$ in free space under the same magnetizing force, is a mere numeric and therefore does not call for a unit name. Thus, specific permeability is generally accepted as

$$\mu = \frac{\text{flux density in medium}}{\text{flux density in free space}} = \frac{B}{B_o} \qquad \text{(numeric)}$$

The *absolute permeability* of a magnetic material, at a specified value of magnetizing force $H$, would then be the ratio of the flux density produced in the material to the exciting magnetizing force $H$, or

$$\mu\mu_o = \frac{\text{flux density in the medium}}{\text{magnetizing force}}$$

$$= \frac{B}{H}\left(\frac{\text{gausses}}{\text{gilberts per cm.}}\right)$$

The precise dimensions of absolute permeability, as regards length, mass, and time, have not yet been ascertained.

In any case, we must agitate for discussion and analysis in all countries, in order to enable international agreement to be reached on some logical basis.

# Simulating Sunlight

## A New Era of Artificial Lighting

BY M. LUCKIESH[1]

Member, A. I. E. E.

*Synopsis.—The beginning of a new era of artificial lighting in which health is to be considered as well as vision is proclaimed in this paper. Facts regarding the health-giving properties of ultra violet radiation from the sun are outlined and the production of similar radiation by artificial means is discussed. Various methods of obtaining the desired rays are mentioned and considerable information is given on a new tungsten filament mercury vapor lamp which has been developed to provide this radiation conveniently and safely.*

* * * * *

THE artificial world—material civilization—represents both the intent and the result of man's declaration of independence from Nature. Artificial light has played a dominant role, for without it the present degree of independence would be greatly curtailed.

When artificial lighting began with the burning of crude materials, the first great new era within which relatively minor ones were born was inaugurated. The second great era began with the practical production of artificial light by means of electricity—the arcs and the filament lamps. We have now passed the threshold of another era which suggests a potentiality as great as the two major ones which preceded it. The possibility of this new era has been sensed by only a few persons—whose work and position direct their imagination beyond the horizon. And this new era of artificial lighting of extended purpose—using radiant energy for health as well as vision—has arrived unannounced in this broader sense.

This dream of simulating sunlight and dispensing whatever health benefits there are in midsummer sunlight, while providing light for vision, has its beginning in the impressive logic of sunlight as a powerful environmental factor. It has been stimulated by some sound scientific facts which have been unearthed during the past 40 years. It has not been influenced by the recent craze for ultra violet radiation proclaimed as a cure-all by charlatans or others who profit blandly or blindly in the twilight zone of knowledge.

No attempt will be made to marshal all the major scientific facts which emphasize the value of sunlight. Admittedly, these are far outnumbered by vague data and unsupported claims. Sunlight does cure and prevent rickets; therefore, it is important to the health of children. In some places the death-rate is highest in or shortly after the season when sunlight is at its minimum. There is some evidence that fewer colds are experienced by a group of persons systematically exposed to artificial sunlight than by a group not exposed. Sunlight is closely related to one or two vitamins—possibly to all. The effect of a single exposure to powerful ultra violet radiation for only a few minutes can be detected for two and sometimes three months after. The possible benefits of sunlight outdoors are intricately interwoven with those of exercise and fresh air. However, few intelligent persons would insist that sunlight is not beneficial. These are examples of facts having sound or only partial foundations. But beneath all this is the powerful logic of sunlight as an environmental factor upon which all life depends directly or indirectly. It has been bathing this earth since the most primitive life began. Plants have developed under its heat and light. Eyes have evolved to see by its energy of certain wavelengths. Vitamin D at least is manufactured by it. Thousands of photochemical reactions selectively utilize its energy of various wavelengths. Viewing the completed picture of which the foregoing is only fragmentary, is it possible to believe that sunlight—so interwoven into life-processes—is not directly beneficial to human beings? Is it not easy to suspect that its benefits extend far beyond present knowledge and even far beyond the ability of our imagination to encompass at the present time?

The most important detail in the production of artificial sunlight is the short-wave cut-off of the spectrum. Ideally, this should be in the neighborhood of $\lambda$ 2900 because no energy of shorter wavelength* reaches the earth from the sun. The upper atmosphere is responsible for this restriction. Apparently, through the formation of ozone, the radiation of shorter wavelengths is absorbed. Practically, the short-wave cut-off for an artificial sunlight can extend somewhat further into the ultra violet. The limiting factor is the production of conjunctivitis or inflammation of the outer membrane of the eye. The long-wave limit of energy which causes this inflammation depends upon the intensity of radiant energy. For example, we may obtain any degree of erythema or sunburn outdoors in sunlight without conjunctivitis under the usual conditions. However, when large quantities of sunlight are reflected into the eyes from the snow, the eyes may become painfully inflamed.

1. Director, Lighting Research Lab., Incandescent Lamp Dept., General Electric Company, Nela Park, Cleveland, Ohio.

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*For brevity, $\lambda$ 2900 means a wavelength of 2900 Angstrom units.

Indoors, in the best lighting practise, the intensity of illumination is only a small fraction of that outdoors during most of the day. Therefore, from a source which approximately simulates sunlight the ultra violet radiation would be of low intensity compared with that of midsummer sunlight. Our experiments with artificial sunlight at intensities of illumination many times those of present lighting practise have not produced any suggestion of conjunctivitis, notwithstanding the presence of relatively large quantities of energy of λ 2800 and of measurable quantities as short as λ 2600. It appears therefore that the practical cut-off for artificial sunlight to be used indoors with the restrictions now operating in lighting practise need not be longer than λ 2800, and perhaps can be even less.

Obviously, in order to be practicable for general lighting and even safe for "self-treatment," it should not be necessary to wear goggles. Sufficient is known of transmitting media so that the "goggles" can be placed upon any source otherwise suitable. Many glasses

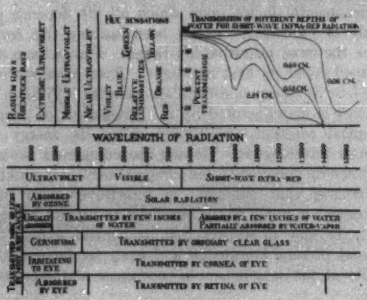


FIG. 1—IMPORTANT DATA PERTAINING TO SPECTRAL RANGES

have been developed for this purpose and more can be made to meet the requirements. It remains only to decide upon the short-wave cut-off. Inasmuch as the spectral cut-off of any glass filter is not abrupt, it is more practical to have it approximately at λ 2800 than at λ 2950, the usual limit of the solar spectrum.

The next point of primary interest is the relative importance of the distribution of energy throughout the spectrum. There is plenty of evidence that a line-spectrum, such as that of the mercury arc with energy of many wavelengths absent entirely, produces results similar to that of outdoor sunlight. Furthermore, photochemical reactions are produced usually over a range of wavelengths and not by a single wavelength. Therefore, it does not appear necessary to reproduce the solar spectrum wavelength for wavelength.

The production of erythema or "sunburn" is usually desired at present as visible proof of the presence of ultra violet radiation. In fact, the energy (near λ 2970) which is most effective in producing erythema appears to be the most effective in preventing and curing rickets. Certainly, in the light of present knowledge the most important ultra violet radiation in respect to life and health seems to be between λ 2800 and λ 3100. Energy measurements by means of physical instruments are valueless for the present purpose until they are interpreted into curative or health value. Erythema measurements are at least a step between physical effect and physiological benefit and from what is known, they appear to be a fair indication of certain curative and preventative results.

Although many tacitly assume that erythema is a necessary forerunner of curative or health value, this has not been proved to be true; in fact, we have positive evidence of beneficial results without any suggestion of erythema or "sunburn." For example, definite improvement in animals having severe rickets has been obtained with tungsten-filament lamps in special bulbs at an intensity of illumination of 20 foot-candles with daily exposures of several hours. In one case, rickets in animals fed upon a restricted diet were prevented for several weeks. Professor R. Adams Dutcher has reported results with an ordinary 50-watt tungsten-filament lamp which indicate definite improvement in rickets in animals. Such investigations indicate that the threshold value of ultra violet radiation is sufficiently low to view with encouragement the possible new era of lighting for health as an accompaniment to lighting for vision. In our indoor world we are exposed to artificial light for several hours daily throughout much of the year.

Of the sources now obtainable for producing an effective substitute for midsummer sunlight, tungsten filament lamps are not without promise, although much research is necessary to establish their value broadly. The mercury arc can be made in a suitable glass so that powerful and safe ultra violet radiation is obtained. The quality of light from the mercury arc is not generally acceptable but tungsten filament lamps can be combined with it to overcome this objection. The carbon arcs and any modifications are possibilities although their disadvantages in general lighting are as serious as they have been heretofore. New sources satisfactory in simplicity, in quality of light, and other important phases are likely to be developed.

The first new practical source for simulating sunlight which has been developed with this possible new era in mind is a tungsten-mercury arc known as the Sunlight (Type S-1) lamp. A tungsten filament operates in parallel with a mercury arc between tungsten electrodes. The hot filament near a pool of mercury vaporizes the latter and the arc is completed almost instantly after the switch is on. The bulb consists of a glass with a suitable spectral cut-off. The lamp can be operated throughout a wide range of angles and it has no movable parts. For general use it has the primary requisite—simplicity.

The Type S-1 lamp is a low-voltage source and the volt-ampere characteristic of the transformer is im-

portant. At present the wattage is approximately 400 but there appear to be no insurmountable obstacles in the way of altering the wattage considerably. The voltages are approximately as follows: no-load, 35 volts; when only filament is operating, 33 volts and 9 amperes; after arc starts, 11 volts and 30 amperes. All this operation normally takes place almost instantly after the switch is thrown. The light is whiter than

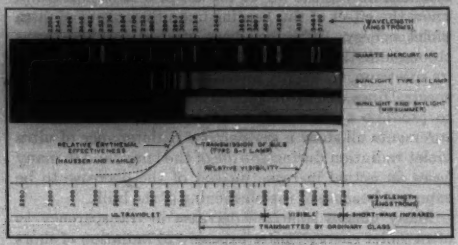


FIG. 2—COMPARING THE SPECTRUM OF THE SUNLIGHT (TYPE S-1) LAMP WITH THE SPECTRA OF THE QUARTZ MERCURY ARC AND MIDSUMMER SUNLIGHT, AND WITH CERTAIN IMPORTANT SPECTRAL RANGES

(Owing to the limitations of photography, it is difficult to illustrate the relative amount of energy in the various portions of the spectrum. The amount of energy emitted by the Sunlight (Type S-1) lamp shorter than λ 2800 is very small, so that the mercury lines between λ 2800 and λ 2600 should show very slightly in this illustration

that which would be obtained from melted tungsten. As measured with the eye and an ordinary photometer, the amount of light which is emitted by the various elements is somewhat under the control of the designer. At present, about 68 per cent is emitted by the tungsten

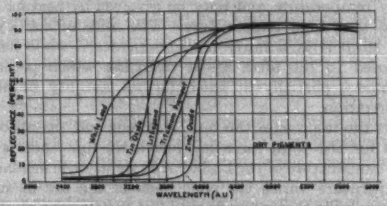


FIG. 3—SHOWING THE PERCENTAGE OF RADIATION OF VARIOUS WAVELENGTHS REFLECTED BY REPRESENTATIVE PIGMENTS IN DRY POWDER FORM

At present, the most important ultra violet region is between λ 2800 and λ 3200

electrodes, 25 per cent by the arc, and 7 per cent by the filament.

Owing to the promise of this new source and also tungsten filament lamps, a good deal of research has been prosecuted in the past year from the point of view of a possible new era of lighting. It has been found that the reciprocity law holds for the production of erythema by radiation from the Type S-1 lamp over a range of 25 to 400 foot-candles at least; that is, equal products of time of exposure and intensity of radiation produce equal degrees of erythema over this range and probably beyond. In other words, if it requires 10 min. at 400 foot-candles to produce a minimum perceptible erythema, 160 min. at 25 foot-candles would produce the same result. This is a very important fact which has been studied elaborately for the first time. In so far as erythema is indicative of beneficial effect, these results are seen to apply within the economic range of illumination levels in general lighting. To conjecture upon the possible benefit of lower intensities of illumination, we may view with encouragement the results already obtained with the mild ultra violet emitted by tungsten filament lamps with special bulbs.

Naturally, in investigations aimed to indicate the possibilities of artificial lighting of the extended purpose under discussion, the foot-candle remains an important

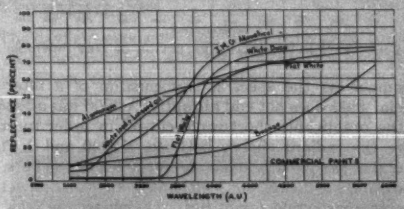


FIG. 4—THE SPECTRAL REFLECTION OF COMMERCIAL PAINTS

factor. It has been found that the radiation from the present Type S-1 lamp is as high as 50 times more effective per foot-candle than midday midsummer sunlight in the production of erythema. On the same basis, the radiation from the quartz mercury arc, with which goggles must be used, is 600 times more effective per foot-candle than sunlight. Of course this difference would be greatly reduced by a glass envelope restricting the utlra violet radiation from the quartz mercury arc to λ 2800 and longer. Even then it would still be more effective per foot-candle than the Type S-1 lamp because its radiation is emitted entirely from the arc which is by far the most effective producer of ultra violet of the three sources in the Type S-1 lamp.

If it were practicable indoors to produce and utilize intensities of illumination from an artificial source comparable with those of midday midsummer sunlight outdoors—7000 to 9500 foot-candles—the ideal substitute would be one which closely approximated the spectral character of such sunlight. However, at the present time, even 200 foot-candles from an artificial source is found to be "difficult to live with" by most persons, particularly at night. Therefore, an effective substitute for sunlight must have much more of the

health-maintaining radiation per foot-candle than midsummer sunlight.

Such a result can be accomplished (1) by extending the short-wave limit further into the ultra violet region and (2) by providing relatively more ultra violet radiation in the spectral region near the short-wave limit of the solar spectrum. In developing the Sunlight (Type S-1) lamp both these expedients have been utilized without sacrificing safety, provided reasonable caution is exercised as is necessary in the case of midsummer sunlight.

The short-wave limit of the best sunlight is at λ 2900.

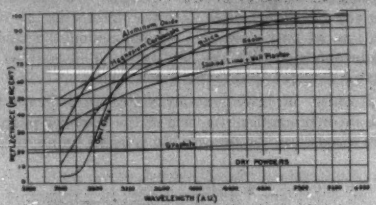


Fig. 5—The Spectral Reflection of Dry Powders

Inasmuch as the spectral transmission of a filter of special glass does not end abruptly, λ 2800 was adopted as the practicable short-wave cut-off in order to conserve the radiant energy between λ 2900 and λ 3100 (which is particularly effective in preventing rickets, in producing erythema, etc.) without being harmful to the eyes in reasonable quantities. Owing to the lack of

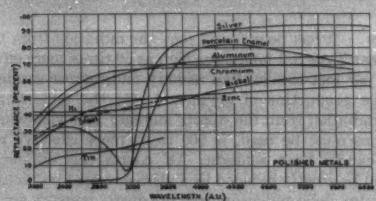


Fig. 6—The Spectral Reflection of a Number of Polished Metals

abruptness of the short-wave cut-off of the glass, slight amounts of radiation of somewhat shorter wavelengths are also transmitted. However, the radiation from Type S-1 lamps has been proved by adequate tests to be so limited in quantity and quality of ultra violet energy that the eyes are safe without goggles under reasonable usage. The ultra violet energy between λ 2800 and λ 3100 is known to be particularly beneficial to health. Therefore, in order to produce an effective substitute for sunlight at reasonable intensities of illumination, relatively much more energy in this region has been provided than that in the solar spectrum.

It is seen that an exact reproduction of the spectrum of sunlight is impracticable so long as popular demand insists upon the same degree of effectiveness from low intensities of artificial sunlight indoors as from high intensities of midsummer sunlight outdoors. This is a very important foundation-stone underlying the production of a sunlight substitute and an understanding of it is equally important.

Inasmuch as the bulb of the Sunlight (Type S-1) lamp blackens during the life of the lamp, it is of interest to know the effect of this coating upon the output of ultra violet energy. This has been studied in three ways throughout the life of the lamp, *viz.*, by photographing its spectrum, by energy measurements of the important spectral lines, and by determinations of the time required to produce a given degree of erythema. These measurements all show a satisfactory maintenance of ultra violet radiation during the life of the lamp, and in many cases an actual increase instead of the decrease to be expected because of the blackening of the bulb.

Many glasses solarize—decrease in transparency to ultra violet energy—after exposure to radiation of short

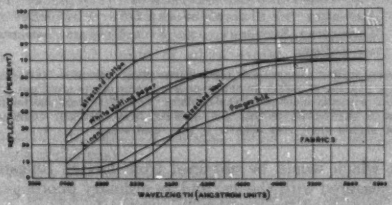


Fig. 7—The Spectral Reflection of White Blotting Paper and White, or Nearly White, Fabric

wavelengths. This effect is usually obtained at ordinary temperature and may be reversed by heating the glass to a high temperature. The bulb of the Type S-1 lamp is at a fairly high temperature while being exposed to the ultra violet radiation which perhaps accounts, partially at least, for its stability or nonsolarization.

As the lamp ages the bulb blackens and the absorption for the total radiation increases, thus increasing the temperature of the bulb. Apparently the increased temperature varies the conditions of the arc in such manner that there is an increase in the amount of ultra violet energy radiated by it sufficient, or more than sufficient, to offset the increased absorption by the deposit on the bulb.

In our studies of the production of erythema by these lamps we have tested a number of them when new and at various times during life. Several persons were exposed to the lamps operated in a Sunlamp equipment, at a distance of 30 in. from the reflector. All indicate a satisfactory maintenance of ultra violet output and many show an increase. Under certain conditions very great increases of desirable ultra violet radiation can be

obtained as the bulb blackens. These results are in accord with measurements of relative energy at certain wavelengths most effective in producing erythema.

We have made other tests to determine whether erythema production is proportional to the energy at certain wavelengths. Within the errors of such measurements we find that the erythemal effectiveness of the radiation from Type S-1 lamps is proportional to the energy at $\lambda$ 2967 or $\lambda$ 3024, in the total radiation incident upon the skin.

Sources such as carbon and mercury arcs, emitting considerable ultra violet radiation, are often used for

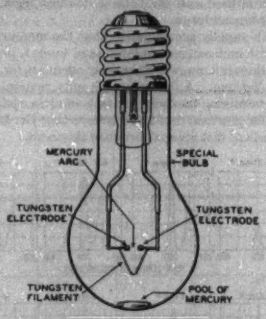


Fig. 8—The Sunlight (Type S-1) Lamp

Over-all length—6.25 in.

fading tests to accelerate the fading. This is partially responsible for the general impression that the ultra violet portion of sunlight and skylight is particularly active in the promotion of fading.

In 1925 we made an investigation* to determine the relative fading by daylight and artificial light in show windows. One factor studied was the relative effectiveness of different spectral regions in sunlight. For this purpose we used nineteen ribbons dyed with various colored dyes, some of them quite fugitive. Transverse strips of these ribbons were exposed to direct sunlight through clear quartz and through various glasses having different short-wave cut-offs but which were highly transparent throughout the remainder of the spectrum. For the majority of the ribbons the reduction of fading as the spectrum was shortened at the short-wave end was little more than might be expected on account of the reduction in total radiant energy transmitted by the successive glasses. However, for half of the ribbons there was a marked difference in fading between exposures under glasses cutting off at $\lambda$ 5570 and $\lambda$ 5770 respectively.

These results are confirmed by a much more extensive investigation recently completed, by the American Association of Textile Chemists and Colorists, with samples of cotton, wool, and silk. They found that the presence or absence of a window-glass cover over the samples exposed to daylight had practically no effect on the fading of 74 per cent of the samples, only a slight effect on 22 per cent of them, but a marked effect on the remaining 4 per cent.

Recently we exposed the same ribbons used in 1925 to the radiation from a Type S-1 lamp in a Sunlamp equipment, the distance being 30 in. In this case a glass cover was not used over the ribbons as was the case in the previous test. The following is a condensed summary of the results.

| | For Same Degree of Fading | |
|---|---|---|
| Illuminant | Foot-Candles | Length of Exposure |
| Gas-filled Mazda | 50 | 2600 hours |
| Gas-filled Mazda | 500 | 240 hours |
| Light from clear sky | (In northeast window) | 18 days |
| Sunlight plus skylight | (In southwest window) | 5 days |
| G. E. Sunlight Type S-1 lamp | 500 | 70 hours |

The daylight exposures were made from dawn to dusk on clear summer days with the ribbons in a fixed position. Those exposed in the southwest window, receiving direct sunlight through glass about five or six hours daily, faded as much in five days as they did in 70 hr.

Fig. 9—Showing the Tungsten Filament, Tungsten Electrodes, and Mercury Arc in Operation in the Sunlight (Type S-1) Lamp

of continuous exposure to the Type S-1 lamp at an illumination of 500 foot-candles.

In entering this broader field an entirely new point of view must be developed toward reflecting and transmitting materials. Most substances, including the usual finishes of walls and ceiling, do not conserve ultra violet radiation between $\lambda$ 2800 and $\lambda$ 3100. However, extensive data are already available which indicate that some common materials such as chromium, aluminum, oxidized aluminum, some white pigments, and plaster are satisfactory reflectors of ultra violet as well as visible radiation. Translucent quartz is inexpensive

*"The Fading of Colored Materials by Daylight and Artificial Light," M. Luckiesh and A. H. Taylor, *Trans. I. E. E.*, 20, 1925, p. 1078.

and other diffusing media can be developed to conserve the desired radiant energy while diffusing the light.

In this brief survey of a possible new era we have reached in our imagination the point where persons are working and playing under simulated sunlight. In many places—nurseries, schools, gymnasiums—abbreviated dress may be utilized. In the work-world is it sufficient to expose only our hands and face? There is no evidence that these areas are insufficient. On the golf course and in many other outdoor activities only these areas are exposed; still, it is believed that sunlight is beneficial. Certainly we know that the benefits of ultra violet radiation are not confined to the area exposed. Chickens, rats, and guinea pigs are cured of rickets, notwithstanding the clothing of feathers or fur over most of their bodies. The medical profession cures rickets in children by exposing their backs or bellies. In fact, there are reasons for believing that the threshold of area exposed, just as of time and intensity, is within practicable limits which can be met in every-day conditions under artificial lighting.

Many questions remain unanswered and there are important gaps in knowledge. However, even in a brief discussion such as this, there are enough facts and sufficient promise to lead us with reasonable certainty from the conception to the realization of a new era of artificial lighting which includes the possibility of health-maintenance.

## Discussion

**L. J. Buttolph:** In Dr. Luckiesh's able analysis of the possibilities in hygienic lighting and his prophecy of a new era in the art there is a suggestion that this may be accomplished by only slight modifications of devices which have already proved their general utility as artificial light sources, and in confirmation of this I wish to call specific attention to the paper entitled "A Dual Purpose Light," by Hughes, Titus, Payne, and Klein in the April, 1927, issue of the *Illuminating Engineering Society Transactions*, in which the conclusion is that "the Cooper-Hewitt glass tube lamp contains a sufficient amount of ultra violet to be a distinct advantage when these health giving rays are desired, and also has the advantage of containing no wavelengths short enough to produce any deleterious effect on the eyes." Dr. Hughes has since studied extensively the relative effectiveness for this purpose of this same standard Cooper-Hewitt lamp, as used in industrial illumination, a Cooper Hewitt lamp identical with the standard lamp but made up in a glass tube of greater ultra violet transmission, such as is used in the S-1 lamp, and a quartz mercury arc as used by the medical profession. He again finds the older standard lamp measurably effective in the prevention of rickets or weak legs in chickens but the lamp in slightly greater ultra-violet transmitting glass many times as effective and for practical purposes comparable with the quartz arcs. Exact ratios will soon be ready for publication. These observations have been based on growth curves, on X-ray photographs of the bone development, and on the calcium content of the bones.

The effectiveness of the standard lamp is due to the use of so thin-walled a glass tube as to transmit a useful intensity of the 3022 line of the mercury arc and relatively still more of the 3132 line. The new glass tubing extends the practical wavelength limit, down to 2900, or slightly less. Lamps equipped with these tubes of enhanced ultra-violet output are being given further study by Dr. Hughes, are in trial operation for general lighting in several industrial plants, and are being used at Cornell University in a study of the possibility of preventing common colds, or at least of decreasing their intensity among students. The work at Cornell University is already being given publicity in the newspapers. The evaluation of general health in an industrial plant is a slow and difficult matter, so as yet the only definite report I can make is that the quality of the light is such as to produce definite tanning from exposure during the ordinary working hours, and in at least one case an operator working very close to a low hung lamp has received an unnecessary artificial burn.

In this connection I would call attention to the fact that a manufacturer of medical equipment is now putting out an artificial sunlight lamp for home use equipped with tube lamps identical in every characteristic with the lamps used for industrial illumination, except that a glass of slightly greater ultra violet transmission is used and the tube is doubled back upon itself into a more compact form.

Evidence is rapidly accumulating that the mercury arc either combined with an incandescent lamp as in the S-1, or alone, as in the Cooper Hewitt lamp, will be entirely adequate for the new era of hygienic lighting. Apparently, the only remaining problem is that of determining the optimum ratio of ultra violet to visible component for practical use, and I believe that Dr. Luckiesh has made an excellent first approximation of this ratio.

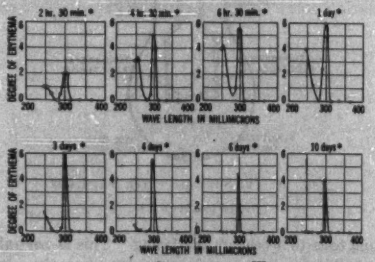


Fig. 1—Relation of Erythema to Wavelength of the Incident Rays for Equal Amounts of Energy. Successive Figures show Changes of the Phenomenon with Time

*After irradiation

**M. J. Dorcas:** I have been interested for some years in the development of sources of light that would be similar to sunshine—you might say simulating sunshine—and partially because of that interest I realize the greatness and importance of this development which Dr. Luckiesh has described to us tonight.

In the source of artificial sunlight in which I have been interested, the carbon arc, the development is slightly different; the result which we get is slightly different; the radiation is slightly different than that which is given by the filament and mercury arc combination, and I should like to discuss very briefly some of those differences and some of the reasons why those differences exist.

Fig. 1. In discussing sunshine, if we are going to simulate sunshine, we must first determine what the sunshine is to be. We can never hope to get an absolute duplication of sunlight that will stay sunlight for very long because the sunlight itself is changing, but you can assume a standard or average sunlight.

One of the most important questions is what will be the short end or short ray of cut-off of that sunshine. This is a series of curves made by Dr. Hauser of Germany, who also made the curve of erythema shown by Dr. Luckiesh. These curves do not conflict in any way with those of Dr. Luckiesh, which show the amount of radiation of different wave lengths required to produce the faintest detectable erythema while the curves now shown record the relative persistence of the different erythemas. If we have equal amounts of radiation of a variety of wavelengths,

we find in two hours and 30 minutes afterwards an erythema around 3000 angstroms, and we get erythema produced by shorter wavelengths. At four hours and 30 minutes those are still growing.

We see that the shorter wavelengths cause an erythema which develops very rapidly and comes to a maximum in about six hours. The longer wavelengths develop much more slowly, and cause an erythema which for several days is still increasing.

From the standpoint of a photochemist, that indicates two separate and distinct photochemical reactions. That means we are getting two separate and distinct kinds of erythema produced. The reactions in the skin are of two separate kinds; the products are different, and therefore the physiological effects are different. It indicates further that we have only two kinds, and that any of the radiation in this one peak here will cause only that one kind of photochemical decomposition, and any radiation in the curve under the second peak will cause a second and a different kind.

That gives us a definite clue as to where the end point or the short-wave cut-off of our artificial sunlight must be if we are going to get an effect that is like sunshine; that is, it must be somewhere around 2750 or 2800 angstroms. Perhaps we can go down a little bit farther than that, possibly down to 2700 or slightly less, without getting any perceptible amount of the kind of effect that is different from that caused by sunshine. This is in perfect agreement with Dr. Luckiesh's ideas. These curves are significant only with respect to the formation of an erythema. They do not indicate anything about any other kind of physiological effect. However, we have the information about the effects of different wavelengths with respect to the formation of Vitamin D, from the pro-vitamin, which is probably one of the sterols, and there is reason from our studies of that reaction to think that a cut-off of 2700 or 2800 angstroms, will be satisfactory as a duplication of sunshine as far as this physiological effect goes.

There might at some future time be some information that would make us cut off our short wave end of the structure at exactly 2900, or 2917, which is the short wavelength end of natural sunshine, but at present we see no reason why we cannot get a duplication of effects by wavelengths as short as 2800.

This comes to the same conclusion as that of Dr. Luckiesh but from a somewhat different line of reasoning. This does not consider the effect on the eyes. If we consider only the matter of causing erythema, if we consider only the matter of the formation of Vitamin D, (the antirachitic effect), we find that this part of the spectrum, around 3000 angstroms, is the most important. The importance of Vitamin D is very great. It cannot be overemphasized.

There are other effects, however. The resistance of the human body to bacterial infections seems to be changed by the exposure to various light sources. It is not definitely proven just what wavelength causes that change in resistance to bacterial effects. Growth seems to be somewhat a function of the amount of light or radiation received. We do not know just exactly what wavelength causes that.

As Dr. Luckiesh pointed out, plants are dependent in general for their very life on wavelengths of radiation as long as 4000, 5000, or perhaps much longer wavelengths. Much of their growth is due to the absorption of radiation by chlorophyl, a colored substance that absorbs visible and ultra-violet radiation of various wavelengths.

In the human body there are many compounds which are colored, and there are at least some theories that those colors are of some significance in absorbing various kinds of radiation. We cannot say definitely at this minute whether these other wavelengths are all of equal importance, or whether they are of comparatively little importance. However, there is some indication that they are of importance, and therefore if we are to get a physiological effect that is in all respects like sunshine, we must have a somewhat comparable ratio of long wavelengths to short wavelengths, or one wavelength to another, the same as we have in sunshine.

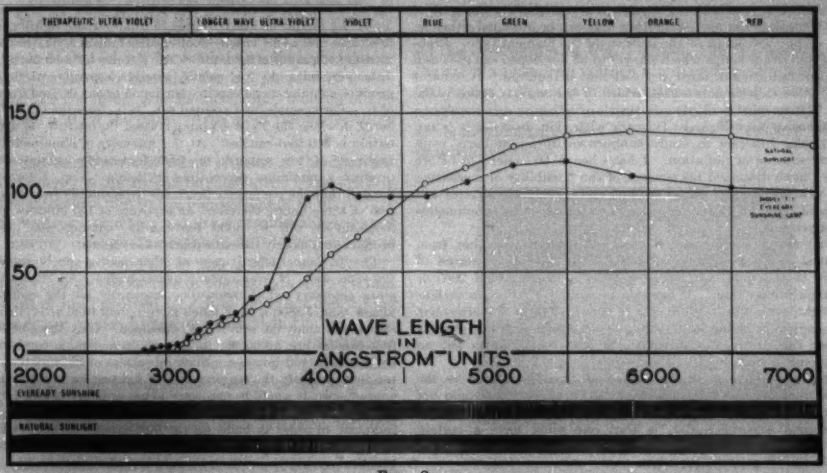


Fig. 2

Fig. 2. This represents one other type of light source, a carbon arc lamp with a somewhat thinner screen than that which was described for the Eveready sunshine lamps in Dr. Lukiesh's paper. This is the curve of energy radiation through the three millimeter thick of screens which is now used in such lamps. We get a very similar duplication of wavelength for the curve which is natural sunlight, and the curve of the carbon arc lamp radiation.

This is a table which shows percentage distribution for different

groups of wavelengths comparing the sum and the above mentioned Eveready carbon arc lamp. The upper row of figures would be the sunshine and the lower the carbon arc lamp. This table is from a recent paper by Greider and Downes. The close approximation of sunshine throughout is shown by this table.

TABLE I
PERCENTAGE DISTRIBUTION OF RADIATION—SUN AND EVEREADY SUNSHINE ARCS. ARCS SCREENED WITH COREX "D" GLASS

| | Anti-rachitic ultra violet 2900-3100 A. | Non-penetrating ultra violet and visible 3100-6500 A. | Penetrating red and infra-red 6500-14,000 A. | Total to 14,000 A. watts × $10^{-7}$ per sq. mm. |
|---|---|---|---|---|
| Sun | 0.019 | 44.3 | 55.6 | 7260 |
| Eveready Sunshine Twin Arc Lamp 12-amp. 28 x 2 volts | 0.09 | 44.5 | 55.4 | 240 |

There is a possibility of a very great variation in the ratio of wavelength of one sort to another that can be obtained either by the carbon arc lamps or these others of the filament type. Probably still other lamps which are yet to be developed can give us a kind of radiation of most any sort that is required. It remains for future experiments to tell which of the various ratios is the one that we need most.

**Herman Goodman:** In work with skin diseases, it is my particular function to study sunburn, artificial sunburn, from many sources of radiation. I have heard Dr. Luckiesh before and I have discussed his concept of the possibility of measuring the vital ultra violet component of various artificial sources and natural sunlight by the foot-candle meter which he recommends to physicians.

The active source of radiation for sunburn, whether from natural or artificial sources, depends, as has been stressed so much this evening, on a very specific radiation, about 2987 or 3000 angstrom units. If one takes a source of radiation such as sunlight, which has a radiation of about 3000, in late afternoon or possibly in spring, fall, or winter, one finds it is not possible under the ordinary time limits of such sunshine to get an erythema or sunburn.

One may have artificial sources of radiation which in the laboratory gives radiation around 2987, and yet one would not get a sunburn. The reason therefor, as far as I have been able to determine experimentally, is that one must have a certain threshold of intensity of this sunburning radiation before the skin shows the effect of the exposure.

It is possible to take a source very rich in sunburning ultra violet, as the mercury vapor arc in quartz, very effective at 24 inches, we will say, operating at 4 amperes, 75 volts direct current, clinical, air-cooled model, and diminish the radiation by various glasses until little of the 2987 passes to reach the skin, and even if exposure is up to two hours one does not get any erythema at all.

We had, for example, a lamp at the hospital which a misinformed nurse had cleansed daily with alcohol mixed with formaldehyde. That lamp did show in the laboratory radiation emitting from the lamp of 2987, yet a patient placed under that lamp and inadvertently kept there one hour and forty-five minutes, did not show any erythema whatsoever. It was equivalent to a very, very mild heat lamp. In estimating what type of radiation gives forth sunburn, one should know what would be the threshold value, which is as yet undetermined in ergs, to be put into such a lamp.

Further, as to the foot-candle meters, it is possible to sunburn in the dark. One can use a piece of Dr. Gage's glass, which cuts off practically all visible light and only permits about 10 per cent of the visible ultra violet to go through. One can get a very nice sunburn in complete darkness in that way. It takes about twice as long without that black filter because the transmission range of the glass is about 54 per cent at 2987, and then again it would show that the ordinary foot-candle meter which measures visible light is not an acceptable measure for the ultra violet component even so far as erythema is concerned in white people who have not been sunburned.

But now let us take a colored man in whom it is not possible under white light to determine whether he has been sunburned or not, and a person who has been very, very much sunburned in the past. I will say that as far as the lay person is concerned, the non-medical attendant, it is very important to let him have a semblance of sunburn which comes from sunburning ultra violet. That is very different from the evanescent redness which comes on very soon, which is due to other parts of the emission, for example, the heat portion of the emission from every source of light whether natural or artificial.

**M. Luckiesh:** Dr. Goodman persists in misinterpreting my suggestion as to the use of foot-candles. He points out several obvious cases in which foot-candles are meaningless or useless. However, when we come to the point of using mercury arcs, Type S-1 lamps, or other sources in dual-purpose lighting—for health as well as for vision—foot-candles remain a very essential measure of quality of light and we can develop for each source the data pertaining to foot-candle minutes exposure which will produce a minimum perceptible erythema or any desired fraction of it. For example, as I pointed out, 30 in. from the G. E. Sunlamp, in which the Type S-1 lamp is used, the intensity of illumination is 400 foot-candles. At this intensity of illumination an exposure of ten minutes or 4000 foot-candle—minutes will produce a minimum perceptible erythema. Also, I have indicated that the reciprocity law holds satisfactorily over at least two or three hours; therefore, an exposure of 160 minutes to 40 foot-candles will be 4000 foot-candle—minutes and would produce very closely the same degree of erythema.

The erythemal effectiveness of other sources can be rated in the same way. For example, a quartz mercury arc with a thin glass accessory which transmits practically all the radiation longer than $\lambda 2800$ is very much more potent from an erythemal standpoint than the source just discussed. Only three or four foot-candles are necessary to produce a minimum perceptible erythema in 160 minutes. Such intensities of illumination are too low to satisfy the requirements of lighting for vision. As a consequence, it would be necessary to use ordinary Mazda lamps or some other light-source which did not supply erythemal radiation in order to build up the foot-candles to take care of lighting for vision. Dr. Goodman does not look at this in a practical manner from the point of view of my paper, which is that of dual-purpose lighting.

If the professional therapist wishes to know the relative effectiveness of the radiation which he is using, he can utilize a foot-candle meter just as effectively as he can utilize any of the other present methods. I am assuming that common sense is used in any case. Dr. Goodman places too much confidence in energy measurements. These are valueless unless interpretable into biological action. The matter is a very simple one of a spectral nature, but this is no place to discuss the simple physics of the subject. There has been a good deal of demand for such measurements as microwatts per square centimeter at a given distance from a source of ultra violet. Anyone who is familiar with spectroscopy knows that energy measurements within a certain spectral range cannot safely be used to appraise illuminants or radiant energy differing widely in spectral character. Such demands arise from too little knowledge which so often has been proved to be dangerously misleading.

I am very much surprised to hear Dr. Goodman say that it is not possible to determine whether or not the skin of a colored person has been sunburned. Erythema is readily visible on the skin of colored persons.

# The Calorimetric Study of the Arc

BY P. P. ALEXANDER[1]

Member, A. I. E. E.

*Synopsis.—The present paper describes an attempt to determine the distribution of energy in the electric arc by the calorimetric method. The total energy input to the arc was measured by a specially calibrated watthour meter. The energy dissipated at the anode and at the cathode was estimated by the temperature rise of the electrodes, which was measured by mercury thermometers. In experiments with the iron, copper, and carbon arcs, the anode and cathode were of the same weight and shape and were provided with an identical heat insulation. Since the ratio between the energies dissipated at the anode and at the cathode was made independent of the losses by radiation and the absolute values of energies involved, its determination was made with sufficient accuracy. In the case of iron or copper arcs in air this ratio was found to be practically unity. The presence of different fluxes alters the distribution of energy between the anode and cathode. In the case of an arc maintained between graphite electrodes, the energy at the anode was much higher than that at the cathode.*

* * * * *

## Introduction

THE total energy input to the arc can be accurately determined by means of the usual measuring instruments. However, when the electric arc is used as a tool for electric welding, it is useful to know not only the total energy in the arc, but also the distribution of that energy between the anode and cathode. This information is desirable for the purpose of determining the conditions for the most rapid melting of the electrode and for the effective fusing of the plates to be welded.

As has been shown by many physicists, the distribution of energy in the arc can be calculated. The heating of the cathode is due to the bombardment of its surface with positive ions which acquire a considerable velocity by moving through the cathode fall. This energy is increased a small amount by the heat of neutralization of these ions on the surface of the cathode, by a certain amount of heat evolved by oxidation reactions taking place either on its surface or in its vicinity, etc. The most important factors which determine the heating of the cathode are the ratio between the positive and negative ions in the immediate vicinity of the surface of the cathode, and the value of the cathode fall. These factors have been determined with precision for arcs maintained between non-vaporizing electrodes in such gases as helium, argon, and mercury, but corresponding values for an iron arc maintained in air are not known as yet with certainty. The anode is heated principally by the bombardment and by the absorption of released latent heat of condensation of the incoming electrons. We must also know for our calculations the value of the anode fall and the ratio between the electrons and the positive ions. However, at the present time, it is practically impossible to calculate with sufficient approximation the heat evolved at the cathode and the anode of a short iron arc of any considerable intensity.

The experimental method of determining the distribution of energy in such an arc is, therefore, the only alternative. Although it cannot claim great precision, in the case of an iron arc of a type similar to that used in welding, it gives some useful information on this subject.

A great difficulty in making the necessary measurements is the inherent peculiarity of the iron welding arc. As the oscillogram in Fig. 1 shows, the voltage across the arc is a pulsating voltage of an average frequency of 300 cycles. When a molten globule passes across the arc from the rapidly melting electrode to the weld, the arc is momentarily short circuited and its voltage drops practically to zero.

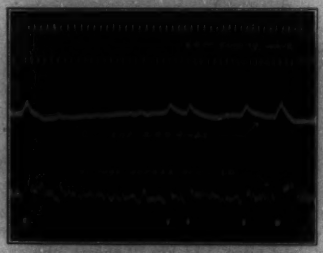

Fig. 1—Oscillogram of Arc Current and Voltage

Since the molten metal from the electrode is deposited into the opposite crater, all the energy consumed in melting the electrode is mechanically transferred to this crater. In other words, the energies put into the cathode and the anode are periodically added together. Except for radiation and other losses, the total energy of the arc is eventually transferred into the weld. The speed of welding, however, depends not only on the total energy of the arc, but also on that part of the total energy of the arc which is utilized in melting the welding wire. In other words, it depends on the distribution of energy in the arc.

## Experimental Method

As a first approach to the solution of this problem, the following method was developed to measure the

1. Research Engineer, Thomson Research Laboratory of the General Electric Co., Lynn, Mass.

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ratio between the energy input of the anode and the cathode. The underlying thought in planning these experiments was to approach as near as possible to the conditions under which the iron arc is used as a welding tool and yet to eliminate all the unessential factors which might obstruct the solution of the problem. As has been mentioned above, one of these factors is the short circuiting of the arc by the molten globules.

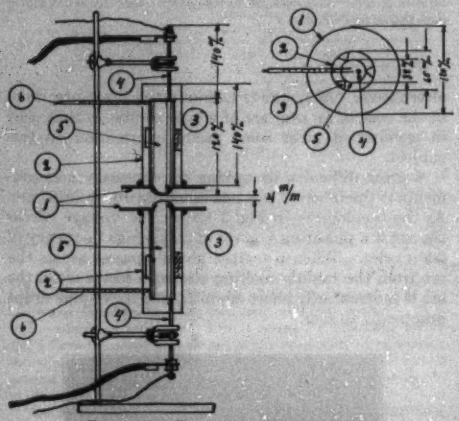


Fig. 2—Arc Electrodes Used in Tests

1. Asbestos, 3 mm. thick
2. Cylinder of 0.12 mm. polished copper
3. Cork spacer
4. Brass rod
5. Electrode, polished steel cylinder, 38 mm. in diameter
6. Thermometer

The first series of tests, therefore, was conducted under conditions in which the short circuiting of the arc did not take place. As Fig. 2 shows, the anode and cathode consisted of small steel cylinders of identical shape and weight. They were polished to reduce the losses by radiation and except for the small surface at one end, were protected by an efficient heat insulation, consisting of a cushion of dry air enclosed in a cylinder of thin polished copper sheet. Near their outer ends these electrodes were provided with holes in which thermometers of the same calibration as to heat capacity and sensitivity were inserted.

As Fig. 3 shows, direct current was supplied by a constant potential source of 275 volts. A heavy resistance balance supplemented by considerable reactance connected in series insured a supply of current, practically independent of small variations in the voltage of the arc. Also, since the heat capacity and heat insulation of the anode and cathode were practically identical, variations of voltage and current in the arc during the observation would affect both electrodes equally. In other words, the error from this cause may be introduced in estimating the total input energy but not in determining the ratio between the energy input of the anode and cathode. The time of the burning of the arc was purposely made very short, ranging from 30 to 300 seconds. This resulted in a comparatively small temperature rise, and, therefore, small losses by radiation or conduction. In most of the experiments, the difference between the total measured energy input to the arc and the sum of the energy measured at the anode and at the cathode was less than 20 per cent, which indicates that these measurements were sufficiently exact for the purpose in view.

The first series of experiments was made with a constant distance of 4 mm. between the electrodes. This distance was adopted because the average length of the iron welding arc is usually of this value. In successive tests, the currents were increased by steps from 30 amperes up, until at approximately 135 amperes there was a melting of the tips of the electrodes, which periodically shorted the arc. At this point, the molten metal bridged the gap for a fraction of a second every two or three seconds. In every case, the bridge of molten metal was disrupted by the short circuit current, and the parts of the disrupted globule were then separated by the equal surface tension of the molten metal on the anode and cathode.

No transfer of metal from the upper electrode to the lower one was observed. This condition of the test approached the conditions met in the metallic welding arc, yet did not contain the factors obscuring the real picture of the distribution of energy in the arc. The temperature curves shown in Figs. 4, 5, and 6 indicate that in all these experiments the energy delivered to the cathode was practically equal to that received by the anode.

Fig. 7 shows the temperature curves of the copper arc. The measured ratio between the anode and cathode energies was almost equal to one.

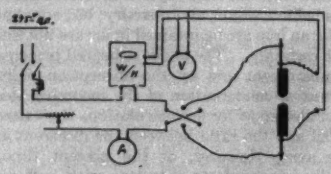


Fig. 3—Circuit Connections for Tests

The second series of experiments was conducted for the purpose of determining the influence of the relative position of the anode and cathode on the distribution of energy in the carbon or iron-carbon arcs.

Table I gives the results of these measurements. The figures given in this table are not averages but are individual tests. However, prior to the tabulation of these results, every test was repeated several times

and it was ascertained that the reported figures represent the most accurate observation for each type of arc.

The total energy developed in the arc was measured by counting the number of revolutions of the aluminum disk connected with the armature of the watthour meter. Since this instrument was specially calibrated for the voltage of the arc, the error in determining the total energy was probably less than 1 per cent.

As has already been stated, the energy received by each electrode was estimated from temperature rise registered by specially calibrated mercury thermometers. The error in these estimates was probably less than 0.3 of one per cent of the energy input into each electrode.

The losses by radiation were estimated by tracing the temperature curves for the cooling electrodes. However, since the losses were the same for both electrodes, they did not enter into the calculation of the ratio between the anode and cathode energies. The total losses from the arc shown in Table I were obtained by substracting the measured anode and cathode energies from the total energy input to the arc. These losses are due in part to the evaporation of atoms from the cathode and anode spots of the arc.

A close observation of the arc, which can be made

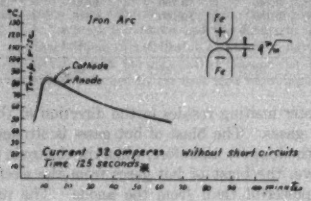



Fig. 4

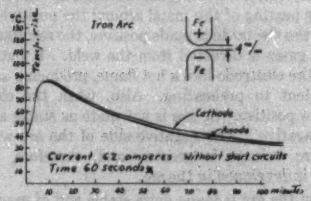



Fig. 5

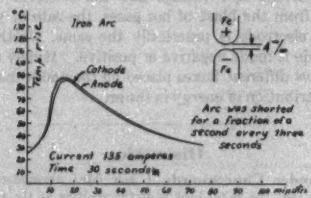
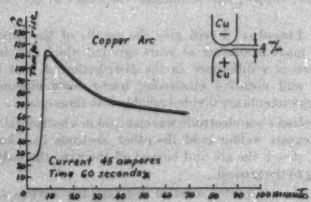



Fig. 6




Figs. 4 to 7—Anode and Cathode Temperature Curves

*Time of burning of the arc

Fig. 8—Drawing Showing Hot Gas Blasts and Arc Core

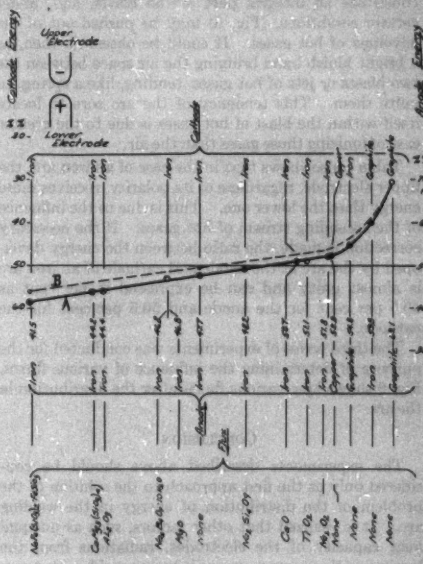



Fig. 9—Curves Showing Ratio between Anode and Cathode Energies for Various Fluxes and Electrodes

TABLE I

| Test No. | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Anode | | Iron | Iron | Graphite | Graphite | Graphite | Iron |
| Cathode | | Iron | Iron | Graphite | Graphite | Iron | Graphite |
| Polarity of the upper electrode | | − | + | − | + | − | − |
| Total energy developed in the arc, in g-cal | | 16,400 | 16,400 | 11,400 | 13,100 | 9,840 | 16,400 |
| Energy measured at the anode, g-cal | | 6,380 | 6,800 | 7,010 | 8,400 | 5,160 | 7,920 |
| Energy measured at the cathode, g-cal | | 7,000 | 6,430 | 3,140 | 3,760 | 4,250 | 5,330 |
| Sum of anode and cathode energies g-cal | | 13,380 | 13,230 | 10,150 | 12,160 | 9,410 | 13,250 |
| Losses by evaporation, radiation, etc., in % | | 18.4 | 19.3 | 11.0 | 7.2 | 4.4 | 19.3 |
| Distribution of energy in % | Anode | 38.9 | 41.4 | 61.5 | 64.1 | 52.4 | 48.2 |
| | Cathode | 42.7 | 39.3 | 27.5 | 28.7 | 43.2 | 32.5 |

more conveniently with longer arcs of 10 mm. to 12 mm., reveals the presence of two distinct blasts of hot gases issuing from the cathode and anode with considerable velocity. These streams exert a considerable repulsive force upon each other and undoubtedly consist of streams of neutral atoms.

The arc core appears as a narrow bright bluish band within these blasts of hot gases. Yet, it does not constitute an integral part of the blasts, and, under certain conditions, (Fig. 8) may be pushed out of the envelope of hot gases. It could be observed, then, as a bright bluish band bridging the air space between the two blasts or jets of hot gases, tending, like a spring, to unite them. This tendency of the arc core to locate itself within the blast of hot gases is due to the greater ease of ionizing those gases than the air.

Table I also shows that in the case of an iron arc, the upper electrode, regardless of its polarity, receives more energy than the lower one. This is due to the influence of the ascending stream of hot gases. If the necessary correction is made, the ratio between the energy developed by the arc at the anode and cathode of an iron arc is almost unity and can be expressed in per cent as 49.5 per cent for the anode and 50.5 per cent for the cathode.

The third series of experiments was conducted for the purpose of determining the influence of various fluxes. Fig. 9 shows how various fluxes alter the distribution in the arc.

## Conclusion

The experiments described above should be considered only as the first approach to the solution of the problem of the distribution of energy in the welding arc. It is realized that other factors, such as unequal heat capacity of the electrodes, radiations from the larger positive crater, etc., will have considerable bearing on the heat distribution between the electrodes. It may be concluded, however, that in an iron arc, the energy developed at the surface of the anode is practically equal to that developed at the cathode.

It should be observed that the above results indicating equal distribution of energy in the iron arc are not in contradiction with the well-known fact that in arc welding the electrode melts faster when it is made positive. Accurate measurements of the arc voltage and the energy of the arc have shown that the cause of the faster melting resides in the direction of the blast of hot gases. The blast of hot gases is stronger from the cathode spot; therefore, when the electrode is made negative, the blast of hot gases from the electrode is more powerful than from the anode. The resultant blast is, therefore, directed downward, which causes greater heating of the metal around the positive crater. When the electrode is made positive, the resultant blast of hot gases is directed from the weld. It bathes the tip of the electrode like a hot flame, producing an effect equivalent to preheating. Also, when the electrode is made positive, the arc is not quite as stable as when it is negative. The negative side of the arc wanders. The arc voltage is greater, and, therefore, greater energy is developed in the arc.

When the arc is made quite stable and of exactly the same current and voltage and the electrode is protected from the blast of hot gases, the rate of melting of the electrode is practically the same, whether the electrode is made negative or positive. It may also be seen how different fluxes placed on the anode may alter the distribution of energy in the arc.

## Discussion

**Alexander Churchward:** I ask Mr. Alexander about showing that the same heat is at the positive as the negative. How does he account for it? We have to reverse the polarity on bronze, copper, and aluminum electrodes to get the proper fusing.

**J. C. Lincoln:** I will give the results of the experiments which I made a number of years ago and which convinced me that there is a difference in the distribution of heat between positive and negative electrodes, under some circumstances. These experiments are divided roughly into three classes.

In all classes one electrode was clamped in a horizontal position and an expert welder held the other electrode in a horizontal position, struck the arc and burned off the wire, the melted wire dropping to the ground.

When the electrodes were of ordinary low carbon steel approximately 0.15, the positive electrode burned off more rapidly than the negative. As a result of approximately 50 experiments, the rate of burn off of the positive would be represented by approximately 56, while the rate of burn off of the negative would be represented by 44.

When higher carbon electrodes were used, approximately 0.30, a similar number of experiments indicated that the rate of burn off of positive and negative electrodes was approximately equal.

When, however, the carbon content was raised still higher to say 0.7 to 1 per cent, the negative electrode burned off more

rapidly than the positive electrode, indicating that with the high carbon electrodes, more heat was produced at the negative than at the positive terminal.

With high carbon electrodes, the rate of burn off of the negative electrode could be represented by approximately 53, while the burn off of the positive could be represented by 47.

These experiments checked up with the well known fact that where low carbon steel electrodes are used, better results are obtained when the work is positive and the electrode negative, because in actual welding it is advisable of course to have all the heat possible developed on the work rather than on the electrode and this is further confirmed by the fact that when high carbon steel is used experience shows that it is advisable to reverse the polarity and make the work negative and the arc positive, because with high carbon steel used for electrode more satisfactory work is obtained with the polarity reversed.

**P. P. Alexander:** The distribution of energy depends on the composition of the electrodes. For instance, if, instead of pure copper we use an alloy such as bronze, the distribution of energy will be different from that observed in the arc mentioned between pure copper electrodes.

In the case of steel we should also expect the distribution of energy in the arc to be influenced by the carbon content in the electrodes.

# Resistance Welding

BY BYRON T. MOTTINGER[1]
Member, A. I. E. E.

*Synopsis.—This paper is directed to engineers interested in the application of resistance welding to the industries. The discussion foreshadows some of the latest tendencies of development. It deals with some fundamentals of design though it is not written as a complete treatise on the subject, nor especially for those engaged in the designing of resistance welding machinery.*

*Differentiation is made between the older form of resistance butt welding and the later method of flash butt welding. The probable action taking place in the flashing zone is discussed, along with the effect that increased potential across the weld has on this action. The main object in flash butt welder designing should be to combine the maximum degree of acceleration of the metals into the flashing zone with the proper and necessary e. m. f.*

*A study of the power division of a typical butt welder shows that the efficiency may be as low as 7 per cent or lower, but that nevertheless it competes with other methods of welding when applied to problems of mass production. The effect of external resistance in a flash butt welding machine is to offset variations in die contact and variations in stock resistance, thus stabilizing the flow of current in the flashing zone.*

*The power factor of welding machines is not regarded by the designers as a major element, since the time of application of the current is at most but a few seconds.*

*No trustworthy factor can be given to determine the power to weld a given unit area of metal. This is necessarily so since the efficiency of all welding machines is low and varies over wide ranges, and the element of time and acceleration of welding, as well as the resistance of the materials, all vary.*

*The critical part of the flashing cycle is at the beginning when the metal is cold. A high rate of acceleration produces the highest and quickest heat, which are essential in producing the best type of weld. The time required for upsetting the weld is as important in producing good welds as is the flashing.*

*The difficulty of designing a combination cam to do both flashing and upsetting of large sections is illustrated with a diagram of a typical cam.*

*Methods of projection welding are illustrated. The bad effect of overheating by the old method of spot welding is shown by photomicrographs. Photomicrographs of "flash spot welds" and "flash projection welds" show that these types of welds have a very fine-grain structure, and are to be used whenever possible, as in many cases they eliminate otherwise necessary polishing to produce a smooth surface over the weld.*

*Seam welding is done between revolving wheel electrodes. Clean stock, such as polished cold-rolled steel, is welded without interruption of the welding circuit. Stock having scale can be welded only by interrupting the current, which introduces the effect of shock. Seam welding is being applied to the longitudinal seams of pipe and the process recently has been speeded up by increasing the frequency of the power supply.*

RESISTANCE welding, as the term resistance implies, depends upon the inherent specific resistance of the metal to be welded, and in practise the welding heat is created by passing an electric current of sufficient density through the metal.

Resistance welding as now applied to the industries is practised under three general heads, as follows: (1) butt welding, (2) spot welding, and (3) seam welding.

There are some instances of resistance welding practised that lie in rather intermediate points between two or more of the above classifications, and such cases are not always easy to classify. However, in general, the three kinds of resistance welding are quite distinct forms, and no difficulty is experienced in classifying them.

## I. Butt Welding

Butt welds are made between two pieces of metal held in dies as shown in Fig. 1. Butt welding comes under two classifications. The older type is known as a "straight butt weld," or frequently called a "resistance butt weld." It is produced by clamping the pieces to be welded between the dies, forcing the pieces together with some pressure, and then applying the welding current. The area of contact, at this stage, is naturally quite restricted, and the small area is soon heated, which flattens down under the pressure and permits other areas to come into contact, and likewise become heated. As the hot metal has a very much greater resistance than the cold metal, there is a dispersing factor introduced which tends to equalize the temperature over the entire surface of the area of contact. The current is applied sufficiently long to permit the joint to become heated to the plastic state, at which time the two pieces are forced together vigorously, and an upset is produced as shown in Fig. 1. This type of

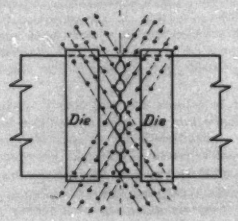



Fig. 1—Appearance of Flashing Action in Butt Welding

weld depends upon the inherent resistance of the metal being welded and likewise upon the resistance of the contact at the joint, and hence has been termed a "resistance butt weld," in order to differentiate between it and the type of weld shown which is generally spoken of as a "flash butt weld."

The difference between the flash butt weld and the resistance butt weld lies in the fact that in the latter the

1. The General Welder Company, Akron, Ohio.

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welding potential is applied to the pieces before they are permitted to come into contact. Immediately upon making contact there is a violent arcing or sparking between the pieces, volatilizing and throwing out the metal about the contacting areas. This action, called "flashing," continues as long as the pieces are made to approach, one toward the other. The violence of the flashing increases with the increase in the speed of approach, assuming that there is sufficient energy to cope with the demand. The flashing period covers two distinct stages. The first stage is usually accomplished under uniform speed of approach, and continues till complete normalcy of areas is secured between the opposing ends to be welded. As soon as uniform flashing over the entire area is secured, then acceleration of the parts becomes necessary. The acceleration causes more metal to be volatilized and thrown out, and this in turn increases the temperature of the ends to be welded. The acceleration plays another very important part. It prevents the heat running back toward the welding dies, and into the unheated sections, which in turn governs the nature of the upset upon completion of the weld. The steps, then, in making a flash butt weld are as follows: Clamp the pieces under the dies, apply the welding electromotive force, cause the pieces to approach at uniform speed until normalcy of areas is secured by flashing, then accelerate the speed of the approaching pieces up to such a point where white heat and plasticity are assured, finish with a quick short upsetting blow. This process will insure the very best type of weld possible to secure, having a strength equal to the original metal and the very least possible upset. This covers the two essential requirements of all commercial mass production welds.

Up to the present time there has not been devised any scientific means for determining exactly what is happening in the flashing zone. From observation it appears that for a given speed of approach of the metals to the flashing zone, the higher the welding e. m. f. is held, the larger will be the flashing particles evolved, carrying with them increased heat and violence, while with decreased voltage, the sparks will be finer, not so hot, and they will be emitted with less violence. This action is well illustrated in practise, when butt welding thin sheets, such as No. 20 gage. Permitting the speed of flashing and degree of upsetting to remain constant, and varying the voltage from time to time alone, it has been found that pin holes will show up in the seam when excessive voltage is applied. This shows that the violent, volcanic action taking place along the seam has torn out pieces of plastic metal, leaving the edge ragged and toothed, to such a degree that the push up was not able to fill the void spaces made by the violent flashing. However, increasing the degree of upset will in most cases fill up the pin holes again.

Before the effect of increasing the voltage across the weld, comes the further and more important consideration of increasing the speed of acceleration of the metals into the flashing zone, along with the problem of securing the proper degree of acceleration. It has been shown by experimental tests that there is no practical limit to the magnitude of the applied welding e. m. f. advisable to use, so long as the proper degree of acceleration is maintained, and so long as the increased current demand does not produce burning under the dies. In fact the major problem of flash butt welder design, lies in the ability to co-ordinate the maximum e. m. f. with the maximum degree of acceleration of the metal into the welding zone.

Before proceeding further with the discussion, it is necessary at this time to make a study of the power division of a typical butt welder circuit. A diagram of such a circuit is shown in Fig. 2. Suppose the area of the steel bar, *A-A*, in the figure to be 1 sq. in.; that its specific resistance is seven times that of pure copper; that the length of the bars, *A-A*, between the dies, *B-B*, is 1 in.; that the length of the welding circuit, external to the dies, *B-B* is 49 in.; and that the area of cross section of the copper parts, *C*, *D*, and *E* is 7 sq. in., (that is seven times the area of the steel bars).

Fig. 2—Typical Butt Welding Machine Circuit

With the above proportions, there is, therefore, just the same $I\,R$ drop in the external welding circuit copper, as there is in the bars between the dies, *B-B*. But since in practical designs there are introduced into the external circuit from six to nine electrical joints, all very difficult to make efficient, it is not an infrequent thing to find welding machines where the loss external to the dies is considerably more than the loss internal to the dies. This is especially true if the die contact resistance between die and weldable material be counted in with the external resistance as is usual. With this consideration, many cases are to be found where the internal loss is but 30 per cent of the total welding circuit. This means that a welding machine requiring 100 kw. to make a certain weld, will have a loss of 70-kw. in the external welding circuit, and only 30 kw. loss in the weldable steel between the dies. The internal loss in the steel between the dies is caused by the $I\,R$ drop in the steel, and the counter e. m. f. of the flashing zone. (Whether it is correct to speak of the drop in the flashing zone as a counter e. m. f. may be open for criticism. It seems to act like the carbon arc, and has so been considered.) The magnitude of the loss cannot be

definitely stated, since there is a number of variable quantities entering into the problem. The current density is a variable, the specific resistance of the steel varies with its make, and it increases with its temperature, while the counter e. m. f. of the flashing zone is dependent upon the initial e. m. f. impressed, and upon the electrical characteristics of the balance of the circuit. In general, however, approximately ½ volt per inch of length is required to drive welding current density through steel. The counter e. m. f. of the flashing zone may be taken, under average conditions at ½ volt, so that the sum of the resistive drop in one inch length of steel, the counter e. m. f. of the flashing zone, and the die contact, represent approximately 2 volts. If this internal loss represents 30 per cent of the total resistive drop, there will be required an initial impressed e. m. f. of 6.7 volts to overcome the total resistive drop. (The reactive component is not taken into consideration at this time.) The above relations may vary over a wide range, depending upon the design, but in general they will be found in practise to lie somewhere close to the above figures, when taking into consideration only normal and average applications of present welding machines.

To the layman it might appear from the above considerations that resistance butt welding presents a very inefficient method of applying electrical energy. When it is understood that of the 30 per cent energy represented between the dies, only 7½ per cent is used to create or generate the heat in the flashing zone, (½ volt is 7½ per cent of the 6.7 volts required to overcome resistive drop), or in other words, but 7½ kw. appears as desired and efficient heat at the welding line, while 92½ kw. is consumed in overcoming unavoidable resistance of the balance of the welding circuit. However, in spite of the apparent inefficiency of the welding machine, it stands today as an accomplished fact that resistance butt welding is the cheapest and most rapid method, producing the most nearly perfect results of all welding methods applied to mass production. An automatic power driven flash pipe butt welding machine welds a 12-in. standard gas or oil line pipe in 7 sec. and consumes 2.7 kw. hr. of electrical energy. This machine produces 40 such complete welds per hour and the machine requires five men in its operation, an average of eight welds per hour per man, the cheapest and most efficient method yet devised for welding together lengths of pipe.

To electrical engineers familiar with the regulative effect of resistance in series with the old time arc lamp, the external losses in the butt welding machine can be largely ameliorated on the grounds of the benefit derived from the regulative effect of external resistance. Take for example an arc operated at 10 amperes, through an external series resistance of 15 ohms, from a 220-volt circuit, having a normal counter e. m. f. at the arc of 70 volts. If the carbons are pulled apart to a point where the current is cut down to 8 amperes, the drop in the external resistance will be cut from 150 volts to 120 volts, leaving an additional 30 volts to be consumed by the arc, or a total of 100 volts at the arc with the 8 amperes flowing as against 70 volts with 10 amperes flowing. This means that a reduction of 20 per cent in current flowing has increased the voltage across the arc by 43 per cent. Hence the stabilizing action of resistance in series with the arc becomes apparent. In exactly the same manner, external impedance in a welding machine becomes an important regulative factor in stabilizing arcing in the flashing zone. In practise, however, it is seldom found necessary to purposely build external impedance into a welding machine, for under the most favorable conditions of design, it is usually sufficiently high. This is especially true of the reactive factor, and every precaution should be taken to cut this factor to the least possible amount. This can be accomplished in a great measure by paralleling as closely as possible the main secondary leads, and avoiding any interlinkage of this circuit with unnecessary parts which will set up a magnetomotive force opposed to the impressed e. m. f.

The power factor of butt welding machines always comes up for consideration. It varies over a wide range, even as wide as the range of application of the machines, ranging anywhere between 45 per cent and 75 per cent. If an average figure were to be hazarded it might be set at 65 per cent. The magnitude of the power factor is not the most important consideration on the part of the designer. It is the power engineer who is most concerned with power factor. The duration of the maximum peak load of the welding cycle is so short, being but a few seconds in the majority of applications, that neither the peak load nor the power factor is as objectionable as it has been thought. It is the universal experience of welding machine engineers, as they go about the country applying machines to industry, that where the nature of the machines are the least known, there is where the power engineers are the most skeptical of their effects to power lines. For example, a welding machine load is welcomed in Detroit, by the Detroit Edison Company as much as any other kind of load, and there is possibly no place in the world where a power company serves more welding machines totaling a greater kv-a.

A study of the current densities found in the normal area of the flashing zone shows that the density does not vary over such wide limits as might be supposed. Of course, if the study is extended to include the beginning of the flash, before normalcy of opposed areas is established, and before normal flashing is established, then the current densities as applied to the whole area, varies from zero to a maximum of approximately 9000 amperes per sq. in., the latter value being that just at up-set, and being dependent very largely upon the total impedance of the closed circuit. However, if the study be confined to the densities in the flashing zone, only after normalcy of flashing area has been established the limit

of the values are found to lie between 4500 amperes per sq. in. and 7500 amperes per sq. in. as the upper limit. That is to say with any density much below 4500 amperes per sq. in. of weldable steel, flashing will be very feeble, unproductive of heat, while with a value of current density approaching 7500 amperes per sq. in. of area of the flashing zone, a very violent flashing will take place, productive of incandescence, and representing in every way the upper limits of current density. If a fair average value is sought, it may be taken at

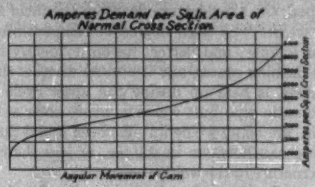


Fig. 3—Average Current Density in Flashing Zone, from Beginning of Flash to Upset

6000 amperes per sq. in. of cross section of weldable area. The curve in Fig. 3 shows the range of progress of current density, from the initial flash to the upset.

From the above considerations of the regulative effect of resistance in series with both the arc lamp and the flashing zone of a welding machine, it is apparent that a small increment of increase in the current density is accompanied by more than a direct proportional increment of increase in the necessary impressed e. m. f. It is apparent, therefore, that the power required to butt weld steel as well as other metals, can not be expressed with any degree of accuracy in terms of kilovolt-amperes per sq. in., (kv-a. per sq. in.) with the expectation of the figure holding good for a range of welding machines having different electrical characteristics. While the current density, as for example with steel, does not vary over such wide limits, the e. m. f. required to produce this density does vary over considerable range, depending entirely upon the electrical characteristics of the welding machine. The kv-a. required to weld a given section is dependent upon time. So there are three variables entering into the problem of power required per unit area, *i. e.*, current density, voltage, and time, and these three variables do not, as repeated tests have shown, vary by the law of direct or inverse proportions. This statement is especially true of the more recent highly intensified acceleration of the flashing cycle where areas of cross section approximating 16 sq. in. are welded by automatic power welders in, say, six seconds.

The result of feeding metal into the flashing zone of a flash butt weld is similar to the results obtained by feeding fuel into a furnace. If the furnace is supplied with sufficient oxidizing means, the faster the fuel is fired into the furnace the more heat is generated. This heat will show up in one or both of two ways. It will appear as increased temperature, or it may appear as a larger quantity of heat units liberated, or as is more probable, it will appear both as increased temperature and as a greater quantity of heat. Similarly with a flash butt weld, if sufficient welding e. m. f. is maintained, the faster the metal is fed into the flashing zone, the greater will be the heat set up. This will show up as increased temperature and also in the larger quantity of heat units produced, part of which is carried away by the flashing materials thrown off, part of which is carried away by convection due to the higher temperature gradient, and a small part of which is directly radiated away.

The critical part of the flashing cycle is usually found to be at the beginning. If sufficient energy is available to start the flashing at uniform speed until normalcy of areas are presented, there is little danger from cessation of flashing, due to freezing at points later on in the flashing cycle. The flashing cam used in the average automatic butt welding machine seldom has an acceleration greater than 3 : 1. In a few extreme instances the acceleration approaches 3½ : 1. It has recently been found that a very much greater ratio of acceleration is possible. The larger ratio is not only possible, but very desirable, if not necessary. In Fig. 4, are shown graphs of two cams, *A* & *B*. The cam, *A*, is constructed with equal increments of rise for equal increments of angular movement. In other words it is a straight line, forming an angle, $\beta$, with the horizontal base line. The cam, *B*, is a logarithmic curve. It is constructed so that the tangent, $\theta$, is approximately eight times greater than the tangent, $\Delta$, thus producing a final acceleration, eight times greater than the initial speed. The initial move-

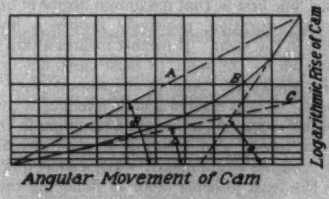


Fig. 4—Graphs of Two Butt Welder Flash Cams

Cam *A* produces uniform motion. Cam *B* produces logarithmic acceleration

ment is taken at the safe maximum speed insuring against freezing. The tangent of the angle, $\Delta$, in this graph is 0.192, while the tangent of the angle, $\beta$, is 0.5151. Therefore if cam, *A*, is to replace cam *B*, the angular velocity of cam, *A*, will have to be slowed down in the inverse ratio of 0.192 : 0.515, or in the ratio of 2.68 : 1. Therefore from a standpoint of time, the cam, *B*, will perform a given flashing cycle in 7½ sec., while cam, *A*, will require 20 sec., to perform the same flashing cycle. The saving in time by the use of the

form of cam, *B*, over that of cam, *A*, is only a part of the benefits derived by its use. The saving in time is in fact only incidental. The benefits lie in the shortened time of the flash produced by the high acceleration of the metals into the flashing zone, which in turn produces the maximum degree of temperature in the shortest possible time, providing the least possible "run-back" of heat. From these two conditions are derived two important

Fig. 5—Photomicrographs of Pipe Butt Weld

A—Complete section, wall of pipe butt weld
B—Complete section, taken to right of weld
C—Taken in the weld
D—Taken to left of weld

results. The first is, that maximum degree of heat with momentary duration, positively insures a fine grain structure in the weld. It further insures a thin lamination effected by the weld, in most cases not exceeding 0.001 in. thickness. And in the second place a short "run back" of heat insures a small swelling at the upset. The former condition, a fine grain structure in the weld, insures a tensile and bending strength equal to or greater than the virgin metal; while a short quick upset insures the least possible labor in removing the excess material.

The photomicrographs in Fig. 5, show an automatic pipe butt weld made in six seconds, the wall of the pipe being ⅜ in. thickness. Graph *A* of Fig. 5 is of low power and is intended to be a bird's eye view of the whole section. Graph *B* is of higher magnification, showing the virgin structure of the pipe to the right of the weld. Graph *C* is of the same magnification, showing the grain structure in the weld, while Graph *D* shows the grain structure to the left of the weld. Hundreds of photomicrographs have been made of this type of weld, and all show the same fine grain structure in the weld. This condition can seldom be secured by slow flashing and upsetting.

The time required for upsetting is as important as the degree of acceleration and the time required for the flashing cycle. Here again, tests have shown that the quicker and sharper the upset action has been, the more complete and perfect has been the fusion in the weld. If the upset is made slowly, it must then be forced to a much greater degree to form a good weld, and the weld will be accompanied by an objectionable amount of squeezed out material. It is evident from a study of welds made with varying lengths of time in upsetting, that the instant the abutting pieces touch, and flashing is stopped, the temperature drops on the inner surfaces of the weld. The high degree of temperature necessary for fluidity, and perfect fusion, evidently falls the instant flashing ceases, and it does so whether the welding current is held on during the upset cycle or not. In automatic pipe butt welding, where areas as large as 16 sq. in. are being welded, it has been found that if the upsetting can be done in 0.1 sec. or less the required grain structure in the weld is preserved.

It is a difficult problem to design a combined flashing and upsetting cam to weld the larger areas. Two problems are presented. The first problem is to be able to make the comparatively slow moving flashing cam perform the upset in the short space of time, and the second problem is to be able to design this slowly moving cam so it can exert the necessary foot pounds required to upset the weld. Take for example a combined flash and upset cam shown in Fig. 6. If such a cam is designed to flash and upset three sq. in. of steel, it may be found advisable to make the minimum radius about 4½ in. Permitting an idle zone from *O* to *D*, the active flashing portion of the cam extending from *D-E* & *C*, will cover about 270 deg. If the cam is provided with ½ in. of upset at *C*, and the cam roller is 4 in. minimum diameter, the main cam will have to turn approximately

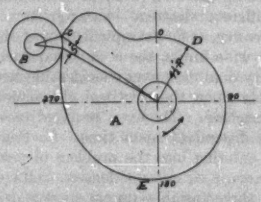


Fig. 6—Typical Combination Flash and Upset Cam, Used for Small Cross-Sections

5 deg. to complete the upset. If the upset takes place in 0.1 sec., it will require 5.4 sec. to complete the flashing cycle, (270 deg.) or 7.2 sec. for the cam to make one complete revolution. The cam chosen probably illustrates quite fairly, average design proportions for a combination flashing and upsetting cam used on welding machines up to three sq. in. capacity. However, for welding considerably larger sections, even three or four

times that of the above, or where for example an area of 36 sq. in. must be flashed and upset automatically, the above combination cam can no longer be made to meet the necessary requirements. Heretofore all such sections have been flash butt welded by hydraulic power. To accomplish this by motor power fully automatic, it has been found necessary to introduce into the welding machine two systems of cams. One system is confined to the flashing cycle, and the other is confined to the upsetting cycle. The flashing cycle requires, inherently, from fifty to one hundred times more time than the upsetting cycle. At the same time it requires only a fractional part of the energy required

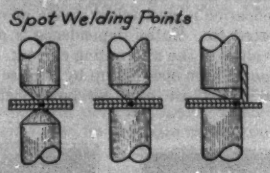


Fig. 7—Typical Spot Welding Electrodes

for upsetting. When the two systems are used the upsetting cam is timed or synchronized with the flashing cam. With this arrangement the speed of the flashing cam can be varied at will, or the amount of the flashing cam permitted to become operative can be varied without effecting the time of the upset cycle. The amount of flashing, of course, is dependent upon the relative time that the upset cam functions. Two large butt welding machines have been constructed along this line, one welding up to 16 sq. in., and the other welding up to 36 sq. in., and both have proved beyond doubt the correctness of the principle. (This feature is being protected by patents.)

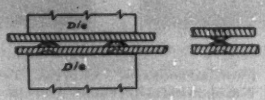


Fig. 8—Methods used in Projection Welding, Showing Electrodes

## II. Spot Welding

Spot welding, while not so old as butt welding, has now been practised for many years, and it is accomplished essentially by the use of two copper electrodes, variously formed as in Fig. 7. The electrodes thus formed are on opposite sides of overlapping sheets, and a powerful current of short duration is passed from electrode to electrode, passing through the sheets. The magnitude of the current is so proportioned that the sheets are heated to plasticity, whereupon an extra force is exerted upon the sheets by the electrodes, and they are forced together and thus welded. The area thus welded is usually small, ranging from 1/8 in. diameter up to extreme diameters of about 1/2 in., depending upon the plate thickness, quality of plate, etc.

The current density required for welding by this method varies much with the thickness of the sheets, quality of the sheets, diameter of the points, and the time of duration. For a rough comparison between spot welding and butt welding a factor of 20 might be taken as giving fair average conditions. That is to say a current density of about 120,000 amperes per sq. in. of spot weld area is required. This figure can be used only for rough calculations, and a closer figure can be given only by one experienced in these requirements.

An improvement over the old method of spot welding has come into use, known as projection welding. In this case plain flat electrodes are used above and below the sheets to be welded, as in Fig. 8. Before welding, one or both of the plates are projected by a forming die. At the left in Fig. 8 only one plate, the lower one, is projected, while at the right both plates are projected.

The essential thing to secure in both spot welding and projection welding is proper heat control. A large

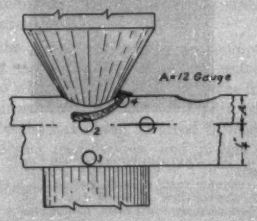


Fig. 9—Plat of Photomicrographs, Typical Spot Weld

majority of these welds either show burning or they are overheated to such an extent as to show a very poor grain structure. Fig. 9 shows diagrammatically a typical weld between a No. 12 gage polished cold rolled sheet and a 1/4-in. cold rolled sheet. The upper electrode was pointed, while the plates rested upon a flat lower electrode, both shown in part only. Photograph A in Fig. 10 was taken at (1) in Fig. 9. It shows the longitudinal laminations caused by rolling the sheet. The upper dark band is the small open space between the sheets darkened by the copper etching solution. Photograph B taken at position (3) low down in the sheet next to the lower electrode, shows overheating, poor arrangement of grain structure, and even burning. Position (2) was very similar to position (3), and for brevity has been omitted. Photograph C of position (4), taken right under the upper electrode, shows the cooling effect of contact with the upper electrode by the band adjacent to it, leaving the rolling laminations plainly visible. Overheating is shown lower down, however, and in the extreme lower corner burning is in evidence.

The recently developed methods of "flash spot welding," and "flash projection welding," entirely eliminate all tendency toward burning, and insure a fine grain structure, accompanied by an entire rearrangement of crystals of the most favorable nature. The photomicrographs in Fig. 11 show typical flash projection welds made between two twelve-gage cold rolled sheets. Three of these photographs show the same weld using three different powers of magnification. These three were taken without changing the axis of the field of the microscope. The microscope was focused at the very extreme edge of the weld. The curved shape of the projection is plainly visible.

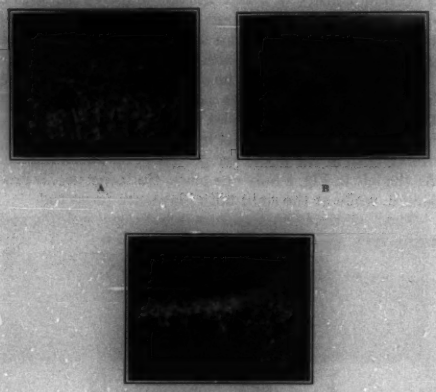


Fig. 10—Photomicrographs of Flash Weld

A—Showing virgin sheet at position (1) in Fig. 9
B—Showing effect of current, position (3)
C—Showing effect of current, position (4)

Flash spot welding and flash projection welding accomplish in this field, exactly what the rapidly accelerated flash and quick upset accomplish in the field of butt welding. Both are dependent upon the theory that high heat, quickly secured, and held for a short duration only, will invariably produce a fine-grain structure in the weld.

## III. Seam Welding

It is not felt necessary to go into the theory or application of seam welding at this time. The process in short is a refined application of spot welding. In place of pointed electrodes, as in spot welding, the electrodes are usually formed like wheels. These wheel electrodes are caused to roll on opposite sides of overlapping plates, and a rapid succession of welds is made in this way. The circuit may be interrupted rapidly by mechanical means, as is usually the case in welding stock coated with scale or otherwise unclean, while in welding polished cold rolled sheets it is quite generally the practise to omit the interruption of the circuit, depending in this event upon the cyclic interruption caused by the alternating current. The process in general finds application in welding cans, automobile gas tanks, and various other receptacles of this kind. A highly refined application of seam welding is to be found in the manufacture of light wall steel pipe and tubing. In this application a mechanical means of interruption is not resorted to. Entire dependence is placed upon the cyclic values of the alternating current. The process has recently been speeded up by the use of frequencies higher than those used for power purposes. In this application each alternation forms a weld or "stitch." The metal is passed at a speed which causes the welds to overlap just enough to insure a completely welded seam.

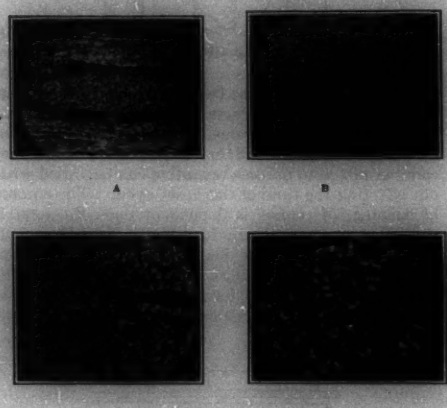


Fig. 11—Photomicrographs Showing Typical Flash Projection Welds with Different Powers of Magnification

The author desires to thank Mr. Paul C. Zarrs, Chief Engineer, The General Welder Company, for valuable suggestions, and for assistance in producing the photomicrographs herewith shown.

# Starting Performance of Salient-Pole Synchronous Motors

BY T. M. LINVILLE*

Associate, A. I. E. E.

*Synopsis.—This paper presents an analysis of the sub-synchronous speed phenomena of a salient pole synchronous motor in which formulas and equivalent circuits are developed, making it possible to calculate the torque and current for a broad range of conditions. Equations in terms of the impedances of the direct and quadrature axes are first derived from the revolving field point of view. The equivalent circuits for the two axes are then set up and expressions for the separate impedances of the circuit elements established. Adequate means of taking into account the combined effects of salient poles, incomplete amortisseur windings, and open or closed field windings are presented.*

*The results obtained are illustrated by a comparison of the predicted performance and test data for a large 60-pole motor. The calculated distribution of current between the amortisseur bars of the same motor is shown by curves. Other curves show the calculated performance of the motor with and without continuous end rings between the poles and with the field winding open and closed. A final example shows the theoretical effects of changing the positions of the bars in the poles of a large waterwheel generator.*

* * * * *

## I. Introduction

THE extensive application of synchronous motors in fields with diverse starting requirements has created a need for accurate methods of predicting their starting characteristics. However, despite the rapid developments in their use, no adequate means for the predetermination of the accelerating torques and currents of commercial motors has heretofore been published. Many important papers dealing with this general question have been presented, but all have been based on more or less arbitrary assumptions which have seriously limited the generality and the usefulness of the methods.

Particularly important contributions have been made by Fechheimer,[5] Putnam,[10] and Mauduit,[11] the first named having developed simple approximate formulas for the starting characteristics, Putnam having introduced methods of allowing for the effects of salient-poles, and Mauduit having attempted to calculate the effect of incomplete windings. However, none of these methods permits accurate determination of the combined effects of pole shape, arbitrarily disposed amortisseur windings, and closed field windings. The methods described in this paper are believed to be adequate for the predetermination of the starting performance of any practical salient-pole synchronous motor.

The method of analysis employed is first to derive current and torque equations in terms of the impedances of the direct and quadrature axes of the machine, and then to set up complete equivalent circuits for the armature, field, and amortisseur windings in each axis, from which the impedances of the two axes can be calculated. The general equations have already been given by Park,[5] in his paper on *The Two Reaction Theory of Synchronous Machines*, formulas (42) to (47). They are here derived from a physical point of view, whereas he derived them wholly by the use of operational mathematics. The equivalent circuits for the two field axes are believed to be novel, and are quite interesting, as they involve the consideration of the mutual and differential leakage reactances of several dissimilar windings linking parts of a magnetic circuit of non-uniform permeance.

Within the limitations of the few assumptions listed in the next section, which are almost universally employed, and which are approximately true for commercial machines, the method is highly dependable. Excellent results have been obtained through its use in practical design calculations, and it has afforded a means for studying the effects of the various factors which influence starting performance, in a way not heretofore possible. Examples of the application of the method are given in the concluding section of the paper.

## II. Assumptions

1. The armature conductors are effectively sinusoidally distributed in each phase. That is, the mutual inductance of the armature and field circuits is considered a first harmonic only with respect to the electrical space angle. If it is desired to correctly allow for the harmonics due to the armature winding, they can be represented by separate equivalent circuits in series with the fundamental as described by Arnold.[12]

2. Saturation and hysteresis are negligible. As saturation exists, to some degree, in practically all commercial machines, it is necessary, in view of this assumption, to use the results with judgment. Where saturation must be accounted for, judicious shading of the results will allow the method to be used with good accuracy.

## III. Per-Unit Representation of Quantities

All quantities are expressed as a fraction of their normal values and when so expressed are termed

*Engineering General Dept., General Electric Co., Schenectady, N. Y.

5. For references see Bibliography.

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per-unit quantities.[4] Normal or unit quantities are defined as follows:

Unit voltage is normal rated phase voltage.

Unit current is normal rated phase current.

Unit torque is the torque of normal three-phase power.

Unit m. m. f. is the m. m. f. produced by the equivalent square wave value of armature reaction due to normal three-phase current. Hence, expressed in ampere-turns,

$$A = \text{unit m. m. f.} = \frac{3\,N\sqrt{2}\,I}{2\,P}$$

where $N$ is the effective number of armature turns, and $P$ is the number of poles.

Unit flux is the sine wave fundamental of normal field flux which rotating at synchronous speed generates unit voltage. Hence,

$$\phi_f = \text{unit flux} = \frac{\sqrt{2}\,E}{2\,\pi\,f\,N\,10^{-8}}$$

Unit impedance is that impedance through which normal voltage at normal frequency causes normal current to flow. In terms of unit m. m. f. and unit flux, unit impedance equals

$$\frac{3\,\pi\,f\,N^2\,\phi_f\,10^{-8}}{A\,P}\ \text{ohms.}$$

Unit speed is synchronous speed.

## IV. Torque and Current Equations

Since the total m. m. f. or current of a synchronous motor, operating at any sub-synchronous speed, is composed of components, pulsating at slip frequency in the direct and quadrature axes, it may be resolved into two rotating currents, one going forward and the other backward over the poles at $s$ times synchronous speed, where $s$ is the per-unit slip. Since the per-unit velocity of the poles is $(1 - s)$, the forward current moves at a per-unit speed $(1 - s + s)$ or (1) and the backward component rotates at a per-unit speed of $(1 - s - s)$ or $(1 - 2\,s)$.

The forward current is,

$$i_f = 1/2\,(i_d + i_q), \tag{1}$$

and the backward current is,

$$i_b = 1/2\,(i_d - i_q) \tag{2}$$

where $i_d$ and $i_q$ are the components of total armature current in the direct and quadrature axes, respectively, each referred to its individual axis, 90 deg. from the other.

The procedure now is to determine the voltage produced in each phase of the armature winding by these currents. Both may be resolved into stationary pulsating currents in the two rotor axes. When all quantities are expressed as per-unit values, flux is the product of current and impedance, and voltage is the product of flux and frequency. Hence, the pulsating air-gap fluxes in the two axes of the machine may be determined in terms of the currents and the impedance of each axis. Then, when these are resolved into total forward and backward rotating fluxes and each is multiplied by its respective speed of rotation, the voltages produced in the armature are found to be, a forward voltage,

$$e_f = \left[\, i_f\,\frac{z_{ad} + z_{aq}}{2} + i_b\,\frac{z_{ad} - z_{aq}}{2}\,\right](1), \tag{3}$$

and a backward voltage,

$$e_b = \left[\, i_f\,\frac{z_{ad} - z_{aq}}{2} + i_b\,\frac{z_{ad} + z_{aq}}{2}\,\right](2\,s - 1) \tag{4}$$

where $z_{ad}$ and $z_{aq}$ might be termed the impedances of armature reaction, since they correspond to the commonly used reactances of armature reaction, namely, $x_{ad}$ and $x_{aq}$.[4] These reactances are the particular values of $z_{ad}$ and $z_{aq}$, respectively, at synchronous speed.

As the machine is assumed to be connected to a bus of sine wave voltage, of sufficient capacity to maintain balanced voltages at normal frequency, the impressed voltage, $e_o$, must be balanced by the sum of the voltage, $e_f$, and the stator impedance drop due to the forward current. Also the summation of voltages, having a frequency of $(1 - 2\,s)$ in the armature circuits, must be zero. Hence;

$$e_o = 1 = i_f\,\frac{z_{ad} + z_{aq}}{2} + i_b\,\frac{z_{ad} - x_{aq}}{2} + i_f\,(r_1 + j\,x_1) \tag{5}$$

and,

$$O = i_f\,\frac{z_{ad} - z_{aq}}{2} + i_b\,\frac{z_{ad} + z_{aq}}{2} + i_b\left[\,\frac{r_1}{2\,s - 1} + j\,x_1\,\right] \tag{6}$$

These equations may now be solved simultaneously for $i_f$ and $i_b$, but the solution may be greatly simplified by substituting the terms,

$$z_d = z_{ad} + r_1 + j\,x_1 \tag{7}$$

$$z_q = z_{aq} + r_1 + j\,x_1 \tag{8}$$

$$z_d' = z_{ad} + \frac{r_1}{2\,s - 1} + j\,x_1 = z_d + \left[\,\frac{r_1}{2\,s - 1} - r_1\,\right] \tag{9}$$

$$z_q' = z_{aq} + \frac{r_1}{2\,s - 1} + j\,x_1 = z_q + \left[\,\frac{r_1}{2\,s - 1} - r_1\,\right] \tag{10}$$

Substituting these relations and solving,

$$i_f = \frac{z_d' + z_q'}{z_d\,z_q' + z_d'\,z_q} \tag{11}$$

$$i_b = \frac{z_q' - z_d'}{z_d\,z_q' + z_d'\,z_q} \tag{12}$$

At 50 per cent speed these equations are indeterminate but here,

$$i_f = \frac{2}{z_d + z_q}$$

$$i_b = 0$$

The impedances $z_d$ and $z_q$ are determined by equivalent circuits which are established in the next section.

The derivation of the equations will be made clearer by outlining the procedure as follows:

1. Resolution of the stationary, pulsating m. m. fs. in each axis of the machine into forward and backward rotating components, $i_f$ and $i_b$.
2. Resolution of these rotating m. m. fs. into stationary pulsating components in each axis of the machine, returning to the original condition but now having the pulsating m. m. fs. split into components in terms of $i_f$ and $i_b$ in each axis.
3. Determination of the pulsating air-gap flux components as the product of the m. m. fs. with the impedance of armature reaction in each axis.
4. Resolution of the fluxes into rotating flux waves.
5. Calculation of the voltages produced in the stator by the rotating flux waves.
6. Solution of the stator voltage equations for the currents $i_f$ and $i_b$.

The average power transferred to the rotor is the real part of the vector product of the forward (impressed) voltage and the forward current, minus the stator losses, hence,

$$P_{av} = e_f \cdot i_f - i_f^2 r_1 - i_b^2 r_1/(1 - 2s) \qquad (13)$$

and, as per-unit torque is equal to per-unit power, the average torque is,

$$T_{av} = \text{real of } i_f - i_f^2 r_1 - i_b^2 r_1/(1 - 2s) \qquad (14)$$

These two equations are given by Park.[8]

## V. Equivalent Circuits to Determine the Impedance of Each Axis

To evaluate the equations for torque and current it is necessary to determine the impedances, $z_{ad}$ and $z_{aq}$. Each of these impedances is the impedance offered to a m. m. f. sinusoidally distributed along the surface of the stator across the pole pitch, pulsating sinusoidally with respect to time at slip frequency. The variation in the air-gap, the amortisseur bars, the field circuit, and the pole structure are symmetrical, in one axis about the center line of the pole, and in the other axis about the center line between poles. The stator m. m. f. is also symmetrically distributed about the same center in each axis. Consequently the impedance of either axis may be determined as a multiple circuit transformer problem using an equivalent circuit.

As the amortisseur bars are often of different shape, size, and material, having an unknown current distribution, they cannot be considered together as one circuit but the two bars adjacent to the center line of each axis can be so considered. The next two adjacent bars may be considered as a second circuit, and so forth until all of the bars are accounted for. Thus instead of a single circuit formed by the amortisseur winding, there is a number of nested circuits, all symmetrical about the center line in each axis. The determination of rotor impedance then, as a transformer problem, involves a sinusoidally distributed primary winding, an irregular air-gap in the magnetic circuit, and a multiple number of nested secondary circuits.

Consider the stator winding in the direct axis. The voltage impressed on this winding will always be balanced by the resistance drop and by the self-induced voltage due to the flux which the winding creates. This flux is divided into two components, *i. e.*, the leakage flux and the flux which crosses the air-gap and is mutual with the rotor circuits. Hence, the stator winding is represented by a circuit composed of a resistance and two reactances in series as shown in Fig. 2A. The formulas by which these impedance elements are calculated are given in Appendix A.

Now consider any rotor circuit. The stator flux which is mutual with this circuit (that is the stator flux which links the circuit) may be calculated by considering the span of the circuit and the distribution of the stator flux across this span. The method is demon-

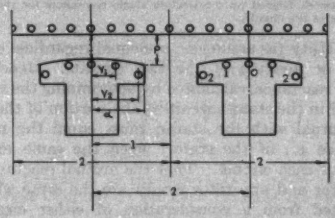



Fig. 1—Magnetic Structure of a Salient-Pole Synchronous Motor

strated in Appendix B. The mutual reactance of the stator with the rotor circuit may then be determined by calculating the voltage in the rotor due to the mutual flux which exists when unit current* flows in the stator. The mutual flux is, of course, a part of the total air-gap flux and the mutual reactance is therefore a portion of the reactance due to this total flux. It is illustrated by the reactance $x_{ab}$ in Fig. 2A. The air-gap flux set up when unit current flows in the stator and the portion of it which is mutual with a rotor circuit of span $y_1$ is shown in Fig. 3A.

In order to establish an equivalent circuit, representing the complete axis of the machine, every circuit in the axis must be placed on the same base. This can be done if unit current for any circuit is taken as that current which produces a definite m. m. f., since by calculating their impedance constants on the basis of the same m. m. f. any number of circuits may be joined into an equivalent network.

Now consider that a current producing an arbitrarily

*Reactance is usually calculated on the basis of a unit current of one ampere, giving the result in ohms. The unit current spoken of in this section of the paper is, therefore, a current of one ampere and unit m. m. f. is the m. m. f. resulting therefrom. These unit quantities are not to be confused with those defined in Part III which are for a complete 3-phase machine.

chosen unit m. m. f. flows in any rotor circuit. A portion of the resulting flux is mutual with the stator, a portion of it is leakage flux, and some is mutual with other rotor circuits. The portion which is mutual with the stator must induce the same per-unit voltage in the stator circuit as the stator flux mutual to the rotor, induced in the rotor circuit. This is because the mutual inductances of two circuits, in a medium of constant

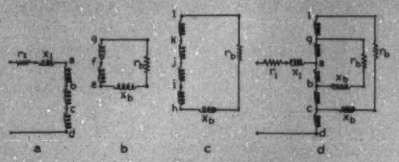


FIG. 2—EQUIVALENT CIRCUITS OF A SYNCHRONOUS MOTOR

a. Equivalent circuit for the armature winding
b. Equivalent circuit for a rotor winding of pitch $y_1$
c. Equivalent circuit for a rotor winding of pitch $y_2$ ($y_2 > y_1$)
d. Network formed by substituting single reactances for the mutual reactances of the circuits

permeability (as assumed), are equal regardless of size, shape, or position of the two circuits. Hence, the mutual reactance, calculated by determining the voltage induced in the stator circuit by the portion of the rotor flux mutual with the stator, must equal the mutual reactance $x_{ab}$ of the stator, when the same m. m. f. exists for each circuit. That the mutual reactances of the stator and any rotor circuit are the same whether calculated from a consideration of either circuit is demonstrated in Appendix A.

All of the flux created by a rotor circuit which does not cross the air-gap is considered as leakage. Of the flux which crosses the gap only a portion is effective in establishing a reaction in the stator winding. That is, due to the fact that the turns of the stator winding are assumed to be sinusoidally distributed, only the fundamental of the flux wave set up by the rotor circuit is mutual with the stator. However, the entire flux is mutual with all rotor circuits outside of (having a greater span than) the one being considered. Hence, the flux mutual to the stator is different from that mutual to other rotor circuits by the amount of the harmonic fluxes, other than the fundamental, existing in the flux wave. These harmonic fluxes give rise to reactances usually termed differential leakage. The air-gap flux produced when unit m. m. f. exists in a rotor circuit of span $y_1$ is illustrated in Fig. 3B.

Letting unit m. m. f. exist in the circuit, the leakage reactance may be calculated by determining the voltage induced in the circuit by the leakage flux. The voltage induced by the total flux crossing the gap may next be calculated giving the reactance which is mutual to all outside rotor circuits. The rotor circuit is then as shown by Fig. 2B where the reactance, $x_{ag}$, is the reactance due to the total flux crossing the gap, $x_b$ is the reactance due to the leakage flux, and $r_b$ is the resistance of the circuit. The fundamental of the total air-gap flux may next be calculated, and the reactance due to it, which is the mutual reactance of the stator and the rotor circuit, determined. This is naturally a portion of the reactance $x_{ag}$ and is shown in Fig. 2B as $x_{af}$.

Any other rotor circuit of greater span will consist of the same reactances calculated in the same way except that the mutual reactances will be greater. Such a circuit is shown in Fig. 2C where, $x_{bl}$, is the total reactance due to the flux crossing the air-gap and is mutual to all outside rotor circuits; $x_{bf}$ ($= x_{ac}$) is the mutual reactance of the circuit with the stator winding; $x_b$ is the leakage reactance; and $r_b$ is the resistance. The mutual reactance with an inside circuit is again determined by considering the distribution of the flux and the

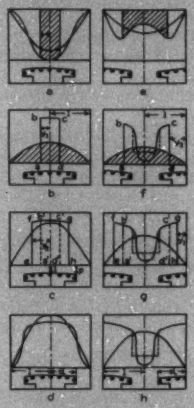


FIG. 3—APPROXIMATE AIR-GAP FLUX WAVES AND THEIR FUNDAMENTALS

Established by unit m. m. f. in the various windings, each acting alone
a. Armature winding—direct axis
b. Rotor winding of pitch $y$-1—direct axis
c. Rotor winding of pitch $y$-2—direct axis
d. Field winding
e. Armature winding—quadrature axis
f. Rotor winding of pitch $y$-2—quadrature axis
g. Rotor winding of pitch $y$-1—quadrature axis
h. Rotor winding of pitch $y$-0—quadrature axis

Dotted lines in the quadrature axis diagrams show the assumed flux distribution based on the reduction of the interpolar space to an equivalent uniform gap

span of the inside circuit. The mutual flux is naturally equal to the mutual flux created by the inside circuit, as the m. m. f. of this circuit is the same and the magnetic path is identical. This is illustrated by the equal areas $a\,b\,c\,d$ and $a'\,b'\,c'\,d'$ in Figs. 3B and 3C respectively. The mutual reactance is illustrated by $x_{ab}$ in Fig. 2C ($= x_{ag}$) Fig. 2B.

Circuits have now been set up for the stator winding and an indefinite number of rotor circuits. It remains to combine these into an equivalent single network. One reactance may be used to replace any two mutual reactances of any two circuits. Hence, replacing every

pair of mutual reactances by single reactances, the stator winding and the rotor circuits join to form the equivalent network of Fig. 2D.

The network representing the quadrature axis is established in the same fashion and is identical. The only difference between the two axes is that the calculation of the circuit constants for the quadrature axis involves consideration of the interpolar space, which is more difficult than a consideration of the uniformly varying air-gap over the pole face. The treatment of the quadrature axis is given in Appendix B.

In order that the flux involved in the calculation of each reactance may be clearly understood, the following table is presented giving the relation between the reactance elements of Fig. 2D and the areas of the flux diagrams in Fig. 3.

| Reactance | Flux |
|---|---|
| $x_{ab}$ | Shaded area Fig. 3A for $y_1$ = shaded area Fig. 3B |
| $x_{ac}$ | Area beneath flux wave Fig. 3A for $y_2$ where $y_2 > y_1$ = area of fundamental Fig. 3C |
| $x_{bc} = x_{ac} - x_{ab}$ | (Area beneath flux wave of Fig. 3A for $y_2$) − (area beneath flux wave, Fig. 3A for $y_1$) where $y_2 > y_1$ |
| $x_{ad}$ | Area of fundamental Fig. 3A |
| $x_{bg}$ | Area $(a\ b\ c\ d)$ Fig. 3B = area $(a'\ b'\ c'\ d')$ Fig. 3C |
| $x_{ag}$ | [Area $(a\ b\ c\ d)$ − area of fundamental Fig. 3B] = [area $(a\ b\ c\ d)$ Fig. 3B − shaded area for $y = y_1$ in Fig. 3A] |
| $x_{e1}$ | Area $(e\ f\ g\ h)$ Fig. 3C |
| $x_{a1}$ | [Area $(e\ f\ g\ h)$ Fig. 3C − area of fundamental Fig. 3C] = [area $(e\ f\ g\ h)$ Fig. 3C − area beneath flux wave of Fig. 3A for $y = y_2$] |
| $x_{g1}$ | $x_{a1} - x_{ag}$ |

The table has been made showing the relation between the reactances of Fig. 2D and the areas of the flux waves produced by the direct axis circuits. The relations between the flux waves produced by the quadrature axis circuits and the elements of Fig. 2D, when the network is applied to this axis, is given by the same table when Figs. 3A, 3B, and 3C are replaced by Figs. 3E, 3F, and 3G, respectively.

A brief review of the method used to establish the equivalent network representing either axis of the machine will be helpful. Each circuit is considered separately using an arbitrary unit m. m. f. on which to base the calculation of its constants. Letting the unit m. m. f. exist in any particular circuit, the flux is divided into two components, the leakage and the mutual fluxes, and the reactances due to each are calculated separately. The parts of the remaining flux mutual with other circuits are then found and the corresponding reactance determined. In this manner each circuit is determined in terms of its leakage and mutual reactances. The mutual reactances of two circuits with respect to each other may be replaced by a single reactance so that, by applying this rule, the separate circuits join to form the network of Fig. 2D.

That any number of inductively coupled circuits can be joined into a network by replacing their mutual reactances, with respect to each other, by common reactances can be demonstrated provided all of the circuits are in a medium of constant permeability. This demonstration is proof of the fact that the equivalent network of Fig. 2D exactly represents each axis of a synchronous machine having separate, nested, rotor circuits. To make the network general it must be extended as described in the following discussion.

All of the air-gap flux across the pole face is assumed to link the field circuit and unless there are bars in the interpolar space this circuit has the maximum span. So long as all of the bars are in the pole face, the network of

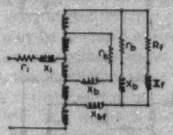



FIG. 4—EXTENSION OF THE EQUIVALENT CIRCUIT TO ALLOW FOR MUTUAL COUPLING OF THE POLE TIP BARS AND THE FIELD WINDING

Fig. 2D exactly represents either axis of the machine. When bars are in the pole tips, however, the rotor circuit formed by them has the same mutual reactance with the stator and all inside bar circuits as the field circuit. That is, careful calculations have failed to show an appreciable difference for practical dimensions of the magnetic structure. When the bars in the pole tips are well below the pole face, as shown in Fig. 1, some of the field leakage flux passing between the tips of adjacent poles will link the bar circuit when the distance between the pole tips is sufficiently small. Consequently, in some cases there is a mutual reactance* between the pole tip bars and the field. The portion of the field leakage flux linking these bars may be calculated and will, of course, result in the same reactance in the bar circuit as in the field. Hence, to make the network general, including the case of pole tip bars, this mutual reactance of the bars and field must be added, as shown in Fig. 4, where it is illustrated as $x_{bf}$. As the field leakage reactance, calculated by the formula given in Appendix B, includes the total pole tip flux it is necessary to subtract from it the reactance which is mutual with the pole tip bars. The field circuit is naturally non-inductive in the quadrature axis so that the network for this axis

*This reactance is in addition to the mutual reactance which is due to the flux completing the magnetic circuit through the armature iron.

is unaltered. In practical calculations, $x_{bf}$ may be assumed zero. It is, therefore, omitted in the circuit shown in Fig. 5A.

The circuits (as illustrated) exactly represent an actual machine having individual end rings for every pair of symmetrically placed bars; that is, a machine having truly nested rotor circuits. In an actual machine the resistance drop in the end ring of any bar circuit is common to all other bar circuits. These mutual resistances of the bar circuits may be exactly represented by resistances placed in the network as shown in Figs. 5B and 5C. In the direct axis, Fig. 5B, the resistance is not mutual to the field winding. Therefore, the field circuit is connected across its mutual reactance with the stator as a separate circuit. This involves a slight approximation, since it destroys the proper mutual reactance between the field and the amortisseur bar

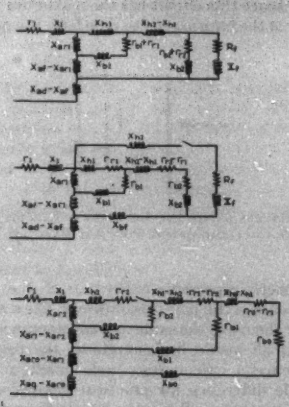


FIG. 5—COMPLETE EQUIVALENT CIRCUITS

a. Direct axis circuit suggested for practical calculations
b. Alternating direct axis circuit
c. Exact circuit for the quadrature axis

circuits. The author's experience in making calculations substantiates the conclusion that it is more accurate to assume the amortisseur bar circuits to be truly nested circuits having individual shielded end rings, except in cases of very low rotor frequency. Hence, the end ring resistance is added to the bar resistance in the equivalent circuit, shown in Fig. 5A, which is suggested for practical use. The neglect of the mutual effect of end ring resistance is based on the fact that it is a factor of less importance than the proper mutual reactance of the field winding and the bar circuits. The reactance $x_{A3}$ is the difference between the reactance due to the total field flux which crosses the air-gap and that due to the fundamental of this flux. The latter reactance is the mutual reactance with the stator as is brought out in the discussion of rotor circuits in general.

There is a certain amount of end ring leakage reactance which is mutual to all of the rotor bar circuits. This can be taken care of in the same way as the end ring resistance, and, consequently, can either be considered in calculating the reactances $x_{A1}$, $x_{A3}$, etc., in the circuits of Fig. 5 or added to the bar reactance $x_b$. In most cases it is entirely negligible.

Although no formulas are given for calculating the constants of an equivalent circuit for a pole collar, the existence of which would necessitate an additional branch of the network, the procedure in developing the formulas and the circuit would be exactly similar to the treatment of the field winding. It has been found that where a pole collar is situated at the base of the pole its reactance may be sufficiently high so that its influence on torque and current is slight. Eddy currents in the rotor spider have also been found to have slight effect as the branch of the network which can be developed to represent them is of high impedance in most cases. Eddy currents in the poles themselves have relatively little effect on torque. They have been neglected in this presentation. The method, however, can include these factors.

As the field circuit may be either opened or closed, a switch is placed in the field winding branch of the direct networks, Figs. 5A and 5B. The resistance in this branch includes any external resistance through which the field may be closed.

Also, as the end rings may or may not be continuous between poles, a switch is placed in the portion of the quadrature axis network representing the circuit formed by the pole tip bars. The condition of open end rings (incomplete squirrel cage) has no effect on the network other than opening the switch illustrated in Fig. 5C.

In Fig. 6 the circuit is extended to the case of a double squirrel-cage winding. The circuits formed by the upper and lower bars in any pair of symmetrically placed slots have the same mutual reactance with the stator windings. A portion of the leakage flux of each links the other, causing a mutual reactance between the bars which is greater than the mutual reactance with the stator. As the leakage reactance of each circuit is calculated including this additional mutual reactance, the latter must be subtracted. The remaining reactances plus the bar resistances form the circuit impedances, which are connected in parallel with the mutual reactance in series as shown in Fig. 6.

The final proof of the equivalent circuits is the fact that they satisfy the voltage or flux linkage equations which can be written for the separate circuits of the machine.[8] These equations are not written here since it is considered more appropriate to establish the circuits on physical reasoning, of which the equations are simply a mathematical expression.

## VI. RESULTS

Appendices give the formulas and curves by A and B

which the separate impedances of the circuit elements for the direct and quadrature axis circuits, respectively, are calculated. The calculation of these circuits gives the factors $z_d$, $z_q$, $z_d'$, and $z_q'$ needed to evaluate Equations (11) and (12), determining the currents $i_f$ and $i_b$. The results may then be used to evaluate Equation (14) for torque. The direct axis impedances, $z_d$ and $z_d'$, are calculated from identical circuits except for the

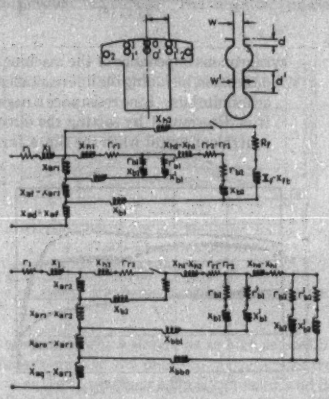


Fig. 6—Complete Equivalent Circuits Representing

a. The direct axis, and (b), the quadrature axis, of a synchronous motor having a double amortisseur winding

stator resistance, $r_1$, which, in the case of the impedance $z_d'$, is $\left(\frac{1}{2s-1}\right)$ times the normal value used in the circuit for $z_d$. The same difference holds for the quadrature impedances $z_q$ and $z_q'$.

The formulas of Appendices A and B show that the per-unit reactances of the networks are constant for any value of slip but that the per-unit resistances are inversely proportional to the slip. Once having calculated the networks, they can be repeated with new resistance values. Doing this several times, using appropriate values of slip, determines the complete speed-torque and speed-current characteristics.

The total armature current is given by the superposition of the current $i_f$ of fundamental frequency, and the current $i_b$ having a frequency of $(1-2s)$ times the fundamental. That is, the armature phase currents, $i_1$, $i_2$, and $i_3$, are:

$$i_1 = i_f \cos \omega t + i_b \cos t\,(2s-1)\,\omega t \tag{15}$$
$$i_2 = i_f \cos(\omega t - 120°) + i_b \cos(2s-1)(\omega t + 120°)$$
$$i_3 = i_f \cos(\omega t - 240°) + i_b \cos(2s-1)(\omega t + 240°)$$

where time is measured from the instant when the two current vectors, $i_f$ and $i_b$, are coincident in phase 1. At 100 per cent slip the current vectors rotate at equal speeds with a constant phase angle between them. Hence, vector addition must be used and, when the axis of phase 1 and the direct axes coincide, the resulting phase currents are:

$$\bar{i}_1 = \bar{i}_f + \bar{i}_b$$
$$\bar{i}_2 = \bar{i}_f \,/\, -120° + \bar{i}_b \,/\, +120°$$
$$\bar{i}_3 = \bar{i}_f \,/\, +120° + \bar{i}_b \,/\, -120° \tag{16}$$

When the direct axis is ahead of the axis of phase 1 by an angle $\theta$ the phase currents are:

$$i_1 = i_d \cos\theta - i_q \sin\theta$$
$$i_2 = i_d \cos(\theta - 120) - i_q \sin(\theta - 120)$$
$$i_3 = i_d \cos(\theta + 120) - i_q \sin(\theta + 120)$$

or,

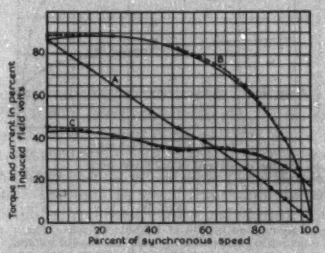
$$\bar{i}_1 = (\bar{i}_f + \bar{i}_b)\cos\theta + j\,(\bar{i}_f - \bar{i}_b)\sin\theta$$
$$\bar{i}_2 = (\bar{i}_f + \bar{i}_b)\cos(\theta - 120) + j\,(\bar{i}_f - \bar{i}_b)\sin(\theta - 120)$$
$$\bar{i}_3 = (\bar{i}_f + \bar{i}_b)\cos(\theta + 120) + j\,(\bar{i}_f - \bar{i}_b)\sin(\theta + 120)$$

From Equation (15) it is apparent that the current in any phase at any speed other than zero, 50, and 100 per cent slip pulsates irregularly with time. That is, an ammeter in any phase will pulsate (noticeably at speeds close to zero, 50 and 100 per cent slip although the pulsations may be too rapid at intermediate speeds to be noticed on an ordinary meter). At any intermediate speed the maximum value of the pulsating current will be,

$$i = i_f + i_b \tag{17}$$

and the minimum value is,

$$i = i_f - i_b \tag{18}$$




Heavy curve—test data
Dashed curve—calculated data
Curve $A$—Induced field volts (multiply scale by 100)
Curve $B$—Torque in per cent of full load torque
Curve $C$—Line current in per cent of full load current. (Multiply scale by 5)

Fig. 7—Comparison of Calculated Results and Test Data

1450-hp., 60-pole, 120-rev. per min., 4600-volt synchronous motor for compressor drive. (Field open)

These maximum and minimum values are important, as at speeds close to zero and 100 per cent slip both currents may be of nearly the same frequency, adding or subtracting directly over a relatively long period. This causes the familiar beats when a synchronous motor slowly starts up or pulls in or out of synchronism.

The effective current at any speed can be determined

by taking the square root of the mean square of Equation (15) over a cycle whose period is equal to the reciprocal of the highest common factor of $\left(\frac{\omega}{2\pi}\right)$ and $\frac{(2s-1)\omega}{2\pi}$. This current, is

$$i = \sqrt{i_f^2 + i_b^2} \qquad (19)$$

At speeds close to 50 per cent, slip, $i_b$ is of very low frequency, and therefore at these speeds the current pulsates between a maximum of $\sqrt{i_f^2 + i_b^2}$ and $i_f$.

The formulas have been used with marked success.

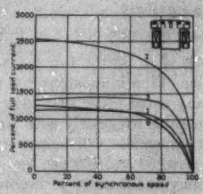
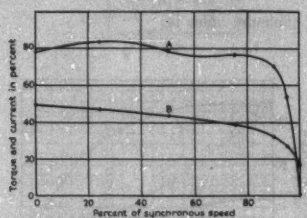



FIG. 8—CALCULATED CURRENT DISTRIBUTION (APPROXIMATE) IN THE AMORTISSEUR WINDING

Of a 1450-hp., 60-pole, 120-rev. per min., 4600-volt synchronous motor. Open end rings. Field closed through 10 times its own resistance




Curve $A$—Torque in per cent of full load torque
Curve $B$—Line current in per cent of full load current. (Multiply scale by 5)

FIG. 9

Calculated torque and current of 1450-hp., 60-pole, 120-rev. per min., 4600-volt synchronous motor with complete amortisseur winding. (Closed end rings. Field closed through 10 times its own resistance)

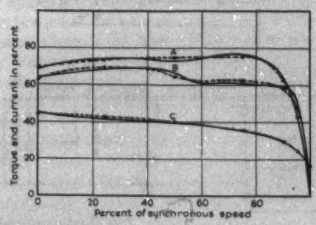
To illustrate the degree of accuracy obtained, a comparison of calculated and test results is shown in Fig. 7 for a 60 pole, 1450-hp., 120-rev. per. min.—4600-volt, 0.8-power-factor motor. The calculated currents in the amortisseur bars of this machine are plotted as a function of speed in Fig. 8. Figs. 9 and 10 afford a comparison of the calculated torque and current for the condition of closed and open end rings. Fig. 10 illustrates the calculated effect of external resistance in the field circuit. Finally, Fig. 11 shows the effect of changing the number and position of the bars, keeping constant copper, in the poles of a large waterwheel generator rated at 77,500 kv-a., 68 poles, 88.2 rev. per min., 13,800 volts, 0.8 power factor.

This final illustration is obtained by a rearrangement of Equation (49), reference 8, resulting in the following expression for per-unit damping torque for small angles of oscillation,

$$T_d = \text{Real of } \delta' e^2 \left[ \frac{z_q - z_q(s)}{z_q z_q(s)} \cos \delta^2 + \frac{z_d - z_d(s)}{z_d z_d(s)} \sin \delta^2 \right] \qquad (20)$$

where

$z_d$ = synchronous impedance of the machine in the direct axis, including the line reactance up to an infinite bus. Line resistance is neglected. It is determined by solving the direct axis equivalent circuit when the slip, $s$, is zero.




Heavy curve—test data
Dashed curve—calculated data
Curve $A$—Induced field amperes (divide scale by 2)
Curve $B$—Torque in per cent of full load torque
Curve $C$—Line current in per cent of full load current. (Multiply scale by 5)

FIG. 10—COMPARISON OF CALCULATED RESULTS AND TEST DATA

1450-hp., 60-pole, 120-rev. per min., 4600-volt synchronous motor for compressor drive. (Field closed through 10 times its own resistance, open-end rings)

$z_d(s)$ = impedance of the direct axis of the machine when the rotor is slipping at a per-unit speed $s$. It is determined by solving the equivalent circuit when all rotor resistances are divided by $s$.

$z_q$ and $z_q(s)$ are the corresponding quantities for the quadrature axis.

$e$ = per-unit voltage of the infinite bus.

$\delta'$ = maximum angle of deviation in radians from the normal position.

Fig. 11A shows the calculated damping torque of the generator for an oscillation, having a total amplitude of one radian, as a function of the average position angle, $\delta$. Curves are given for six different designs of the amortisseur winding. The lowest curve shows the damping due to the field alone, and the higher curves show the effects of adding amortisseur windings of different spans.

The damping torque at no-load, $\delta = 0$, is zero without an amortisseur, and is negligible if the span of the

amortisseur is less than about two-thirds of the pole face, but increases rapidly as the span approaches the full width of the pole. When the end rings are continuous between the poles a large increase in no-load damping is secured, but the damping in the neighborhood of maximum synchronous output is affected to a relatively small degree.

Fig. 11B shows the effect of the amortisseur design on the sub-transient reactances The negative phase se-

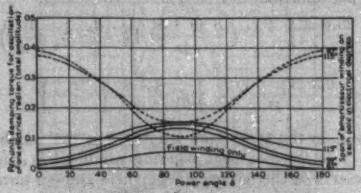



FIG. 11A—DAMPING TORQUE *vs.* POSITION ANGLE OF THE 77,500-KV-A. GENERATOR

Heavy lines—Open end rings between poles
Dotted lines—Closed end rings between poles
Constant cross-section of copper, uniformly distributed over the span, is assumed

quence reactance, which should be as high as possible to limit phase-to-ground and phase-to-phase fault currents, decreases as the amortisseur span is increased, and is low when the end rings between the poles are closed. Thus, these calculations make possible a rational decision on the best amortisseur design, taking into account both favorable and unfavorable factors.

The curves shown were calculated for a frequency of

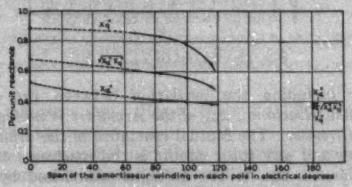



FIG. 11B—SUBTRANSIENT REACTANCES OF THE 77,500-KV-A. GENERATOR *vs.* THE SPAN OF THE AMORTISSEUR WINDING

Constant total cross-section of copper, uniformly distributed in the pole face, is assumed. The end rings are assumed open, except for the points on the extreme right of the figure

hunting of 0.6 cycles per second and with a 25 per cent reactance between the generator and an infinite bus. Also, a constant total cross-section of copper in the amortisseur bars was assumed for all spans.

## VII. ACKNOWLEDGMENTS

So many individuals participated in the developments described, that it is not possible to properly acknowledge their separate contributions. Special acknowledgment is due, however, to Mr. P. L. Alger, who initiated the study, suggested the equivalent circuit method of analysis, and supervised the work. The author is particularly grateful to him for his work in the preparation of the data and for many suggestions concerning the final writing of the paper. Acknowledgment is also due to Mr. R. H. Park, who developed the complete equations and the mutual relationships of the various windings, and to Mr. Ralph Hammar, who conceived the method of properly caring for the differential leakage reactances of the rotor circuits, and who also developed formulas for the circuit constants. Figs. 13, 14, and 15 are taken directly from a previous paper by R. W. Wieseman.[3]

## VIII. DERIVATION OF FORMULAS FOR THE ELEMENTS OF THE EQUIVALENT CIRCUITS

*General Method.* Following the method employed by Doherty and Nickle in *Synchronous Machines, I*,[4] the flux waves illustrated in Fig. 3 are obtained as the products of the m. m. fs. acting at points along the armature surface and the permeance coefficients applying to the magnetic path at corresponding points. The permeance coefficient and the m. m. f. are expressed as functions of the distance, $y$, along the armature surface. The product of the two may then be integrated to find the flux between any two values of $y$.

By flux plotting it has been found that the permeance distribution for the first harmonic of armature m. m. f. is given by the reciprocal of the effective air-gap* and may be expressed as,

$$P = \frac{\alpha^2}{\alpha^2 + (\rho - 1)\, y^2} \tag{21}$$

where $\alpha$ is the ratio of pole arc to pole pitch and $\rho$ is the ratio of maximum gap to minimum gap. This expression is accurate for values of $y$ less than the pole arc. It holds as a good approximation for greater values, but for such values it is easier to use data derived from flux plots. Through the use of these plots the calculation is simplified and the accuracy maintained. Hence, in appendices A and B, use if made of Figs. 13, 14, and 15, based on data derived by Wieseman,[3] from flux plots for a great many pole structures.

*Per-Unit Base.* In Part IV, it was stated that the impedance elements of all circuits must be calculated on the basis of the same unit m. m. f. in order to allow the circuits to be joined into equivalent networks representing the direct and quadrature axes of the machine. To avoid confusion a m. m. f. of 0.4 $\pi$ times one ampere turn is chosen. The impedance elements of the circuits are, therefore, calculated in equivalent ohms on a one-turn base. Actual ohms are, of course, the number of turns squared, times the equivalent one-turn ohms. The advantage in basing all impedance calculations on

*The effective gap is defined as the actual gap corrected for slot fringing.

an arbitrarily chosen unit m. m. f., is that it conveniently takes account of the turn ratio between circuits. This is especially helpful when there are several circuits, each having a different number of turns.

In addition, it is desirable to express all of the impedance elements as per-unit quantities. It follows immediately from the definitions of unit m. m. f., flux, voltage, and impedance, given in Part III, that unit impedance on the basis of an equivalent armature winding, in each axis of the machine, having a single turn, is,

$$\text{Unit impedance} = \frac{2\,\pi\, f_n\, \phi_f\, 10^{-8}}{A}\ \text{ohms} \qquad (22)$$

where $\phi_f$ is normal or unit flux, $f_n$ is normal frequency and $A$ is the equivalent square wave value of armature reaction ampere turns, defined in Part II as unit m. m. f. A one turn winding of this impedance in each axis will produce exactly the same effects as the actual armature winding. The impedance of a single turn winding which will produce the same effect when the impressed frequency is $s\,f_n$, corresponding to the frequency of rotor currents at a given slip $s$, becomes,

$$\text{Unit impedance} = \frac{2\,\pi\, s\, f_n\, \phi_f\, 10^{-8}\ \text{ohms}}{A} \qquad (23)$$

The per-unit base is, therefore, proportional to the impressed frequency, *i. e.*, normal volts are proportional to the frequency. As the equivalent circuits are established for the purpose of evaluating currents whose frequency with respect to the rotor is $s\,f_n$, unit impedance for all rotor circuits is given by Equation (23). Since the armature currents pulsate at two frequencies, namely, $f_n$ and $(1 - 2\,s)\,f_n$, the per-unit base for impedance to current of the first frequency is given by Equation (22) and that to current of the second frequency is given by,

$$\text{Unit impedance} = \frac{2\,\pi\,(1 - 2\,s)\, f_n\, \phi_f\, 10^{-8}}{A}\ \text{ohms} \qquad (24)$$

These values of unit impedance, Equations (22), (23), and (24), are obtained when the definition of unit impedance, given in Part III, is multiplied by two-thirds to convert to the normal impedance of one phase and then is successively divided by the number of poles, to convert to terms of one axis, and by the number of turns per pole squared to convert to terms of an equivalent one-turn winding in each axis.

## Appendix A

### Impedance Constants for the Direct Axis Circuits

*Armature Resistance*, $r_1$. Armature resistance is expressed as a per unit quantity by the ratio of ohms per phase to unit impedance. Hence at 75 deg. cent.,

$$r_1 = \frac{8.8\, A\, P\, (M\, L\, T)}{f_n\, N\, K_c^2\, \phi_f\ (\text{area cond.})} \qquad (1a)$$

where $K_c$ is the combined pitch and distribution factor, $P$ is the number of poles, $(M\,L\,T)$ is the mean length of turn, and $N$ is the number of turns in series per phase. For convenience all formulas are expressed in terms of $A$, the unit m. m. f., and $\phi_f$, the unit flux. All lengths and areas are in inch units when not expressed as fractions of a unit length.

*Armature Leakage Reactance*, $x_1$. The most accurate formula for this reactance is one derived by Alger, the derivation for which has already been published.[1] As a per unit quantity it is,

$$x_1 = \frac{25.5\, A}{K_c^2\, \phi_f}\left[\frac{P\,L}{S}\left(\frac{3\,p + 1}{4}\right)\left(\frac{d_2}{w} + \frac{d_1}{3\,w}\right) + \frac{0.3\,(3\,p - 1)\,D}{P}\right] + \frac{1.4\,A}{F}\left[\frac{P}{S}\right]^2 \qquad (2a)$$

where $L$ is the gross core length, $S$ is the number of slots, $p$ is the per cent winding pitch, $D$ is the gap diameter, $F$ is the no-load air-gap field ampere turns per pole, $w$ is the slot width, $d_2$ is the depth from the top of the slot to the first coil, and $d_1$ is the total depth of

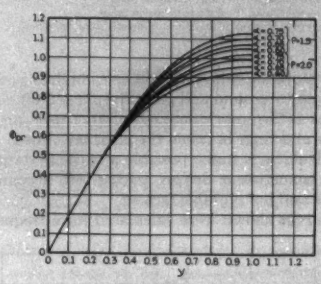



Fig. 12—Graph of $\phi_{ar} = f(y)$

copper including the insulation between the coils.

*Mutual Reactance*, $x_{ar}$, *of the Armature Winding and Rotor Circuits*. The mutual reactance of the armature winding and any rotor circuit is the reactance of the rotor circuit due to the linkages established by the armature flux. In order to determine it the flux distribution must be known. Since the reactance is calculated for equivalent one turn armature and rotor windings in each axis, the distribution of m. m. f. produced by a current of one ampere is,

$$\text{m. m. f.} = \frac{4}{\pi}\left[0.4\,\pi\cos\frac{\pi}{2}\,y\right] \qquad (3a)$$

The flux between any two values of $y$ is the integral of the product of m. m. f. and permeance. Hence, from Equations (21) and (3a),

$$\phi_{ar} = \int_0^{y_2} 2\,\frac{1.6\,\alpha^2\cos\pi/2\,y\,d\,y}{\alpha^2 + (\rho - 1)\,y^2} \qquad (4a)$$

This expression may be expanded and integrated by

parts, or the flux wave may be plotted and the area beneath the curve, between any two values of $y$, determined graphically. Since it is desired to take the integration only between limits of $y = 0$ and any positive value of $y$, either method makes it possible to plot the mutual flux, $\phi_{ar}$, against values of $y$. In Fig. 12 this plotting has been done for several values of $\alpha$, the ratio of pole arc to pole pitch, and $\rho$, the ratio of maximum

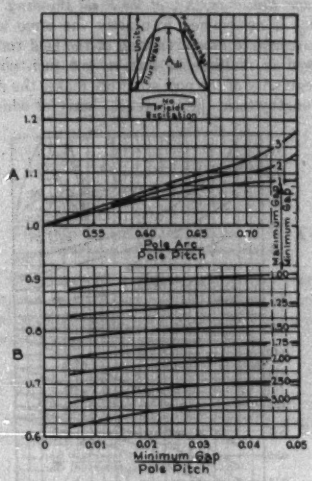



FIG. 13—FUNDAMENTAL OF THE AIR-GAP FLUX WAVE

When a salient pole synchronous machine is excited by only a sine wave armature m. m. f. whose axis coincides with the pole center.

Maximum value of actual flux wave equals fundamental $A_{d1} = A \times B$

gap to minimum gap. Hence, the mutual flux may be read from the curves.

As the product $2\pi 10^{-8}$ times frequency is common to all reactance calculations as well as unit impedance it may be omitted from both. Then, per unit reactance will be given directly by the ratio of the flux, $\phi_{ar}$, produced by a m. m. f. of one ampere turn, to $\phi_f/A$. That is, on the basis of unit m. m. f., $A$, per unit reactance is the ratio of the flux produced to normal flux. $\phi_f$ must first be determined in terms of the area of a sine wave of base 2 and an ordinate depending upon the m. m. f. of the field. If the no-load air-gap ampere turns are designated by $F$, the maximum density of the field flux is $0.4\pi F$, since the maximum permeance of the gap is taken as unit permeance. From the curves of Fig. 14, the maximum ordinate of the fundamental of the field flux is, $0.4\pi A_1 F$. Hence the total fundamental flux is,

$$\phi_f = 1.6 A_1 F \tag{5a}$$

Then, the per unit reactance is,

$$x_{ar} = \phi_{ar} \frac{A}{A_1 F} \tag{6a}$$

The curves of Fig. 12 include the factor 1.6 of Equation (5a).

*Reactance, $x_{ad}$, of Armature Reaction.* The reactance of armature reaction is reactance due to the sine wave fundamental of the total air-gap flux wave produced by normal armature current at synchronous speed. Equation (6a) is a good approximation for $x_{ad}$ when $\phi_{ar}$ is determined for $y = 1$. The calculations may also be made, easily and accurately, by the following method. The maximum density of the flux wave produced by one ampere turn is, $0.4\pi(4/\pi) = 1.6$. Then from Fig. 13, the maximum ordinate of the fundamental of the flux wave is, $1.6 A_{d1}$. Hence, the total fundamental

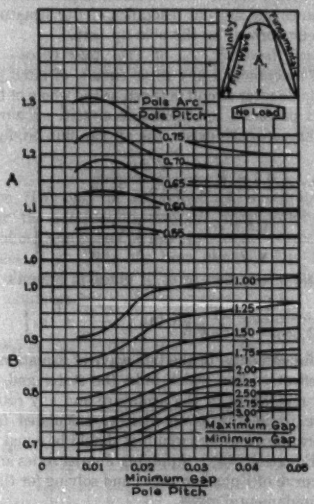



FIG. 14—FUNDAMENTAL OF THE NO-LOAD FLUX WAVE IN THE AIR-GAP OF A SALIENT-POLE SYNCHRONOUS MACHINE

Maximum value of actual flux wave equals unity Fundamental $A_1 = A \times B$

flux, expressed as the area of a sine wave of base 2 and maximum ordinate $1.6 A_{d1}$, is,

$$\phi_{ad} = \frac{6.4}{\pi} A_{d1} \tag{7a}$$

The ratio of this flux to $\phi_f/A$, where $\phi_f$ is given by Equation (5a), gives as a per unit quantity,

$$x_{ad} = \frac{4}{\pi} \frac{A_{d1}}{A_1} \frac{A}{F} \tag{8a}$$

*Mutual Reactance, $x_{af}$, of the Armature and Field*

*Windings.* In this case, Equation (**6a**) again gives a good approximation, but here also another expression may be derived which is simple and accurate. When a m. m. f. of one ampere turn is produced by the field circuit the maximum density of the resulting flux is $0.4\,\pi$. From Fig. 14, the maximum density of the sine wave fundamental of the flux wave is $0.4\,\pi\,A_1$. The total effective flux linking the armature then, is, $1.6\,A_1$. The ratio of this flux to $\phi_f/A$ gives the following expression for the per-unit mutual reactance of the field and armature windings.

$$x_{af} = \frac{A}{F} \qquad (\mathbf{9a})$$

Flux plots show that there is very little error in assuming that the circuit formed by bars in the pole tips has the same mutual reactance with the armature winding as the field winding has. Hence, Equation (**9a**) also determines the mutual reactance of the armature and the circuit formed by the pole tip bars.

*Mutual Reactance, $x_{rr}$, of Two Rotor Circuits.* The mutual reactance of any rotor circuit, of pitch $y$, with any outside rotor circuit is taken as the whole of the air-gap flux produced by the inside circuit. If a m. m. f. of one ampere-turn exists, the air-gap flux produced is,

$$\phi_{rr} = 0.8\,\pi \int_0^{y_n} \frac{\alpha^2\,d\,y}{\alpha^2 + (\rho - 1)\,y^2} \qquad (\mathbf{10a})$$

$$= \frac{0.8\,\pi\,\alpha}{\sqrt{\rho - 1}} \text{ arc tan} \left[ \frac{\sqrt{\rho - 1}}{\alpha} y_n \right] \qquad (\mathbf{11a})$$

The ratio of this flux to $\phi_f/A$ gives, in per-unit terms,

$$x_{rr} = \frac{\pi\,\alpha}{2\sqrt{\rho - 1}} \frac{A}{A_1 F} \text{ arc tan} \left[ \frac{\sqrt{\rho - 1}}{\alpha} y_n \right] \qquad (\mathbf{12a})$$

The fundamental of the flux wave of Equation (**10a**) is the effective flux which links the stator and, if the mutual reactances of the armature and any rotor circuit are to be the same whether calculated from a consideration of either circuit, it should be equal to the flux of Equation (**4a**). Applying Fourier series analysis to the curve of Equation (**10a**) and solving for the area of the fundamental gives,

$$\phi = 3.2 \int_0^{y_1} \frac{\alpha^2 \cos \pi/2\,y\,d\,y}{\alpha^2 + (\rho - 1)\,y^2}$$

which is equal to $\phi_{ar}$ from Equation (**4a**).

*Leakage Reactance, $x_{bn}$, of the Amortisseur Circuits.* This reactance is calculated by the usual method of integrating the product of the permeance of an elemental magnetic path, the m. m. f. acting on the path, and the turns linked by flux passing through the path. The leakage reactance of an amortisseur circuit is due to the slot and slot opening leakage flux of two bars. Hence, for a current of one ampere the leakage flux is,

$$\phi_{bn} = 6.38\,l_b \left[ \frac{d}{w} + P_s \right] \text{lines}$$

where $l_b$ is the length of one bar, $d/w$ is the ratio of the depth to the width of the slot opening, and $P_s = \frac{d_s}{3\,w_s}$ for a rectangular slot or 0.625 for a round slot. The ratio of this flux to $\phi_f/A$ gives the per-unit reactance,

$$x_{bn} = 6.38 \left[ \frac{d}{w} + P_s \right] \frac{Al}{\phi_f} \qquad (\mathbf{13a})$$

*Leakage Reactance, $X_f$, of the Field Winding.* This reactance is determined in exactly the same way as the bar reactance except that all of the field turns are considered in multiple to form a one turn winding. The irregularity of the pole structure makes the derivation a lengthy task, the theoretical basis for which has

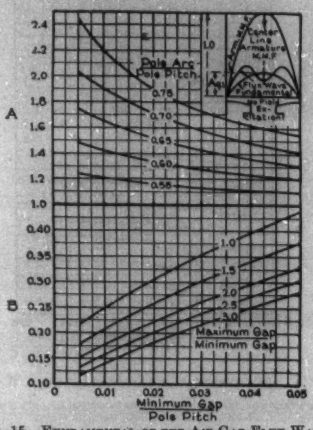



FIG. 15—FUNDAMENTAL OF THE AIR-GAP FLUX WAVE

Maximum value of armature m. m. f. equals unity. Fundamental $A_1 = A \times B$

already been published.[3] The per-unit value of the reactance is given approximately by,

$$X_f = \frac{A\,l}{\phi_f}\,(L_h + L_l) \qquad (\mathbf{14a})$$

where $L_h = \frac{3.6\,h}{m} + \frac{1.4\,d}{l}$, and

$$L_l = 14\left(\frac{d_t}{c} - 0.25\right) + 5.5\left(\frac{a}{c} + 0.20\right) - 4\left(\frac{a}{c} - 0.5\right)^2$$

The nomenclature is explained by Fig. 16.

*Resistance, $r_{bn}$, of the Amortisseur Circuits.* The per unit resistance of an amortisseur circuit, at 75 deg. cent. is twice the ohmic resistance of a single bar divided by unit ohms, Equation (**23**). Therefore,

$$r_{bn} = 26.3\,k\,\frac{l_b}{a_b}\,\frac{A}{s\,f\,\phi_f} \qquad (\mathbf{17a})$$

where $k$ is the ratio of the resistivity of the metal to that of copper, $l_b$ is the length of one bar, $a_b$ is the cross-sectional area of the bars, and $s\,f$ is the product of per cent slip and normal frequency.

*End Ring Resistance, $r_{rn}$.* This resistance is twice the resistance of a single end ring between the bars of any amortisseur circuit. As a per unit quantity at 75 deg. cent. it is,

$$r_{rn} = 26.3\,k\,\frac{l_r}{a_r}\,\frac{A}{s\,f\,\phi_f} \qquad \textbf{(18a)}$$

where $l_r$ is the length of one ring section between the bars and $a_r$ is the cross-sectional area of one ring.

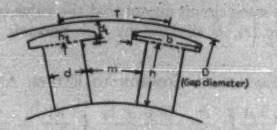



Fig. 16—Key to the Nomenclature Used in the Formula for Field Leakage Reactance

*Field Resistance, $R_f$.* This resistance is determined by the mean length of turn and the product of the cross-sectional area $a_f$, of the conductor and the number of turns, $n_f$. The per unit expression is,

$$R_f = 13.1\,(K+1)\,\frac{(M\ L\ T)}{a_f\,n_f}\,\frac{A}{s\,f\,\phi_f} \qquad \textbf{(19a)}$$

$K$ here is the ratio of external to internal resistance of the field circuit.

## Appendix B

### Impedance Constants for the Quadrature Axis Circuit

The impedance constants for the quadrature axis are determined by the same method as those for the direct axis. The resistance and leakage reactance of the armature winding are constant for all practical purposes regardless of the rotor position. Hence they may be calculated in the quadrature axis by formulas (**1a**) and (**2a**) respectively.

*Mutual Reactance, $x_{ar}$, of the Armature and Rotor Circuit.* Consider a current of one ampere to flow in an armature winding of one effective turn producing a sinusoidal m. m. f. in the quadrature axis. The resulting air-gap flux will be treated in two parts, namely, that portion over the pole face and that in the interpolar space. The flux between any two points on adjacent pole faces, symmetrically located about the center line between poles is,

$$\phi_{ar} = \phi_{ar}' + \phi_{ar}''$$

where the flux over the pole face is, from Fig. 1,

$$\phi_{ar}' = 2\int_{y_n}^{\alpha} .4\,\pi\,\frac{4\,\alpha^2 \sin \pi/2\,y\,d\,y}{\pi\,(\alpha^2+(\rho-1)\ y^2)} \qquad \textbf{(1b)}$$

and $\phi_{ar}''$ is the flux in the interpolar space.

Flux plots have shown that there is very little error (since only the magnitude of the flux is desired) in determining the flux in the interpolar space on the assumption that the m. m. f. acts on a constant permeance, $\sigma/\rho$ where $\sigma$ is a fringing coefficient determined

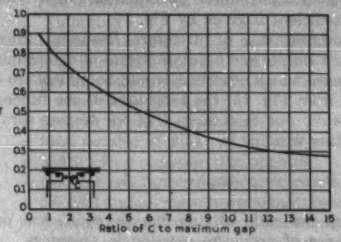



Fig. 17—Graph of $\sigma = f$ (c/Max. Gap)

from flux plots. The flux in the interpolar space is then,

$$\phi_{ar}'' = 2\int_{\alpha}^{1} \frac{0.4\,\pi\,\sigma\,(4/\pi \sin \pi/2\,y)\,d\,y}{\rho} = \frac{6.4\,\sigma}{\pi\,\rho}\cos\frac{\pi\,\alpha}{2} \qquad \textbf{(2b)}$$

Equation (**1b**) may be expanded and integrated by parts or the integration may be done graphically. Values of $\phi_{ar}'$ may then be plotted against corresponding values of $y$. This has been done in Fig. 18 for several ratios of pole arc to pole pitch and maximum gap to minimum gap. Based on these curves,

$$\phi_{ar} = \phi_{ar\alpha}' - \phi_{ar\gamma n}' + \frac{6.4\,\sigma}{\pi\,\rho}\cos\frac{\pi\,\alpha}{2} \qquad \textbf{(3b)}$$

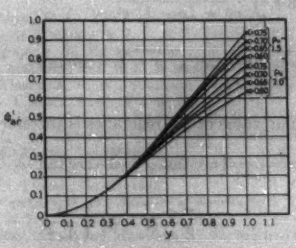



Fig. 18—Graph of $\phi_{ar}' = f\,(y)$

where $\phi_{ar\alpha}'$ is the ordinate of the curve of Fig. 18 at $y = \alpha$ and $\phi_{ar\gamma n}'$ is the ordinate at any particular value of $y$ corresponding to the span of the rotor circuit for which the mutual reactance is being calculated. The per-unit value is determined by the ratio of $\phi_{ar}$ to $\phi_f/A$. Hence, when $\phi_f$ is expressed as in Equation (**5a**)

$$x_{ar} = \left[ \phi_{ar\alpha}' - \phi_{ar\nu n}' + \frac{4}{\pi} \frac{\sigma}{\rho} \cos \frac{\pi \alpha}{2} \right] \frac{A}{A_1 F} \tag{4b}$$

The curves of Fig. 18 are modified to include the constant 1.6 introduced by Equation (**5a**). The fringing coefficient is given by Fig. 17.

*Reactance, $x_{aq}$, of Armature Reaction.* Flux plots afford a simple and accurate means of determining this reactance which otherwise would be difficult to derive. Thus from Fig. 15, the total area of the fundamental flux wave due to a m. m. f. of one ampere turn in the armature winding is,

$$\phi_{aq} = \frac{6.4}{\pi} A_{q1} \tag{5b}$$

Taking the ratio of this flux to $\phi_f/A$, the per-unit reactance of armature reaction is, therefore,

$$x_{aq} = \frac{4}{\pi} \frac{A}{F} \frac{A_{q1}}{A_1} \tag{6b}$$

*Mutual Reactance, $x_{rr}$ of any Two Quadrature Axis Rotor Circuits.* This reactance may be taken as due to the total air-gap flux established by the inside circuit. Again this flux may be considered to be made up of two parts. The flux in the interpolar space may be determined with good accuracy by considering the m. m. f. to be of constant value acting on a uniform gap of permeance $\sigma/\rho$. Then

$$\phi_{rr} = \phi_{rr}' + \phi_{rr}''$$

where the flux in the interpolar space is,

$$\phi_{rr}'' = \frac{0.8\, \pi\, \sigma\, (1 - \alpha)}{\rho}$$

and the flux over the pole faces is,

$$\phi_{rr}' = 0.8\, \pi \int_{y_n}^{\alpha} \frac{\alpha^2\, d\, y}{\alpha^2 + (\rho - 1)\, y^2}$$

$$= \frac{0.8\, \pi\, \alpha}{\sqrt{\rho - 1}} \left[ \text{arc tan} \sqrt{\rho - 1} - \text{arc tan} \frac{\sqrt{\rho - 1}}{\alpha} y_n \right] \tag{9b}$$

The per-unit value of the reactance is therefore,

$$x_{rr} = \left[ \frac{\pi\, \alpha}{2 \sqrt{\rho - 1}} \left( \text{arc tan} \sqrt{\rho - 1} - \text{arc tan} \frac{\sqrt{\rho - 1}}{\alpha} y_n \right) + \frac{\pi\, \sigma}{2\, \rho} (1 - \alpha) \right] \frac{A}{A_1 F} \tag{10b}$$

The *leakage reactance* of the rotor circuits is calculated by the same formula as for the direct axis circuit, *i. e.*, Equation (**13a**). Likewise the resistance of the rotor circuit is given by Equation (**17a**). These two formulas hold for all quadrature axis circuits except the one formed by bars at the pole centers. In this case the effective impedance is twice that given by Equations (**13a**) and (**17a**) since each bar is a common conductor for two adjacent quadrature axes. The end ring resistance is calculated in all cases by Equation (**18a**) regardless of whether the amortisseur is complete or not.

## Appendix C

### Assembled Formulas

In this appendix the formulas necessary to calculate numerical values for all parts of the equivalent circuits, Figs. 5A and 5C are assembled. The solution of the circuits gives numerical values for $Z_d$ and $Z_q$ which, with the impedances $Z_d'$ and $Z_q'$, completely determine the starting performance. $Z_d'$ and $Z_q'$ are determined from the same circuit except that the value of armature resistance, $r_1$, is divided by the per-unit frequency $(2\, s - 1)$.

### Equations Common to Either Axis

$$x_1 = \frac{25.5\, A}{K_c^2\, \phi_f} \left[ \frac{P}{S} \frac{(3\, p + 1)}{4} \left( \frac{d_b}{w} + \frac{d_1}{3\, w} \right) + 0.3 \frac{(3\, p - 1)\, D}{P} \right] + \frac{1.4\, A\, P^2}{F\, S^2} \tag{1c}$$

$$r_1 = \frac{8.8\, A\, P\, (M\, L\, T)}{f_n\, N\, K_c^2\, \phi_f\, (\text{area cond.})} \tag{2c}$$

$$x_{bn} = 6.38 \left[ \frac{d}{w} + P_s \right] \frac{A\, l}{\phi_f} \tag{3c}$$

where $P_s = \dfrac{d_s}{3\, w_s}$ for rectangular slots or .625 for round slots.

$$r_{bn} = 26.3\, k \frac{l_b}{a_b} \frac{A}{s f \phi_f} \tag{4c}$$

where $k$ is the ratio of resistivity of the bar material to that of copper.

$$r_{rn} = 26.3\, k \frac{l_r}{a_r} \frac{A}{s f \phi_f} \tag{5c}$$

### Equations for Constants of the Direct Axis Circuit, Fig. 5A

$$x_{ad} = 1.27 \frac{A}{F} \frac{A_{d1}}{A_1} \tag{6c}$$

$$x_{ar} = \phi_{ar} \frac{A}{A_1 F} \tag{7c}$$

$$x_{af} = \frac{A}{F} \tag{8c}$$

$$x_{rr} = \frac{1.57\, \alpha\, A}{\sqrt{\rho - 1}\, A_1 F} \text{arc tan} \left[ \frac{\sqrt{\rho - 1}}{\alpha} y \right] \tag{9c}$$

$$x_h = x_{rr} - x_{ar}$$

$$X_f = \frac{A\,l}{\phi_f}\left[\frac{3.6\,h}{n} + \frac{1.4\,d}{l} + 14\left(\frac{d_i}{c} - .25\right) + 5.5\left(\frac{a}{c} + .20\right) - 4\left(\frac{a}{c} - .5\right)^2\right] \quad (10c)$$

$$R_f = 13.1\,(K+1)\,\frac{(M\,L\,T)}{a_f\,n_f}\,\frac{A}{s f \phi_f} \quad (11c)$$

where $K$ is the ratio of internal to external resistance.

### Equations for Constants of the Quadrature Axis Circuit, Fig. 5c

$$x_{ar} = \left[\phi_{ard}' - \phi'_{arun} + \frac{4}{\pi}\,\frac{\sigma}{\rho}\,\cos\frac{\pi\,\alpha}{2}\right]\frac{A}{A_1 F} \quad (12c)$$

$$x_{aq} = \frac{4}{\pi}\,\frac{A}{A_1}\,\frac{A_{q1}}{F} \quad (13c)$$

$$x_{rr} = \frac{1.57\,A}{A_1 F}\left[\frac{\alpha}{\sqrt{\rho - 1}}\left(\text{arc tan}\,\sqrt{\rho - 1} - \text{arc tan}\,\frac{\sqrt{\rho - 1}}{\alpha}\,y_s\right) + \frac{\sigma\,(1-\alpha)}{\rho}\right] \quad (14c)$$

$$x_h = x_{rr} - x_{ar}$$

$$x_{bs} = 12.76\left[\frac{d}{w} + P_s\right]\frac{A\,l}{\phi} \quad (15c)$$

$$r_{bs} = 52.6\,k\,\frac{l_b}{a_b}\,\frac{A}{f\phi_f} \quad (16c)$$

### Nomenclature

$a_b$ = cross-sectional area of amortisseur bar
$a_f$ = cross-sectional area of field circuit conductor
$a_r$ = cross-sectional area of one end ring
$A$ = square wave armature reaction ampere turns
$A_1$ = ratio of maximum ordinate of the sine wave fundamental of the field flux to the maximum ordinate of the actual flux wave
$A_{d1}$ = ratio of maximum ordinate of the sine wave fundamental of the armature flux to the maximum ordinate of the actual flux wave in the direct axis
$A_{q1}$ = same for the quadrature axis
$d$ = depth of amortisseur bar slot opening
$f_n$ = rated frequency of the machine
$F$ = field ampere turns required to produce normal voltage in the armature on open-circuit
$K_c$ = combined pitch and distribution constants of the armature winding
$\phi_{ar}$ = see Fig. 12
$\phi_{ar}'$ = see Fig. 18
$l$ = gross stacking length of armature punchings
$l_b$ = length of one amortisseur bar
$l_r$ = length of end ring between two bars forming a rotor circuit
$M\,L\,T$ = mean length of armature turn
$n_f$ = number of turns per pole in the field circuit
$p$ = winding pitch expressed as a decimal
$P$ = number of poles
$\rho$ = ratio of maximum to minimum gap
$R_f$ = resistance of field circuit as a per-unit quantity
$r_{bs}$ = resistance of bars in an amortisseur circuit (2 bars) as a per-unit quantity
$r_{rs}$ = per-unit resistance of end rings in an amortisseur circuit (2 rings)
$r_1$ = per-unit armature resistance
$S$ = total number of slots
$w$ = width of amortisseur slot opening
$x_{ad}$ = per-unit reactance of armature reaction
$x_{af}$ = per-unit mutual reactance of armature and field
$x_{ar}$ = per-unit mutual reactance of the armature and a rotor circuit formed by bars in the pole face
$x_{bf}$ = per-unit mutual reactance of the field and the pole tip bar circuit
$x_{bs}$ = per-unit leakage reactance of the bars forming and amortisseur circuit
$X_f$ = per-unit leakage reactance of the field circuit
$x_h$ = $x_{rr} - x_{ar}$ = per-unit differential leakage reactance of a rotor circuit
$x_{rr}$ = per-unit mutual reactance of two rotor circuits
$x_1$ = per-unit leakage reactance of the armature winding
$\alpha$ = ratio pole arc to pole pitch
$\phi_f$ = number of lines of fundamental sine wave field flux required to generate normal voltage in the armature on open circuit
$\sigma$ = see Fig. 17.

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## Discussion

**I. H. Summers:** I wish to discuss this paper from the standpoint of its usefulness in making calculations of the behavior of synchronous machines during transients in power systems.

Mr. Linville has assembled in one clear paper all of the important information necessary to enable designers to determine equivalent circuits which adequately specify the starting characteristics. Formulas are also given to enable damping torque to be obtained. Thus, what has been accomplished that is new is that it has been made possible to obtain for any given machine equivalent circuits made up from design data, which will accurately describe not only starting conditions, but also will enable damping torque during disturbances to be calculated. This should make it possible to make step-by-step stability calculations and take damping accurately into account.

**F. W. Gay:** Mr. Linville said he would be delighted to apply his synchronous motor theory to any "practical" system.

There are many synchronous machines which are started at no

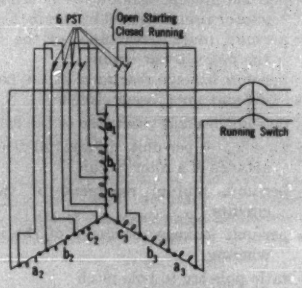


FIG. 1

load, such as frequency changers and slow speed, multiple pole motors. One type for which low-voltage starting is required allows the stator to revolve freely during the starting period. Such machines may readily be designed to start at approximately 30 per cent voltage, although in many cases oil will have to be pumped to the bearings during the starting period. Fig. 1 is a diagrammatic representation of a proposed three-phase motor winding. Each of the three phases consists of three coil groups lettered *a*, *b*, and *c*, respectively. Switch marked 6 *P S T* is left open during the starting period so that the coil groups *a*, *b*, and *c* in each phase are in series. The *b* group of coils in each phase is connected 180 electrical degrees with respect to the *a* and *c* groups, but all three groups have the same phase rotation.

It is obvious that during the starting period, the starting current will pass through all three groups in series and since all three groups have the same rotation, each group will cooperate with the other two groups to turn the rotor in the desired direction. At the two points around the stator where the *a* and *c* groups interleave with the *b* group there will be dead points and at these dead points the polarity of the rotating field will reverse. Its direction of rotation will be the same in all groups around the stator. While the effectiveness of the dead points in starting the rotor will be practically nil the reactance to current interposed by the dead points will also be practically nil. The starting current will therefore be somewhat more than 1/9 of the "across the line current" and the effective starting torque will be substantially the same as if the normally parallel connected machine were thrown across ⅓ voltage except that there will be no voltage drop or reactive kv-a. loss in a starting compensator. After the machine has reached full speed the synchronous motor field is closed while the windings are still connected in series. Windings *a* will generate 100 per cent line voltage, while windings *b* will also generate 100 per cent line voltage but in reverse polarity. The sum of the voltages across *a* and *b* will therefore be zero and the junction of windings *b* and *c* will therefore be at line potential. Windings *c* and *b* will also generate 100 per cent voltage but will be 180 deg. out of phase with respect to each other so that the junction points of windings *a* and *b* will be at neutral potential. Air break disconnecting switch 6 *P S T* may therefore be closed without disturbing the operation of the machine in any respect. Switch 6 *P S T* may consist of a six-pole mechanism operated switch or it may consist of six single pole stick operated switches. The scheme that I have outlined should never be used unless it is positively known that the starting torque required will not exceed the ability of the normally connected machine to start at ⅓ voltage. I should like to ask Mr. Linville if such a starting scheme will work. Is it "practical?"

**C. C. Shutt:** (communicated after adjournment) Mr. Linville's paper presents a novel and comparatively accurate means for calculating the starting performance of salient pole synchronous motors and gives the design engineer a method by which he may apply a part of the theoretical work of Park[1] to actual machines.

In working through a design by the method as outlined in this paper, I found, however, that the labor involved in actually solving the networks in complex notation for a sufficient number of values of slip to determine a speed torque curve, was prohibitive for practical design purposes, even though they were simplified by appropriate transformations. Moreover, it must be remembered that high-speed machines often have 7 or 9 or an even greater number of damper bars per pole, thus giving a very formidable network. To save time and effort the networks, with all constants evaluated for the values of slip, were submitted to

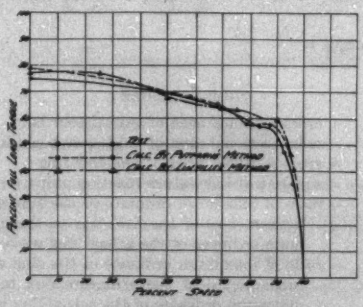


FIG. 2—SPEED-TORQUE CURVE

For a 2700-hp., 120-rev. per min. synchronous motor

an a-c. calculating board. In the hands of an experienced operator, the required values of $Z_d$ $Z_q$, $Z_d'$, and $Z_q'$ were obtained in a reasonable time.

In a paper presented before the Institute some time ago, Mr. H. V. Putman[2] gave a method for calculating the starting performance of synchronous machines, in which he showed, for the first time, an accurate method of calculating the effect on torque and stator current of an imperfect polyphase damper circuit combined with the single-phase field winding circuits. In this paper

1. R. H. Park, *Two Reaction Theory of Synchronous Machines*, Part I, A. I. E. E. TRANS., Vol. 48, July, 1929, p. 716.

2. H. V. Putman, *Starting Performance of Synchronous Motors*, A. I. E. E., TRANS., Vol. 46, 1927, p. 39.

he reduced his method to practical formulas readily applicable to commercial designs.

In Fig. 2 herewith is given a set of speed torque curves for a 2700-hp., 120-rev. per. min., 100 per cent power factor synchronous motor, with its field winding closed through 13 times its own resistance. These curves compare the test values with the values as calculated by each of the two methods. It will be noted that there is but little to choose between the two methods of calculation.

Mr. Linville's method has the added theoretical accuracy of taking into account the effect of armature resistance and non-uniform air-gap. Also, by setting up the networks on a calculating board, the current in each damper bar circuit may be obtained in a comparatively ready manner.

The suggested approximation of neglecting the effect of the mutual resistance of the end rings seems to be well justified when one considers that in present day synchronous motors the specific resistance of the damper bar materials is often several times that of the copper end rings. In case the end rings are of material having higher resistance than copper, it is essential that their resistance be added to the resistance of the bars as shown in Section 5a. The omission of the end ring leakage reactance does not seem justifiable in many cases.

Apparently no account is taken in the rotor slot constant given of any pure leakage flux existing in the gap or interpolar space, due to the m. m. f. of the individual damper bars. I am inclined to question the accuracy of the general approximation of using, in the direct axis circuit, the same values of $X_{ar}$ and $X_{rr}$ for the field winding and the circuit of the bars in the pole tips. It seems reasonable enough for the particular type of pole punching shown, but where the end bars are located a short distance from the ends of the pole tip and open into the gap proper, it is probably worth while to calculate the constants separately and thus add another complication to the direct axis network. This latter method of construction, however, eliminates any mutual reactance betwen this end bar damper circuit and the field circuit due to field leakage flux.

**T. M. Linville:** With reference to Mr. Gay's question, I said that the paper would solve any problem in starting of a practical synchronous motor simply because I couldn't very well include in the paper all the special cases, but there are ideas expressed in the paper which can be applied in a general way and so I think, using these ideas, Mr. Gay's problem can be solved. If he has a problem which involves circuits on a synchronous machine, there will be a solution.

The interesting part of the paper to me is the fact that it deals with mutually coupled circuits and Mr. Gay's problem is exactly that. I think he will find the paper adequate to answer his question. Offhand it is difficult to make an accurate reply. What more mature study will bring forth I cannot say now.

Mr. Shutt's comment that the labor involved in solving the circuits is too great cannot be denied. In high-speed machines I do not propose to solve a formidable network since the number of bars can be easily reduced to an equivalent smaller number. The paper has been published to show the foundation from which accurate practical methods can be derived.

The theory was worked out with the idea of avoiding all assumptions if possible. With the exception of assuming negligible saturation I think this objective has been obtained. All harmonics in the distribution of the armature phase m. m. f. can be taken into account by separate equivalent circuits, in series, with no alteration in the theory. Fortunately this is not necessary. The equation used for the permeance distribution for the first harmonic of armature m. m. f. is only used over the pole face and within this range it will check flux so perfectly that it hardly is an assumption.

I feel that the paper is an improvement over the method presented by Mr. Putman since the assumptions he made are avoided. These assumptions are clearly stated and defined in the TRANSACTIONS.

Still referring to Mr. Shutt's comments, I have shown in the paper how the end ring leakage reactance could be included. The formula for this is easy to derive. I have found it better not to neglect the mutual resistance of the end rings in some cases when calculating the conditions at small values of slip, although this never produces much error unless the stacking is short and the poles few.

The formula for the rotor slot constant, $X_b$, should include a factor to take account of the pure leakage flux existing in the gap due to the m. m. f. of the individual bars. This is an oversight since a factor, which is a function of the gap length, is used in this formula.

Mr. Shutt's final comment, namely, that of using the same values of $X_{ar}$ and $X_{rr}$ for the fielding winding and the pole tip bars, is due to an impression which the paper was not intended to carry. The expression, "pole tip bars" is used to mean bars which actually are in the pole tips and open into the interpolar space. End bars which open into the air-gap should have their constants calculated separately. Mr. Shutt's remarks show an appreciation of the paper which it is pleasing to know exists.

# Ventilation of Revolving-Field Salient-Pole Alternators

BY CARL J. FECHHEIMER*
Fellow, A. I. E. E.

*Synopsis.—The studies were made experimentally and analytically. In the experimental study, a model of hard wood was used, with a multiple of vent ducts of normal width of ⅜ in. each in the stator, the slots and teeth being of approximately average width. A four-pole rotor is distinct from one of a large number of poles; consequently two rotors were built, one of four poles and one of twelve poles, the latter being considered as representative of the greater number. The end bells and the imitations of the end windings were different for the two numbers of poles. In the test results given, data for only standard fiber wedges are included, but other forms were investigated. The vent fingers extended the full depth of the core, thereby enabling measurement to be made of the volume of air per vent per tooth, a rotating vane anemometer with a suitable funnel attachment being employed. The end bells were solid, simulating standard construction and the entrances to the two bells were joined to a common duct, in series with which was a thermal volume meter and an external blower, the speed of which could readily be adjusted. (See Fig. 8.) Pressures were measured in the inner and in the outer end bells. The rotor of the model was driven by a d-c. motor, the power input to which was measured. By this means windage data were obtained, and many of those results are included among other data on the curve sheets.*

*For taking a characteristic pressure volume curve, the first reading was taken with the rotor running at a suitable arbitrary speed, with the external blower stationary, and with its entrance closed. The pressure was then generated by the poles acting as fans, and by the internal fans. For a number of succeeding readings, cardboard orifices with various size holes were placed over the external blower entrance, until that entrance was wide open. Subsequently, the external blower was started, and readings were taken with it running at a number of speeds. The form of curves thus obtained is shown in Fig. 9, the meaning of the three curves being there indicated. One of the limitations imposed by ventilation tests as usually made on an alternator is that only one point on the inner end bell pressure—volume curve is obtained: nearly that at D in Fig. 9. The data thereby obtained do not enable the designer to estimate the volumes, when conditions out of the ordinary are introduced; these would include, for example, the resistance of external ducts of a cooler, or of the influence of greater or less axial length, or of the effect of change in fan proportions, etc. The effects of these and the influence of the structural changes are treated in the paper.*

*At one or more volumes on the pressure-volume curve, volume distribution curves were taken, and from data thereby obtained the influence of axial length was allowed for in the equations derived.*

*In interpreting the results, it is important to eliminate some independent variables. Thus angular velocity may be eliminated, as the pressure is proportional to the square and the volume to the first power of the speed, the shape of volume distribution curve remaining the same. Ample experimental verification was obtained. Machine dimensions were more uncertain, and after many tests it appears that for a given value of end bell pressure and angular velocity, the volume distribution for the shorter machine is substantially the same as for the longer machine with the ends removed. As those tests were many, the number of vents, (or length of machine) is considered in the following list of the 11 structural independent variables: (1) Number of poles; (2) Fans; (3) Number of vents; (4) Wedges in stator; (5) Interpolar spaces; (6) Fan seals; (7) Fan shroud rings; (8) Field coil braces; (9) Plates in end bells; (10) Round and square pole corners; (11) Location of fans. Data for Nos. 4, 8, and 11 are not given in this paper, and not all for No. 2. There were several unusual results obtained, such as breaks in some of the pressure volume curves for four poles. Data are given for various fans, and also without fans, for both numbers of poles. For twelve poles centrifugal and axial (or "scoop") fans were studied.*

*In Appendices 1 and 2 derivations of the more important equations for resistance and volume distribution are given. Appendix 3 covers a method for allowing for air flow through holes back of the core, for various fans, and for external pressure drops. In Appendix 4 the equations for parabolic volume distribution and the method of least squares appear.*

## I. Introduction

THE importance of a systematic study of ventilation of particular types of machines has been realized for a number of years. The success of the study of the multiple radial system of ventilation of turbo alternators, as a result of which the pressures, volumes, and their distribution are calculated,[1,2,3] led to the granting of an appropriation for a systematic experimental and analytical study of ventilation of salient pole alternators early in 1925, and the experimental work which is discussed in this paper, was completed early in 1929. There were many delays and interruptions which were in part responsible for the great length of time of four years. So many tests were made that the results of some of them are omitted. The work was done on a model, the structure of which could readily be altered.

## II. Construction of the Model

The model was made of hard wood, with a multiple of vent ducts of normal width of ⅜ in. each in the stator, the slots and teeth being of approximately average width; there was to be only one finger per tooth; and standard fiber wedges with rounded edges were first employed. A four-pole rotor is distinct from one of a large number of poles, but ten or more poles are sufficiently alike to warrant the construction of only one rotor of the greater number of poles. The final decision as to pole numbers was four and twelve; too much time and expense would be involved if more rotors were to be built. An eight-pole rotor is believed to be sufficiently like twelve poles to justify the use of twelve-pole data; and as few six-pole rotors are built, it is believed that sufficiently accurate approximations can be obtained by averaging the four-pole and twelve-pole data. Both

*Power Engg. Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. For references see Bibliography.

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30-48

the four-pole and twelve-pole rotors were made of wood, and the same stator was used for both. The end bells, and the imitations of the end windings were different for the two numbers of poles.

It was believed that the higher peripheral speeds of large generators should be approached. The four-pole rotor external diameter was 22 in., and the twelve-pole 22⅜ in. Thus with the maximum intended speed of about 2000 rev. per min., the peripheral velocity with twelve poles would be 12,100 ft. per min. Actually, the tests indicated the feasibility of operating at lower angular velocities, as will subsequently be shown. Consequently, most tests were made at 1200 to 1800

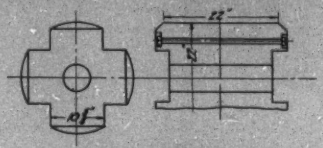


Fig. 1—Four-Pole Rotor

rev. per min. The internal diameter of the stator was 22¾ in., leaving single air-gaps of ⅜ in. for four poles and 3/16 in. for twelve poles, which are about representative air-gaps for the pole proportions adopted. For the four-pole rotor the ratio of pole arc to pole pitch was 0.64, and for twelve poles 0.72, which are also representative.

In the construction adopted for both rotors, the pole sides were the same width as the pole tips, as indicated in Figs. 1 and 2. Thus, the pole sides in the model imitate the outside of the field coils, which in many alternators are substantially the same width as the pole shoes. To have changed the rotors to correspond

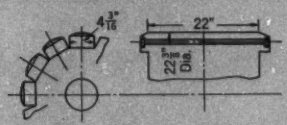


Fig. 2—Twelve-Pole Rotor

to different field coil widths would have prolonged the tests considerably more. However, some tests were made with pieces of wood attached to the sides of the poles of the twelve-pole rotor, thereby reducing the interpolar spaces.

The stator was built up of ten sections of hard wood each 1.5 in. thick, and two end sections 2 in. thick. There was a total of eleven vent ducts, there being no vents beyond the thicker end sections. Each section imitated a package of laminations. The wood sections were square on the outside, each side being 35 in. In order to simplify manufacture, no slots were cut in the wood sections. Instead of this, as shown in Fig. 3, punchings were made with the use of existing dies, the punchings being circular at the inner and outer diameters. One punching was nailed to each wooden section. Then to imitate the coils, blocks of hard wood which just fitted the slots, and were ⅜ in. plus the lamination thickness axially, were nailed to the wood sections. For the earlier tests, fiber wedges of standard construction were fastened to these blocks by means of wood screws. Although special efforts were made to make all wooden blocks and wedges alike, the tests showed considerable variation from one vent duct to the next. Consequently, in later tests with different forms of wedges, micarta blocks screwed on were used instead of wood, and the wedges were then made of brass accurately machined.

In all tests, there was one vent finger per tooth. These were standard construction of 0.094 in. steel riveted to the punchings. They were all one piece, not broken back of the slots as is frequently the case in alternators. The purpose was to insure that the air which entered between adjacent fingers would not escape until it was finally expelled at the rear, thereby permitting of the measurement of the air volume in a single vent duct between two adjacent fingers, *i. e.*, the air volume per tooth. Eight fingers on each side terminated flush with the straight sides of the square

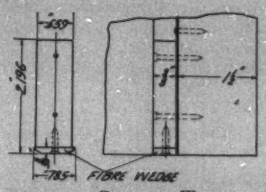


Fig. 3—Imitation of Coil and Wedge at Vent Duct

sections, thus admitting of volume measurements in $3 \times 7 = 21$ positions at each axial vent duct position. (As the fourth side was at the bottom and inaccessible, measurements were made on three sides.) As the restrictions to air flow were chiefly in the teeth, and particularly adjacent to the wedges, the friction offered by the length of the path beyond the teeth did not influence the pressure drop appreciably, and consequently the use of the same stator for four and twelve poles was justified.

Dummy end windings of pine lumber were placed at either end, they being different for the four-pole and twelve-pole rotor. Their proportions were approximately those which would be used in representative alternators. For the four-pole rotor the throw was slot 1 to slot 9, or ⅜ of full pitch. For twelve poles it was 1 to 5, or full pitch (48 slots total). These dummy end windings were easily removed or interchanged.

Standard end bell construction was used. As the stator end windings were longer for four poles than for twelve poles, wider end-bells were adopted for the

former than for the latter. A cross-section of the model is shown in Fig. 5. For simplicity, at the left side of Fig. 5, the rotor, the end windings, and end bells for the four-pole model are drawn, and at the right side they are shown for twelve poles. The original fans and seal rings for four and twelve poles are shown, but there were various fans, and other seal rings tried.

## III. Set-Up for Tests

The scheme for set-up for tests is shown in perspective in Fig. 6. The square wooden model is near the left

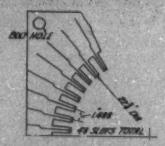

Fig. 4—Stator Tooth and Vent Construction

side of the sketch. The ends of the rotor shaft, after passing through the end bells, are supported by pedestal bearings, and on one end a pulley is mounted, the rotor being belted to a suitable direct current motor. The air enters through the external fan which is also driven by a suitable d-c. motor. After passing through this fan, the air flows past straightening vanes which were adjusted in the early part of the test to minimize errors in the thermal volume meter.

In Fig. 7 part of the four-pole rotor appears in the

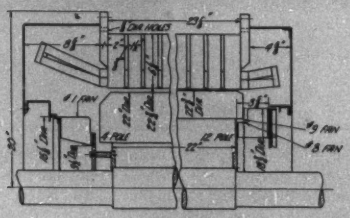

Fig. 5—Model Construction

foreground, the twelve-pole rotor being in the stator. Manometers for measuring the air pressures are mounted on the micarta board above the model. The pressure tube is in part within the inner wall of the end bell. The anemometer in its funnel is on the support for the pedestal. In Fig. 7 the thermal volume meter[4] is that part of the duct with the large number of wires on the outside. The electrical instruments—voltmeters, ammeters, and potentiometers used for the volume meter readings and for the input to the driving motor—are on the table at the left. The tachometer is on the support for the pedestal in Fig. 7.

## IV. Methods of Conducting Tests

A steady source of d-c. voltage was secured for supplying power to the two motors and to the heater of the thermal volume meter. For a given set-up of the model, the rotor was driven at such speed, usually 1200 or 1800 rev. per min., that suitable readings of pressures could be obtained, and the maximum permissible speed of the external fan would not be exceeded for the range in volumes that it was desired to cover. The rotor was run at this speed for about an hour before taking observations, in order that the bearing tempera-

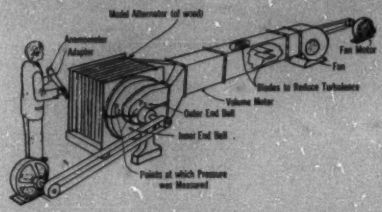


Fig. 6—Test Set-Up for Salient-Pole Alternator Ventilation Study

Approximately to scale—man shows relative size

ture would not change enough to affect the losses therein.

The first reading was taken with the external blower stationary, and with the entrance thereto closed; then the volume of air flowing through the model was negligible. Readings of speed, of pressure in the inner and outer end bells (indicated as $P$ 2 and $P$ 5 in Fig. 6), power input to the motor driving the rotor of the model were taken. The pressure was then generated by the

Fig. 7—The Test Set-up

rotor poles acting as fans, and by the internal fans mounted on the rotor. Following this set of observations, with the external fan still stationary, a cardboard orifice with a hole of suitable size was placed over the entrance to the external fan. As the pressure $P$ 5, on the intake side, was then below atmospheric pressure, the cardboard was held in position by the pressure difference at the fan's entrance. In addition to the readings taken at zero volume, the volume meter

reading was also taken. This was repeated with other orifices until the fan entrance was wide open. Then the external fan was started, and the pressure it generated was added to the pressure generated by the rotor and internal fans. This was repeated at higher fan speeds until the desired range of observations was completed. For all these readings, the model speed was kept the same, except in a few cases when the maximum speed of the external fan had been obtained, the speed of the rotor of the model was dropped in order to secure higher points on the pressure volume characteristic. The input to the d-c. motor was measured for each

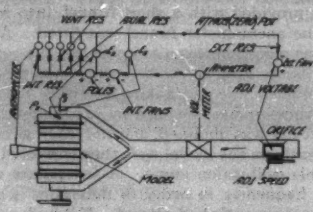


Fig. 8—Electrical Analogy

setting to determine the windage losses. In order that suitable allowance be made for the losses in the motor, belt, and bearings, motor input readings were taken with the model rotor removed from the shaft; in addition, the motor armature $I^2R$ loss was allowed for in the usual way.

The axial distribution of volumes was taken at one or two points on the pressure volume curve. For these, a rotating vane anemometer was used, as shown in Fig. 7. The spacings of the vent duct fingers were uniform, and the tapered sides of the funnel were made so as to fit into the vent duct opening at the rear. To determine the influence of different numbers of vent ducts, some vents were closed for some curves, for which suitable pieces of wood with felt inside held in place with wood clamps were used. The clamps were easily added or removed. The two vents at either end are closed in Fig. 7.

It is believed that the reader will be assisted toward an understanding of the manner in which the tests were conducted by an electrical analogy, as in Fig. 8.

There are three generators (fans) which supply the current: the external fan, the internal fans (at the ends of the rotor) and the poles acting as fans. All fans (or generators) operate at constant speed except the external fan, the speed of which is adjustable. The total current (or volume per unit of time) is measured by means of a thermal volume meter (ammeter $A$ in the electrical diagram). In the electrical diagram the orifices which were used with the external fan at standstill are represented by "External Resistance," and for higher pressures the pressure of the generator analogous to the "External Fan" is varied by any of the usual means. The static pressures are measured in the inner and outer bells,[4] these pressures being indicated as $P_2$ and $P_3$ respectively ($E_2$ and $E_3$ in the electrical diagram), both being measured above (or below) atmospheric pressure, the latter being taken as at zero potential for reference. Between $P_2$ and $P_3$ are the internal fans, so that $P_2 - P_3$ = generated fan pressure.

The air flows against resistance when flowing before and after, and through the internal fans, through the interpolar spaces and air gap, and through the radial vent ducts. These various resistances are indicated in the electrical diagram; thus, the resistance offered during the passage through the interpolar spaces and air gap is indicated as "axial resistance," etc. The ammeters in each vent duct path correspond to the anemometer for taking vent duct volume distribution readings.

The pressure volume curves are of the general form indicated in Fig. 9. $P_2$, the inner end bell pressure curve, is the pressure required to drive the air through the circuits from the end bells to the atmosphere. It includes all the pressure drops in that part of the circuit and the pressure generated by the poles. Evidently, a generated pressure is of opposite sign to a consumed pressure (as in an electrical circuit), and therefore if the pressure consumed by resistance be taken as positive, the pressure generated by the poles acting as fans, is negative. Thus, at point $A$, for zero volume, the pressure is negative, the air being shut off at entrance, and the poles, as fans, tend to "suck" the air out of the end bells. In the diagram of the analogous electric

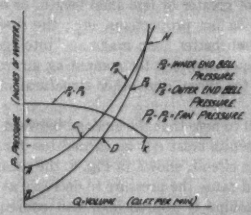


Fig. 9—Diagram of Pressure—Volume Curves

circuit in Fig. 8, the polarity of the three generators is marked + and −. Considering that atmospheric pressure is zero potential in the electrical analogy, if the circuit be opened at a terminal of the "external fan," $E_2$ and $E_3$ will read negative. They will continue to be negative for high external resistances, and $E_2$ becomes positive when the internal resistance exceeds the pressure generated by the poles. At the point $C$ (Fig. 9) the inner end bell pressure is zero, (atmospheric pressure), and the volume then corresponds to the case of open end bells. In the experiments, for most of the readings between $A$ and $C$, the external fan was shut down, and resistances in the form of orifices were used to regulate the flow of air.

In Fig. 9, it is evident that the pressure $P_3$ measured

in the outer end bell is below that of the inner end bell $P_2$ by the amount of the fan generated pressure. Deducting $P_6$ from $P_5$ gives the fan curve. The volume corresponding to the point of intersection, $D$, of the $P_6$ curve with the zero axis is nearly the working point in the usual alternator. There is a slight departure due to the fact that there is generally a small drop in pressure from the entrance to end bell to the entrance to the fan. The $P_5$ and $P_6$ curves approach each other, owing to the increasing internal pressure drop in the fan as the volume is increased. The point of intersection of these two curves at $H$ corresponds to the condition of all pressure generated by the internal fans being consumed by their internal resistance—like an electrical generator on short circuit. Thus the fan pressure $K$ is zero at the same abscissa as $H$. Beyond $H$ or $K$, the fan pressure comes negative, meaning that the internal pressure drop in the fan exceeds its generated pressure. The data obtained in this way for the twelve-pole model agreed very well with the data published[6] previously. The data from fans for the four-pole model did not agree, and that will be gone into later.

One of the limitations imposed by tests as usually made on an alternator is that only one point on the $P_5$ curve is obtained, approximately that at $D$ on Fig. 9. This assumes that volumes and pressures are measured accurately, which is generally not the case. With the introduction of conditions out of the ordinary, such as the resistance of external ducts or of an external cooler, or parallel paths through holes back of the core, or of the influence of greater or less axial length, or of the effect of change in fan proportions, etc., the designer could not do much better than make an "intelligent guess." In this paper methods for computing air volumes and pressures for these, and other structural changes, are included.

It is well to note that the analogy between the air and electric circuits must not be carried too far. Thus, in the electric circuit, shown in Fig. 8, the axial resistance drop would cause the pressure to decrease as the middle of the machine is approached, and consequently the volumes per duct would decrease also. But for the air circuit, as the axial velocity decreases, the static pressure increases (in accordance with Bermoulli's equation) and therefore the stator volume per duct increases also. Again, in the electric circuit, the pressure drop is proportional to the first power of the current, whereas the analogous relation takes the quadratic form for the air circuit when the flow is turbulent.

To the rotating vane anemometer which was used for obtaining the volume distribution curves, a funnel was attached and the other end of the funnel fitted into the space between two adjacent fingers. The anemometer is usually an unreliable device, particularly if it is to be used for measuring air velocities in an open duct. However, when it is desired to secure only relative readings and to measure volumes, instead of velocities, it is fairly reliable and is about as good as any instrument that we know of at present. What we were interested in was the shape of the volume distribution, meaning relative values. One difficulty with an anemometer is that its calibration may change from time to time due to change in friction, or in the shapes of the blades which might be inadvertently bent. Furthermore, owing to static friction in its bearings, the velocity of the air passing through it must attain a certain value before the anemometer will rotate. This also means that a calibration curve does not pass through the origin. The difficulties were overcome by checking the anemometer frequently by means of a small vacuum cleaner motor and fan, provided with a short funnel, into which one end of the anemometer funnel was fitted. A suitable orifice was placed in this air circuit and the square root of the pressure drop across this orifice was proportional to the volume of air. By taking a series of readings and plotting these square roots against anemometer readings a straight line was obtained, and the readings as secured subsequently on the model were then corrected with the use of this calibration curve. A few points would be checked frequently in order to determine whether or not the instrument's had altered. If it had, a complete new calibration curve was obtained.

The funnel as used was about 24 in. long; in the earlier readings the funnel was about half that length, and it was found that when connected to the calibrating device different results were obtained if the anemometer were vertical or horizontal. It was also found that readings were unreliable when used in the alternator model, due to pulsations which did not disappear in the shorter funnel. In general, ½ minute readings were taken so as to conserve time with the large number that were secured. The readings were taken at one side and at the top, there being ten readings in each axial position, which were subsequently averaged and a suitable correction was applied to the average. This saved labor in working up the results, as compared with correcting each reading and then averaging the corrected readings. The errors introduced by the simpler method were undoubtedly of small moment.

After having taken some of the earlier readings, when the difficulty with pulsation was experienced, it was thought that perhaps a better understanding of the phenomenon might be obtained by studying the variation in pressure in the vent duct. Consequently, a special device was designed and was connected to a vent duct opening, the other end of the air column impinging upon a diaphram connected to a small mirror which, in turn, magnified the variations in pressures in ways familar to those versed in the art. A beam of light thrown on this mirror, in much the same way as in an oscillograph, enables an observer to secure a record on a film just as in an oscillograph. In fact, the mirror and light system, etc., were those ordinarily used in an oscillograph. No air flowed through the particular vent opening which was connected with the instrument while a record was taken. One of the records obtained is

shown in Fig. 10, which was taken in the third duct from the center line, at a high point on the pressure volume curve. A study of some of the films indicates how complicated are the phenomena with which we are dealing and therefore how difficult it would be to obtain an analysis based upon fundamentals.

The comparison between magnetic pulsations, frequently obtained on oscillograms, and the air pulsations are interesting. There seems little doubt but that the large pulsations are due to the poles. The fine pulsations are due to the pressure of teeth and slots, *i. e.*, tooth harmonics. These pulsations can be quite easily explained qualitatively. Evidently, when a pole passes

Fig. 10—Static Pressure
1200 rev. per min.
2.54-in. $H_2O$ end-bell press

in front of a vent, the area for axial flow is reduced, and the vent duct velocity and pressure fall, thereby accounting for the large pulsations. The "tooth harmonics" are produced by elastic pressure pulsations due to variation in section as the pole passes from tooth to slot; it is believed that the whole volume of air pulsates slightly, and that viscosity assists to dampen the variations.

## V. Interpretation of Results

*1. Elimination of Some Independent Variables.* As is usual in experimental work, there are many independent variables, and it is important to reduce their number to a minimum. With the existing knowledge of the subject, some of these, such as are associated with the mechanical structure, as the wedge shape, must remain as independent variables. It was found, however, that a few variables are interdependent, and if experimental data are obtained for one set of conditions, they can be applied to another. These are: (1) Rev. per min., (2) Dimensions of machine, (3) Holes back of core, (4) Fans if data were available on fans in fan test model equipment.[4] Experimental data were obtained to verify these interdependent relations, as follows:

*1. Rev. per min.* In Appendix 1 the derivation of the relation between volume and inner end bell pressure is given, the derivation having been obtained by the method of dimensional analysis. As in most rotating apparatus, the pressures generated by centrifugal forces are proportional to the square of the angular velocity. With turbulent flow, and for a given resistance in the circuit, the volume is proportional to the first power of the angular velocity. Consequently, if data are obtained at one speed, they may be applied at any other speed by multiplying the pressures by the square of the ratio of angular velocities, and the volumes by the first power of that ratio. The pressures in the outer end bell are equal to those in the inner end bell minus the pressure across the fan. Since the fan follows the same general laws in regard to the effect of rev. per min., as the machine, the outer end bell pressure does too. (All data for the twelve-pole model have been arbitrarily reduced to 1000 rev. per min. (or 1 rev. per min.), and most of the four-pole data are reduced to 1800 rev. per min., although a few have been reduced to 1 rev. per min.* An example of experimental proof is given by Fig. 11 where data taken at 1800 and 1200 rev. per min. are reduced to 1000 rev. per min. and are on the same curves.

As another example of experimental proof see Fig. 12. The constants in the equation from which the curve is plotted were obtained from the 1200 rev. per min. data, many more points having been obtained than could be plotted, as all of them are crowded at the lower part of the curve. The data taken at as low a speed as 195 rev. per min. fit in very nicely with the calculated curve based upon 1200 rev. per min. data. The check is particularly striking when one considers that the square of the speed ratio is 37.7.

There were various other experimental data obtained, proving that speed can be eliminated as an independent variable. One was the agreement in anemometer readings for the central vent duct taken at 1200 and 1800

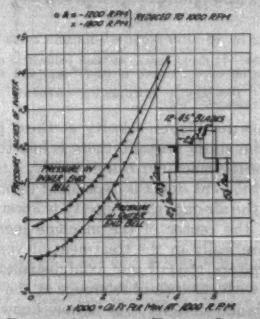


Fig. 11—Pressure—Volume Curves
Twelve-pole rotor—No. 8 fans

rev. per min., and reduced to a common speed. The distribution of volumes per vent is relatively the same for all speeds, the volume per vent being proportional to the first power of the speed.

*2. Dimensions of Machine.* The dimensions of the vent ducts were typical of those for an average machine. Aside from the influences of the structure, the factors

*Most of the four-pole data were taken before the twelve-pole, and were plotted at the speed at which most of those data were taken: 1800 rev. per min. It is obviously better to reduce to 1000 or 1 rev. per min., but too much labor would have been involved to change all the four-pole curve data. Most twelve-pole data were taken at 1200 rev. per min.

which determine the pressure drop through a vent duct are the circumferential and axial velocities of air in the air-gap and interpolar spaces, and the radial velocity in the vents. If for a given length of machine running at a definite angular velocity there is a certain end bell pressure to drive the air through the interpolar spaces to which the pressure generated by the centrifugal action of the poles is to be added, a definite velocity is obtained in the middle vent duct. For any other vent duct the movement of the air axially in the air-gap and interpolar

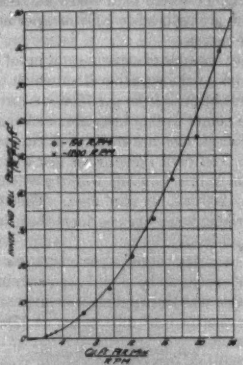

Fig. 12—Pressure—Volume Curve

Four-pole rotor—11 ducts open. All data reduced to ninety rev. per min. No fans on rotor. Drawn in curve calculated from equation:

$$P = 0.108\ V^2 + 0.0162\ V_P - 0.007\ r^2$$

spaces makes for higher velocity at those places and, therefore, the static pressure there is less than it is at the center of the machine; consequently, if the velocity radially in the vent ducts is dependent upon the static pressure in the air-gap, that velocity is lower as the distance from the center of the machine increases. As shown theoretically in the treatment of ventilation of turbo alternators, the curve of axial distribution is that of a cosine with the axis of reference at the position of maximum radial velocity. It is now known that the curve is not so simple as that of a cosine, due not only to the unavoidable losses in the air-gap, but also due to the fact that the radial velocity is not proportional to the square root of the difference of static pressure between the air-gap and the air outside of the punchings. Large numbers of tests have been made on models, simulating vent and other ducts, which have assisted materially in our understanding of these relations. In those experiments, the influences of such things as wedge construction, angle of incidence, gap velocities, heights and shapes of fingers, were studied. Reports covering that work have not been published. Among other deductions, it appears that the influence of the axial movement of the air is relatively small in its effect upon the radial flow in the vent ducts. Changes in circumferential velocity have much more influence. Therefore, in many cases we should not be making a very great error by considering the curves to be those of simple cosine form. In our early work, which was done on the four-pole model, the form of the equation was still further simplified by treating it as a parabola* of the form:

$$Y = a - b\,x^2$$

The axis of reference for $x$ is then at the middle of the machine. Some of the subsequent work which was done with reduced interpolar spaces to imitate very long machines for the twelve-pole model, indicated that it was sufficiently correct to consider the equation to be of this form. Instead of the distribution curve dropping all the way from the center to the extremities, the ends of the curve bend upward. This was even more marked when more efficient forms of wedges were substituted for standard wedges, or when the wedges were omitted entirely at the vent ducts, with rounded coil corners. In any case, however, it appears that for a given value of end bell pressure and angular velocity the distribution curve for the shorter machine is nearly the same as for the longer machine with the ends removed. While shorter models were not actually sub-

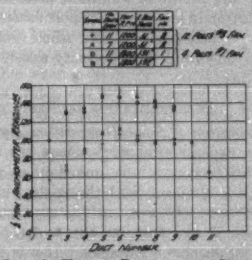

Fig. 13—Volume Distribution Curves

7 and 11 ducts open. Twelve- and four-pole rotors

stituted for the longer one, which would have involved a great deal more time and expense, it is believed that the confirmation of this statement is sufficient, based upon the tests which were made by closing off the ends and by closing the three middle vent ducts. Attention is called to Fig. 13, for which the points have been plotted for seven vents and eleven vents for the four- and twelve-pole rotors. For those tests which are comparable, the end-bell pressures and rev. per min. are the same. Within the range of experimental error, it is believed that this confirms our statement fairly well.

*The expansion of cos $x$ is:

$$\cos x = 1 - \frac{x^2}{2\,!} + \frac{x^4}{4\,!} - \frac{x^6}{6\,!} + \ldots$$

The parabolic substitution therefore makes use of the first two terms of this series.

Attention is also called to Fig. 14. In this case, not only were the outer vent ducts closed, but the three middle ones were subsequently closed with all the others open. If the curves for this latter condition are moved toward the center, they will be found nearly to coincide with the curves for eleven vents.

There are a great number of irregularities associated with the comparison of a full size machine with that of a model, taking into account all the variations in length, interpolar space, air-gap, diameters, etc., but it is believed that sufficiently close approximations can be

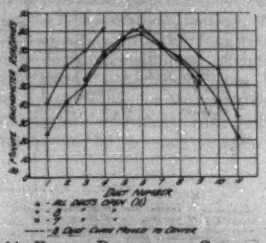

Fig. 14—Volume Distribution Curves

Twelve-pole rotor. No. 11 fans. Showing effect of shorter machine. With hoods. No seal ring. Zero end-bell pressure 1200 rev. per min All data reduced to 1000 rev. per min. Standard wedges. Rounded pole corners. (See Figs. 32 and 33 for fan details)

made with the use of the empirical data obtained from the tests on the model to enable an estimate to be made, with a fair degree of accuracy, of the pressures, volumes, and their distribution. A further treatment of the theory on this subject is given in Appendix II.

*3. Holes Back of the Core.* It is now believed that when solid enclosing end bells are used it is best to put in holes of such size that just about enough air will pass through them to cool the end windings. A method of computing this volume of air and combining it with the other air passing through the vent ducts, is subsequently given in Appendix III. Some of the early tests made on the four-pole model indicated that it was unnecessary to make tests with various sizes of holes or with the holes closed or open. It would be sufficient to make a series of tests just one way. Holes were drilled through the wooden end plates shown in Fig. 5, there being five holes, each 7/8 in. in diameter, at each of the four sides at both ends. Performance curves taken with these holes open, and with them closed by means of corks, are shown in Fig. 15. The curve with the holes open was obtained from the curve with the holes closed by adding the volume given by the area of the holes times the square root of the pressure, times the contraction coefficient 0.85 and the usual constant of 4030. From volume distribution curves the contraction coefficient appears to be 0.83,* which checks very well with the other value. In all subsequent tests these holes were closed as it was felt that, in any case, if the volumes through them were to be computed, or if allowances were to be made for the influence of the volumes through the holes upon the end bell pressure, they would be comparatively simple to calculate.

*4. Fans.* From the beginning of the tests, comparisons were made between the fan performance curves of pressure-volume and those fan performance curves previously published.[6] The first work on the salient pole alternator was done on the four-pole rotor, and it was not found possible to check. For example, refer to Fig. 19. However, those earlier tests were made on fans in which the inner periphery was that of a cylinder, whereas for the four-pole model, the inner surface was that of a cone. The curves do not agree either in magnitude or in general shape. It is believed that it is a decided detriment to make the inside of the fan conical, for it causes most of the air to flow adjacent to the supporting plate near the rotor body. There is, furthermore, a fairly sudden change in the performance, as will be noted from the pressure volume curves and from the fan performance and windage curves such as shown on this same curve sheet. Fans have been

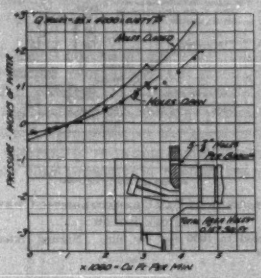

Fig. 15—Pressure—Volume Curves Four-Pole Rotor

Effect of holes back of core for ventilating ends of stator coils. All curves taken with No. 1 fan and are for inner end-bell. The curve for "Holes Closed" is the mean for data taken at 1800 rev. per min. The points plotted for "Holes Open" were taken at 1200 (x & ⊡) and 1800 rev. per min. ⊙ The curve for "Holes Open" was calculated from the "Holes Closed" curve by adding to the vol. at a given pressure

$$Q \text{ holes} = 0.85 \times 4030 \times 0.167 \sqrt{P}$$

made conical inside for four-pole machines because of restriction in space between the shaft and the fan. On the four-pole rotor the fans as they had been built were simulated as far as was possible. It is believed to be highly desirable to repeat some of these tests with fans that are cylindrical inside, even though it would mean making the fans shallow. The indications are that the volume of air can be increased thereby, and furthermore, that the earlier data obtained can be applied directly to fans in salient pole alternators.

On the other hand, it is interesting to note that for the twelve-pole rotor, the fan data agreed very nicely with the earlier tests. This is particularly true in the

*This "contraction coefficient" is fairly high because the plate was thick. Had thin plate been used the coefficient would have approached the usual value of about 0.62.

case of the No. 9 fan. A composite curve, Fig. 16, illustrates this quite clearly. On that sheet, two of the curves were for No. 8 fan, the dimensions of which are given on the same sheet, and that fan is not of the type tested earlier, whereas the other curves for No. 9 fan are directly comparable with the earlier tests.* It appears that, at the larger volumes, the fan as used in the alternator is slightly better than in the early set-up. This is believed to be partly due to the different conditions that obtain in the alternator, which probably assist in restoring some of the velocity head of the air, as it leaves the fan tips, into static pressure. Also, the air can pass directly in between the poles, and they probably act to assist the fan, the air in the bell acting to some extent as a cushion.

It will therefore be seen that for the four-pole model it was desirable to have tests on fans of various dimensions, and as will be seen from the following, a few types of fans were tested with the twelve-pole model. Hence,

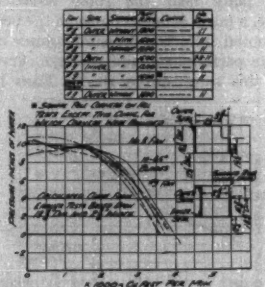

Fig. 16—Comparison of Fan Characteristic Curves Twelve-Pole Rotor

All data reduced to 1000 rev. per min. Normal interpolar spaces Standard wedges

the fans could only partially be eliminated as an independent variable.

## VI. Structural Independent Variables

There was a total of eleven independent variables which are here given in the order of their importance. There are other independent variables which warrant consideration, but owing to limited time and the pressure of other work, their study was not undertaken. The eleven variables are: (1) Numbers of poles; (2) Fans; (3) Numbers of vents;* (4) Wedges in stator; (5) Interpolar spaces; (6) Fan seals; (7) Fan shroud rings; (8) Field coil braces; (9) Plate in end-bells; (10) Round and square pole corners; (11) Location of fans. In this paper the more important and illustrative data for items 1, 2, 3, 5, 6, 7, 9, and 10 are given. Inasmuch as some of these are closely associated with numbers of poles and fans, they will be discussed together, rather than separately. The general theory and methods of using the data are given subsequently in the Appendices.

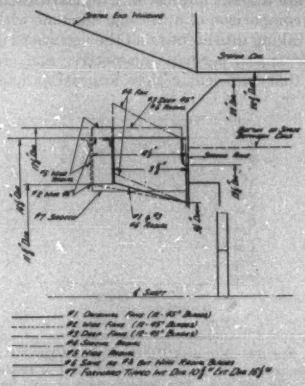

Fig. 17—Fans Tested with Four-Pole Rotor

*A. Four Poles.* The four-pole rotor was tested first. All tests were made with standard wedges, as shown in Fig. 3. Tests were made without any internal fans, as well as with seven pairs of fans. Results of only three types of fans, and of no internal fans, are here-

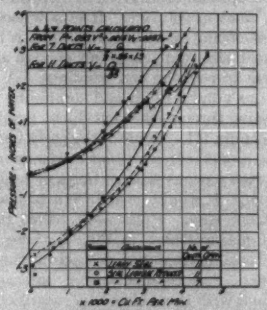

Fig. 18—Pressure—Volume Curves Four-Pole Rotor

Upper curves—inner end-bell
Lower curves—outer end-bell
All curves at 1800 rev. per min.—fan No. 1

with given for the sake of brevity. These three had 12 straight blades each, inclined at 45 deg. to a tangent at the innermost diameter. The data not included were on three radial blade fans, and one set with curved blades terminating with forward tipped blades at the

*In reducing the early data to correspond to these data, No. 9 fan dimensions were taken as a basis. See note on Fig. 16.

*Owing to a few cases of slightly erratic data (such as Fig. 27) several tests were made with full and reduced numbers of vents; that is, the dimensions were not entirely eliminated as an independent variable.

external periphery. The cross-sectional dimensions of the 7 fans are given in Fig. 17.

The first fan was No. 1, for 45 deg. inclined straight blades, whose proportions are similar to those frequently used in alternators. The tests obtained showed that the pressure-volume curve for this fan had a peculiar dip in it, as indicated in Fig. 18. This dip appears also in the windage loss curve, Fig. 24, and it was believed that if the fan could be worked in the valley of the curve instead of on the rising part, the windage loss would be considerably reduced. It was also found that the fan performance from the earlier tests could not be checked. In order to meet the first conditions, namely, of securing more efficient fan operation, two other fans were made—No. 2 and No. 3—both having 45 deg. straight blades; No. 2 was wider than No. 1, the diameters being the same, and No. 3 was deeper for the same width. In regard to not being able to check with earlier tests, it appeared that it would be necessary to make tests on a

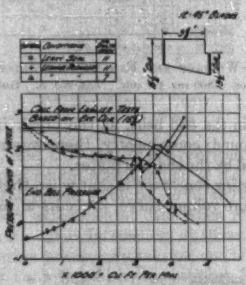

Fig. 19—Fan Characteristic and Pressure-Volume Curves

Four-pole rotor—1000-rev. per min.—No. 1 fan. Holes back of core closed. Effects of leakage

large number of fans in order to determine which fan would work best, as it seemed we could not use the earlier data.

Referring again to the dip in the curves, it will be seen from Fig. 18 that, with eleven vents, for the pressure in the external end bell to be zero, (corresponding nearly to the conditions in an alternator), the curve is worked on the rising part. With the wide fan, No. 2 (see Fig. 20), for zero outer end bell pressure the working point is nearly at the dip in the curve. This volume is about 1.78 cu. ft./min. for 1 rev. per min., or 3200 cu. ft./min. for 1800 rev. per min. Fig. 21 shows that for this volume the windage is practically at its minimum value, so it would seem that a fan of these proportions would be suitable for a machine of the proportions that were used. However, had the machine been shorter, it would have been worked on the rising part of the pressure volume curve and the gain would not have been achieved in regard to low windage. In so far as No. 3 fan is concerned, Fig. 22 indicates that increasing the external diameter was not in the right direction. In this case the break with 11 ducts is beyond the range of this curve and occurred at about 4500 cu. ft./min. at 1800 rev. per min. The windage curve, Fig. 23, also indicates that the fan was not worked at the valley as desired for zero outer end bell pressure. The indications are that the most favorable fan is either No. 2 or No. 1,

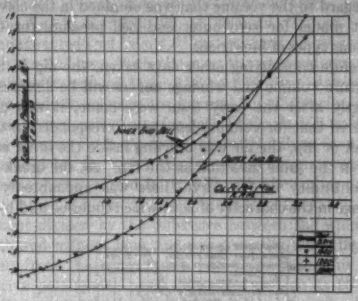

Fig. 20—Pressure—Volume Curves

Four-pole rotor—11 ducts open. Holes back of core closed. Reduced to 90 rev. per min. No. 2 wide 45 deg. fans

although it would seem that the use of plates in the end bell to lower the windage over a given range, as will subsequently be described, is somewhat helpful.

During the tests on No. 2 fan, through a misunderstanding, tests were made in the reverse direction. It is of great interest to note that, with the fans reversed, considerably less pressure is needed to drive the air

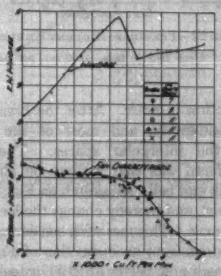

Fig. 21—Fan Characteristic and Windage Loss Curves

Four-pole rotor. 1800 rev. per min. No. 2 fan. (Wide 45 deg.) Holes back of core closed

through the stator than with them running forward. This led to a speculation: it might be possible to reduce the pressure drop by terminating the blades radially, or, better, to curve them so that they bent forward at the outer diameter, as in many general purpose commercial centrifugal fans. As the blades were to be made fairly deep, it was also thought that

radial blades might work out satisfactorily. The anticipated gain by tipping the blades forward was not obtained, either as regards volume or windage; nor were radial blades quite as good as inclined blades, from the ventilation standpoint, although possessing the advantage of lower stresses for wide high-speed fans. There is not much difference between the various curves in regard to the volume that was obtained in the eleven duct model for zero outer end bell pressure for the various types of fans tried.

Before considering other data taken, the dip in the pressure volume and windage curves will be discussed. Shortly after the early tests were made, it was discovered that for volumes less than corresponded to the break or dip, the air was whirling inside the inner end bell in the same direction as the fan. At the break or discontinuity in the curve there was undoubtedly a change in the character of flow, which could be told by a

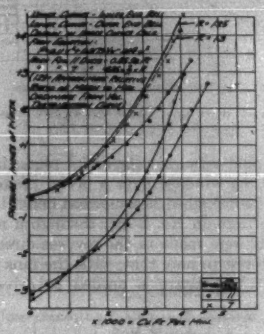

FIG. 22—PRESSURE—VOLUME CURVES

Four-pole rotor. Deep (No. 3) fans—1800 rev. per min. Holes back of core closed

marked reduction in noise. After the break the whirl subsided considerably, and most of the air passed directly to the interpolar spaces. Therefore, the suggestion offered was that a plate be placed at the parting of each end bell, (see sketch on Fig. 24), so as to reduce the whirl, and thereby change the location of the break in the curve. This met with considerable success, as will be evident from an inspection of Fig. 24. The start of the break now begins at 2100 instead of at 3160 cu. ft. per minute. A machine similar to this model can then readily be operated beyond the break in the curve. For the condition of the outer end bell pressure being zero (*i. e.*, the approximate usual working point), the volume is substantially the same as before (2950 instead of 3030 cu. ft./min.). For 2950 cu. ft., the inner end bell pressure has been reduced from 1.45 in. to 1 in. of water.

It will also be seen that the windage loss for equal volumes of 2950, is reduced from 4.65 to 3.35 kw., or to 72 per cent of the former value. The change in fan characteristic, as in Fig. 24, due to the use of the plate, is also of interest. For the conditions under which the twelve pole rotor was tested, there was probably but

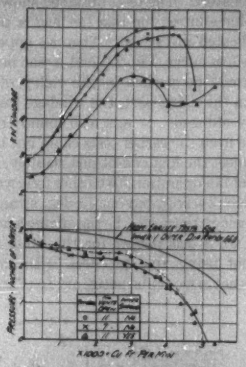

FIG. 23—WINDAGE AND FAN CHARACTERISTIC CURVES

Four-pole rotor. 1800 rev. per min. Fan No. 3. Holes back of core closed

little whirl in the end bells, as the break in the curve was never found; consequently, there was no improvement effected by the end-bell plates.

An interesting conclusion is that when there is a break in the pressure volume curve, it occurs at substantially

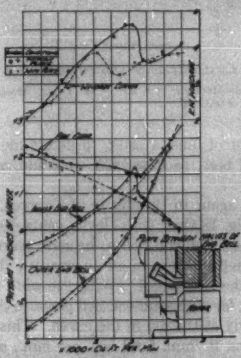

FIG. 24—PRESSURE—VOLUME, FAN CHARACTERISTIC, AND WINDAGE CURVES

Four-pole rotor—1800 rev. per min. Fan No. 1. Curves showing effect of plate in end-bell. Holes back of cores closed. 11 vents open

the same volume (for a given angular velocity) irrespective of the number of stator vent ducts. This will readily be seen from an inspection of Fig. 18, where the "valley" of the inner end bell pressure curves for both seven and eleven vents occurs at about 3800 cu. ft. per

minute. For seven vents, if the outer end bell pressure is zero, the volume is 2700 cu. ft./min. Referring, then, to Fig. 24, at 2700 cu. ft., the working point is beyond the break, giving lower end bell pressures. It was also found that if nothing be changed except the number of vents, (the rotor being the same as to length, etc.) the windage loss curve was nearly the same for seven and eleven vents. (See Figs. 23 and 25.) Consequently, read on Fig. 24 the approximate windage for seven vents at 2700 cu. ft., giving 3.25 kw. with plates, as compared with 4.48 kw. without plates, or a reduction to 72.7 per cent.

Tests were also made without internal fans, some pressure volume and windage data being plotted in

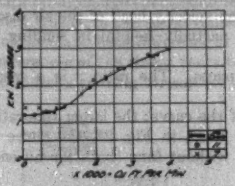

Fig. 25—Windage Curve
Four-pole rotor—1800 rev. per min. No fans

Figs. 12, 26, and 25. Fig. 12 was previously discussed, as being experimental corroboration of the form of the equation of the pressure volume curve, and of the agreement between experimental data when reduced to a common speed. It is interesting, as shown in Fig. 26, that for positive pressures, the outer end bell pressures were greater than the inner, the contrary having been the case with internal fans until very high pressures and volumes were obtained. This is necessarily so, as, without fans, there is the "resistance drop" from the entrance to the outer end bell, to the inner end bell. While that drop is present also with internal fans, the pressure generated by the fans overcomes that drop and adds to the inner end bell pressure. The drop can, of course, be reduced by enlarging the entrance passages, or by placing suitable guide vanes therein,[7] although it is seldom that the gain thereby achieved is warranted. Without fans, for zero outer end bell pressure and eleven vents, the volume is 1440 cu. ft., as compared with 3130 cu. ft. with No. 1 fan (Fig. 18), or 46 per cent of the volume with fans.

Comparing the inner end bell pressures for no fans and for No. 1 fans (Figs. 18 and 26), it will be seen that less pressure is needed without fans (thus, at 3000 cu. ft. the pressure is reduced from 1.46 to 1.08 in. of water) before the break in the curve. After the break the pressure is slightly less with fans. (As an example, at 4000 cu. ft. it is 2.03 in. with fans, as compared with 2.47 in. without them.) This is as might be expected, as with the whirl before the break, the resistance to flow is increased. There is probably some whirl without fans too, though not so great as with fans below the break. Therefore, after the break the pressure drop has been very materially reduced with fans; but, as the whirl is still present without fans at the corresponding volume, there is no reduction in pressure. There were no tests made without fans and with the end bell plate.

As might be expected, the windage loss is less without than with internal fans for the same volume. Thus, from Fig. 19 and Fig. 25, at 3000 cu. ft./min., the windage is reduced from 4.62 kw. (without plates in end bells) to 2.57 kw. With plates, at the same volume, the windage is reduced from 3.38 to 2.57 kw. Attempts were made to compare the internal fan efficiencies with those of the earlier tests for both four-pole and twelve-pole rotors. Such attempts met with failure even for twelve poles, for which the fan characteristic pressure volume curves agreed fairly well with the earlier data. The fan efficiencies were determined from the fan power output divided by the difference between the windage with and without fans, and was generally much higher than from the earlier tests. In some cases, for the twelve pole model, peak efficiencies as high as 90 per cent were obtained. This is, of course, absurd. It is believed that much of the velocity head at discharge from the fans is not lost; that is, that the air moves into the interpolar spaces at fairly high velocities, and the

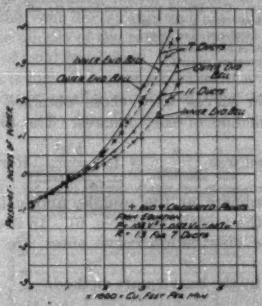

Fig. 26—Pressure—Volume Curves
Four-pole rotor. 1800 rev. per min. No fans on rotor
Note: Pressures in inner end-bell are lower than in outer

kinetic energy in the streams as they leave the fan tips is largely the same kinetic energy in the axially-moving streams in the interpolar spaces and air gap. Considering the fan separate from the rotor, (as was done in the foregoing method of calculating the fan efficiency from the windage with and without fans), the kinetic energy (velocity head) is charged twice, which, according to the theory advanced of only partial loss of kinetic energy, is incorrect. It would seem that external fans are usually more efficient than internal, considering each as units, but it is believed that as the internal fan and rotor act as a unit in which much of the kinetic energy of discharge from the former is used in the latter (which

is not the case with external fans and no internal fans) the combination with internal fans may, in many cases, prove to be more efficient from the standpoint of power consumed in windage.

*Four-Pole Volume Distribution Curves.* As was previously explained, the volume distribution curves were taken with a rotating vane anemometer, each reading being for one-half minute, and the average of 11 readings at a given axial position, suitably corrected, gave one point on each of the curves. Owing to irregularities in the vent ducts, these points do not all fall on smooth curves, and for the four-pole model,

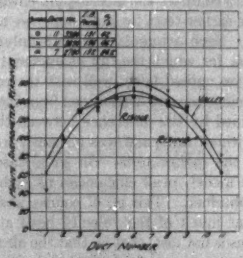

Fig. 27—Volume Distribution Curves

Four-pole rotor. Conditions that were same for all 3 curves
1. Internal fans—No. 1 (45 deg.)
2. Speed = 1800 rev. per min.
3. Holes back of core closed
4. End-bell pressure (nearly)

the drawn-in curves were those obtained with the aid of the method of least squares. The form of the equation used was $\frac{y}{y\,max} = 1 - \frac{b\,x^2}{a}$. Here, $a$ is the maximum ordinate at the middle, and $x$ is the distance from the middle (duct No. 6). In the tables on each volume distribution curve sheet are values of $\frac{a}{b}$ obtained by the least square method.

The three curves in Fig. 27 are for No. 1 fan. The end bell pressures for all three were substantially the same. The lower curve for eleven ducts was taken at a point on the pressure volume curve before the break (Fig. 18), and the upper curve after the break. The area under each curve is proportional to the volume per unit of time, and, therefore, there was more air flowing when the upper curve was taken than for the lower curve. According to previous statements, the curve for seven ducts should coincide with that for eleven ducts, but there are departures in this case, the seven-duct curve being flatter. Considering the complexity of the phenomenon and the inaccuracies of measurement by anemometer, very close agreement cannot be expected. It is believed that the assumption made and used in the subsequent mathematical treatment of the coincidence of the distribution curves is justified, especially since great accuracy in ventilation calculations is unnecessary.

The two upper curves in Fig. 28 were taken with and without the plate in the end-bells for nearly the same volume, but with pressures of 0.70 and 1.30 in. respectively. This is a confirmation of the gain to be effected when there is a break in the curve, and as shown in Fig. 24. The lowest curve was taken without internal fans with zero end bell pressure, corresponding to the condition of open or no end-bells. The corresponding curve with nearly zero end bell pressure, but with fans, is shown by the intermediate curve, indicating that the fans are helpful even though the terminal pressures axially are atmospheric (zero for reference). It would seem that the velocity head of the air discharged from the fans is partially helpful in sending air into the interpolar spaces. The ratio $\frac{a}{b}$ is a measure of the "flatness" of the curve; the larger this ratio the flatter the curve. Thus, in Fig. 28, the curve with fans is flatter than without fans (both for no end-bells), the values for $\frac{a}{b}$ being 36.3 and 24.7 respectively.

Data for No. 2 fan are similar, and the distribution curves are not included.

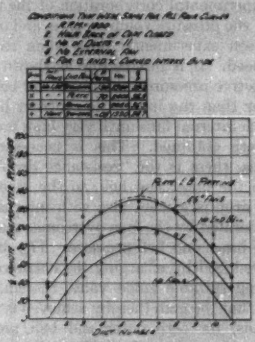

Fig. 28—Volume Distribution Curves
Four-pole rotor

In Fig. 29 volume distribution curves for No. 3 deep are shown. The two upper curves are interesting in that, for one curve there were inner shrouds on the fans, but not for the other. The curve taken with shrouds is the flatter, meaning that the volume distribution is more uniform, the maximum volume per vent being nearly the same. There was a difference in end bell pressure, the pressure being higher with shrouds. The volumes were nearly proportional to the square root of the end-bell pressures. It is usually considered

advisable to omit the shroud, as then the air entering between field coils is believed to be more effective in cooling the field coils for their full depth. As will be seen from the two curves taken with inner shrouds, the upper one is relatively the flatter $\left(\frac{a}{b}\right.$ is higher; also, $\left.\frac{y\ min}{y\ max}\right.$ is higher$\left.\right)$. This has been found to be the case in all experiments: other things remaining unchanged, the higher the pressure (and volume) the more the volumes per vent duct approach uniformity. This phenomenon can be explained with the aid of unpublished data on discharge coefficients for bent ducts. This coefficient (the $C_d$ in the turbo ventilation papers) is the ratio of the static head difference at the inner and outer circumferences of the stator vents to the velocity head of the radially moving stream at the minimum

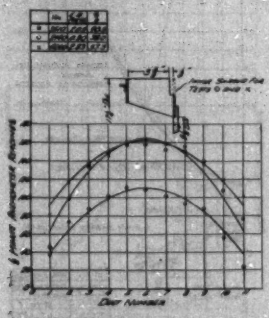

Fig. 29—Volume Distribution Curves
Four-pole rotor. 1800 rev. per min. No. 3 fan (deep with 45 deg. blades)

vent duct section. It was found that $C_d$ is not a constant, but varies with the velocity of the streams. Thus, from the vent duct stationary model experiments, it was found that, with standard wedges, $C_d$ increases with the radial duct velocity. That is, the radial flow is a little less than proportional to the square root of the static pressure. Consequently, as the end bell pressures and volumes are increased, the velocities in the vents at, or near, the middle of the machine do not increase so rapidly as those near the ends, for which latter the volume change is more nearly proportional to the square root of the pressure.

In Fig. 30 are shown three volume distribution curves taken without internal fans, for nearly the same end bell pressure, the three curves being taken at different angular velocities. It will be seen at a glance that the lower the speed, the flatter is the distribution curve. This is as one would expect; for, if the curves were to be alike, it would imply that the end bell pressures were proportional to the square of the angular velocity. But since in this case the end bell pressures are substantially the same, the curve at, say, 1200 rev. per min., corresponds in form to one at an end bell pressure of 2.25 times as great for 1800 rev. per min., and we have previously seen that the higher the end-bell pressure, the flatter the curve. Another point of view is that at

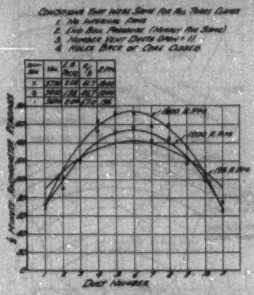

Fig. 30—Volume Distribution Curves
Four-pole rotor. Group variable = rev. per min.

the higher speeds the poles, acting as fans, are more effective in generating useful pressure to drive the air through the vent ducts; and that action is more effective as the middle of the rotor is approached where the influence of axial flow is less.

Fig. 31 is included largely because it affords another comparison of smaller number of vent ducts with the total vents. The data for all curves on this sheet were

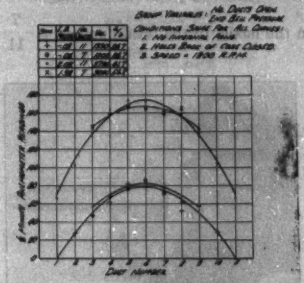

Fig. 31—Volume Distribution Curves
Four-pole rotor

taken without internal fans, and for the two lower curves the external fan was not running. Here, again, it will be seen that for the lower end bell pressures, the curves are steeper.

*Four Poles—Pressure Volume Curves with Reduced Number of Vents.* As the stator vent duct section is decreased by reducing the number of vent ducts, the end bell pressure needed to overcome the resistance in

the stator is increased for the same volume. The increase is dependent upon the volume distribution, and upon the axial velocity in the interpolar spaces and air-gap. Mathematical analyses are given in the appendices, and calculated points are recorded on Figs. 18, 22, and 26. The same constants were used in the equations for seven and eleven vents, but equivalent

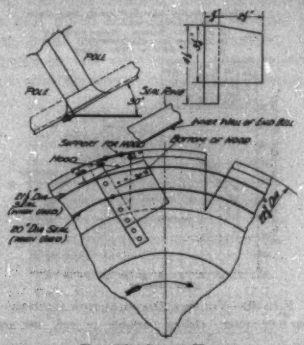


FIG. 32—SCOOP FANS
21¼ in. diameter seal ring used without hoods
20 in. diameter seal ring used with hoods

radial vent duct velocities were different, and they were not given simply by decreasing the area in the stator vents in proportion to the number. Thus, for seven vents the equivalent stator section is taken as 1.3 times the actual. In Appendix II Equation (31) gives this value of $R$ to be $1.5 - 0.5\,C^2$ where $C$ is the ratio of vents in the model to the total number $= \frac{7}{11}$ in this

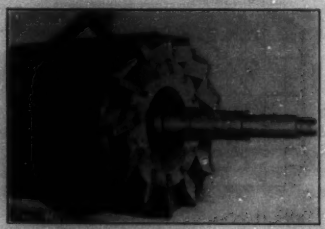

FIG. 33—SCOOP FANS ON TWELVE-POLE ROTOR

case. (Note that this equation is applicable to four poles only, and in calculating an alternator, it is first necessary to reduce the number of vents to the equivalent in the model).

*B. Twelve Poles.* With twelve poles the fan grouping consists of no fans, 45 deg. fans, and scoop fans. The 45-deg. fans were made similar to those built before and called No. 8 fans, a sketch of which will be found in Fig. 16. A slightly narrower fan with the same blade angle but of the same external and internal diameters, was tried out and compared with No. 8 fan and found to be more satisfactory. This is called No. 9 (see sketch in Fig. 16). The scoop fans were called No. 11 as the one that was first tried, No. 10, was made incorrectly. The scoop fans are shown to scale in sketch, Fig. 32. In Fig. 33 they are shown mounted on the rotor. Pressure volume curves taken with No. 8 fan are shown in Fig. 11.

Owing to an error the first tests on the twelve-pole rotor were made with sharp pole corners, and it was shortly before the scoop fans were to be tried that this error was discovered. The corners were intended to imitate those of field coils which are always rounded on the outside. Tests were then repeated with No. 9 fan;

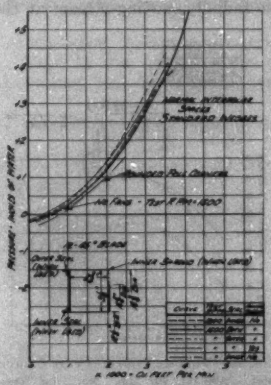


FIG. 34—COMPARISON OF PRESSURE—VOLUME CURVES
Twelve-pole rotor. No. 9 fans. All data reduced to 1000 rev. per min.
Square pole corners except on . . . . . Pressures measured in inner end-bell

and for some other tests, such as without any fans, the time did not permit of repetition. All of these tests which were made up to the time that the pole corners were rounded, and some of those which were made immediately after, were made with standard wedges. For reduced interpolar spaces, the pole corners were rounded.

It is believed that the composite curve, Fig. 34, is of considerable interest in that it combines various curves with and without fans, with square and rounded pole corners, all with standard wedges. It will be noted that for no fans with sharp pole corners the pressure volume curve is nearly the same as with No. 9 fans with rounded pole corners. With No. 9 fans with sharp pole corners there is an appreciable increase in pressure for a given volume. Another interesting point to be noted from this curve is that tests were made with

inner and outer seals, and the combination of inner and outer seals. The meaning of these will readily be seen from the sketch. The differences are not great so far as inner end bell pressure is concerned.

One of the interesting curves is Fig. 16, which is a composite of a great many fan curves, all on centrifugal type fans. There, it will be seen that the various curves are substantially in agreement whether they were taken with No. 8 fan or No. 9 fan, whether with rounded pole corners or square pole corners, whether with the inner or outer seal, and whether with or without shroud rings and with 7, 9, and 11 vent ducts. They also agreed quite well with the earlier fan tests. This latter point is particularly gratifying in that one can use the earlier data and apply them directly to salient pole alternators

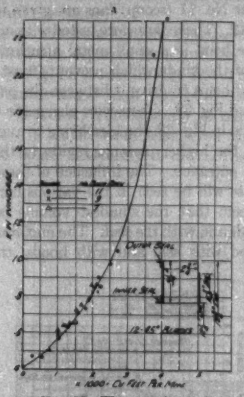

Fig. 35—Windage Loss Curve

Twelve-pole rotor. No. 9 fans. Seal at outer and inner periphery. No inner shroud—(Beyond 16¾-in. dia.) Square pole corners. Data reduced to 1000 rev. per min.

for eight or more poles, with fans of uniform diameters. A valuable point is that No. 9 fan gives substantially the same performance as No. 8 fan for the same diameters, although it is ⅞ in. narrower. In Fig. 35, points for windage for 7, 9, and 11 vents open all seem to lie on the same curve. It should be noted, however, that in actual machines, the one of shorter length would be provided with narrower fans, giving less volume, and therefore the windage loss would be less for the shorter machine. Nor should one conclude from Fig. 35 that, for the same volumes, the short and long machines have the same windage. Since more pressure is needed for a given volume with the short machine, the windage should be slightly higher. The two upper curves in Fig. 23 tend to bear out this statement.

The pressure volume and windage curves for no fans and eleven vents are shown in Fig. 36. These curves were taken with square pole corners. The pressure drop between the outer and inner end bells is so small that the two pressure-volume curves are nearly coincident.

The volume distribution curves are summarized in Fig. 37, and on that same sheet their equations are given with the numerical values of the constants. The drawn-

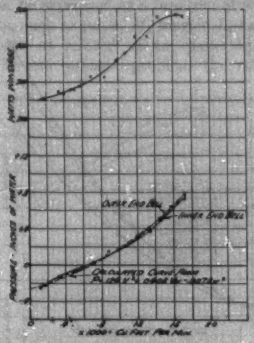

Fig. 36—Pressure-Volume and Windage Curves

Twelve-pole rotor. No fans. Square pole corners. 11 vents open. Data reduced to 1000 rev. per min.

in curves are the plots of the equations, the points being from tests for the conditions given in the table.

The areas between adjacent poles were reduced by attaching strips of wood to the pole sides. The normal interpolar space plus the gap area, for one end only, was

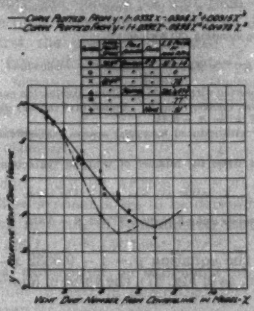

Fig. 37—Summary of Distribution Curves

Standard wedges with normal and with reduced interpolar spaces for normal case, half number of vents = 5.5 for reduced spaces, half number of vents = equiv. of 7.7. Maximum ordinates were not the same, but they are referred to unity as maximum

42.4 sq. in., and after being reduced it was 30.3 sq. in. In Fig. 38, pressure-volume curves are plotted for these two conditions. The full-line curves are the plots for equations whose constants were determined from those two tests. The equivalent number of vents for smaller

interpolar spaces, in accordance with the theory in Appendix II, is $\frac{42.4}{39.3} = 1.4$ times the normal number of vents. Substituting this value of 1.4 for $C$ in Equation (22) in Appendix II, (using the values for the constants

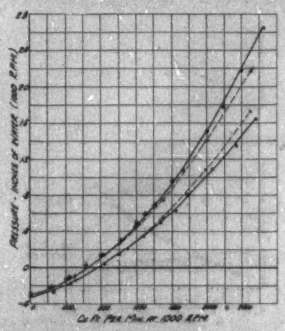

FIG. 38—EFFECT OF REDUCED INTERPOLE SPACES

Twelve-pole model. Original wedges. Rounded pole corners. 11 ducts open. Centrifugal fan No. 9; inner seal.

⊙ Test points original interpolar space = 42.4 sq. in.

▲ Test points reduced interpolar space = 30.3 sq. in.

Full lines plotted from equations intended to represent the curves. For both of these $V = \frac{Q}{0.85}$ ft. per min.

Lower full curve equation (42.4 sq. in.)

$$\frac{P}{\gamma} = 0.141\ V^2 + 0.040\ V v - 0.0096\ v^2 \qquad (1)$$

Upper full curve equation (30.3 sq. in.)

$$\frac{P}{\gamma} = 0.25\ V^2 + 0.0313\ V v - 0.00873\ v^2 \qquad (2)$$

Dotted curves plotted with the aid of volume distribution curves, obtaining therefrom average velocity ratio $R$. Equation of velocity distribution from Fig. 37 was used, when $R = 0.85$.

The machine with reduced interpolar spaces was equivalent to having $\left(\frac{42.4}{30.3}\right) = 1.4$ times the number of vents in the original model. In plotting curve +, Equation (1) was used. For curve X, Equation (2) was employed.

●Calculated points using Equation (1) and $R = 0.815$

as given in the equation $y = 1 - 0.0332\,x - 0.0308\,x^2 + 0.00315\,x^3$, as in Fig. 37), the value of $R$ is determined. The equivalent vent duct velocities now are $\frac{Q}{A\,R}$ where $Q$ is the volume, and $A$ the vent duct area at the minimum section.* With these velocities and equation $\frac{P}{\gamma} = 0.141\,V^2 + 0.040\,V v - 0.0096, v^2$, the upper dotted curve on Fig. 38 was obtained. This agrees quite well with the test data for reduced interpolar spaces. By choosing a slightly lower value for $R$, practically exact agreement is obtained.† The lower dotted curve was obtained in a similar manner, taking $C = \frac{1}{1.4}$, and using the constants for the pressure equation which fitted the upper full line curve.

As might be expected, the effect of reducing the interpolar spaces is to make the volume distribution curve more peaked. This will be clear from an inspection of Fig. 39. The curve for reduced interpolar spaces can now no longer be approximated by a parabola, but for normal spaces, the approximation is still fairly good.

Curves for No. 11 (scoop) fans are given in Figs. 14, 40, 41, and 42. These fans were tested with and without hoods. The hood is a small metal attachment to the main part of the blade which prevents most of the air escaping and helps to drive it between the poles, shown in Fig. 32 and Fig. 33. Tests were also made with a seal ring as shown in Fig. 32, the idea being to avoid leakage of air from the higher pressure region in the end bell back to the entrance. The influence of these different arrangements will be seen in the various curve sheets. It would seem that the smallest volume is obtained with no hoods and with the seal. The maximum volume was obtained with seal and with hoods, these latter

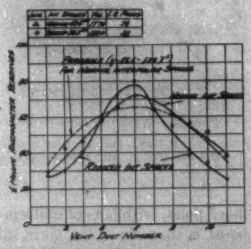

FIG. 39—VOLUME DISTRIBUTION CURVES

Normal and reduced interpolar spaces. Twelve poles. No. 9 fans Standard wedges

volumes being of the order of 1700 cu. ft. at 1000 rev. per min. With No. 9 fan, other things being the same, the volume is about 1900 cu. ft./min. It would seem, therefore, that from the standpoint of volume the centrifugal fan is to be preferred.

*The velocities are always in thousands of feet per minute. The pressures $\left(P \text{ or } \frac{P}{\gamma}\right)$ are in inches of water.

†Checking back on the tests for reduced interpolar spaces or reduced numbers of vents, it was found that using the value of $R$ obtained with use of the volume distribution equation as given in Fig. 37, the calculated end-bell pressures were slightly different from tests. It was found convenient to plot values of $R$ against $C$, by means of which very close agreements with tests were secured.

With one exception, there is less cu. ft./watt windage with the scoop fans than with No. 9 fans. This is shown on Fig. 42. The one exception is the case of no hoods and with internal seal. It is questionable whether the use of scoop fans is warranted, particularly considering the greater complication.

The scoop fan data are believed to be of considerable interest; for example, the shapes of the pressure-volume curves of the fans of Fig. 41. They are entirely different from what one usually gets from the centrifugal fan, and approach more nearly the more efficient propeller type fans. The volume distribution curve, Fig. 14, for seven ducts and eleven ducts, as well as with the three middle ducts open, namely, that there were eight total, show all of them to be in agreement provided the two halves of the eight-duct curve are moved toward the center.

In laying out the scoop fan, the practise that is ordinarily followed was departed from and the scoop angle was made 30 deg. as shown in Fig. 32. This is a considerably smaller angle than had been used prior to that time. However, from a study of parallelograms of velocities, it would seem that even this angle is slightly too large. Certainly it did not seem to be too small.

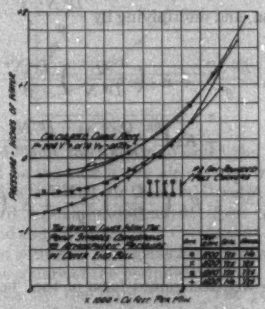

Fig. 40—Pressure Volume Curves

Twelve-pole rotor. No. 11 fans. Pressures in inner end-bell. All data reduced to 1000 rev. per min. For fan details refer to Figs. 32 and 33


## Acknowledgments

This study of salient-pole alternator ventilation extended over more than four years, and during that period the writer was assisted successively by Dr. H. B. Holroyd, Messrs. Theodore Williamson and Sterling Beckwith. The vent duct coefficient study referred to was conducted by Mr. E. L. Harder, and was supplemented by Mr. C. E. Peck. The instrument for recording pulsations of vent duct pressures was designed by Mr. G. W. Penney. All of these men did valuable work, which the writer is pleased to acknowledge.


## Appendix I

### Derivation of the Relation of Volume to Inner End Bell Pressure: The Resistance Equation

The form of the equation is derived by dimensional analysis.* According to the principles, any physical quantity can be expressed as a function of some fundamental units, such as mass, $M$, length, $L$, and time, $T$, and these are so related as to make dimensionless products. In our present problem the relations be-

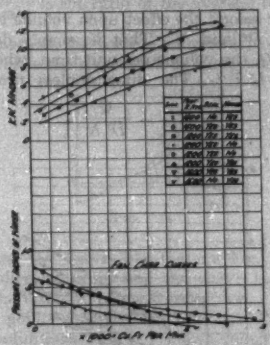

Fig. 41—Fan Characteristics and Windage Curve

Twelve-pole rotor. No. 11 fans. All data reduced to 1000 rev. per min. For fan details refer to Figs. 32 and 33. Standard wedges. Rounded pole corners

tween pressure and volume per unit time, as affected by machine dimensions and speed will be determined. Consider first the pressure generated by the rotor acting as a fan, and the quantities entering are then:†

| Quantity | Symbol | Dimensions |
|---|---|---|
| Pressure | $P$ | $M\,L^{-1}\,T^{-2}$ |
| Mass density | $\rho$ | $M\,L^{-3}$ |
| Rotor diameter | $D$ | $L$ |
| Rev. per min. | $N$ | $T^{-1}$ |

The product may be written as $P\,\rho^x\,D^y\,N^z$; the values of these exponents are to be determined.

Expressing in terms of fundamental units,

$$(M\,L^{-1}\,T^{-2})\,(M\,L^{-3})^x\,L^y\,T^{-z} = K$$

Then the summation of exponents of like units must be equal to zero, in order that the product be dimensionless:

*For excellent treatises on Dimensional Analysis see Bibliography 8 and 9.

†As the generated pressure is very small compared with the total pressure, the air may be considered to be incompressible. Also, in highly turbulent flow, viscosity has little effect. As is well known, the change in Reynold's number in the region considered has little influence upon the pressure drop, although it may be of sufficient moment to warrant consideration for extreme values. In this treatment, those effects are neglected. There are various discussions on Reynold's number, as for example, Gibson's "Hydraulics and its Applications," 1925 ed., p. 49.

Exponents of $M$: $1 + x = 0$
Exponents of $L$: $-1 - 3x + y = 0$
Exponents of $T$: $-2 - z = 0$

Whence $x = -1$
$y = -2$
$z = -2$

And $P \rho^{-1} D^{-2} N^{-1} = I I_1$

or,
$$\frac{P}{\rho D^2 N^2} = I I_1 \tag{1}$$

Consider second the effect upon volume of the same quantities, $D$* and $N$. That is, simply drop $P$ and substitute $Q$, the volume per unit time, whose dimensions are $L^3 T^{-1}$. The dimensionless product thus found is:

$$I I_2 = \frac{Q}{D^3 N} \tag{2}$$

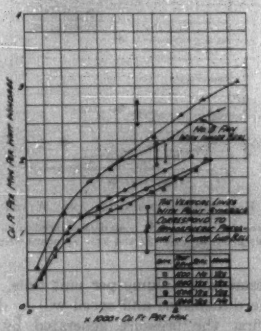

FIG. 42—RELATIVE WINDAGE LOSS CURVE

Twelve-pole rotor. No. 11 fans. Reduced to 1000 rev. per min. For fan details refer to Figs. 32 and 33. Standard wedges. Rounded pole corners

These two dimensionless products, $I I_1$ and $I I_2$, must evidently be related in some way to each other in the salient pole alternator. This relation may be written:

$$\frac{P}{\rho D^2 N^2} = \varphi\left(\frac{Q}{D^3 N}\right) \tag{3}$$

Where $\varphi$ denotes some function.

Or
$$P = \rho D^2 N^2 \varphi\left(\frac{Q}{D^3 N}\right) \tag{4}$$

If the rotor acts as a fan, the pressure is known to be proportional to $\rho D^2 N^2$; so, for one term we may consider that

$$\varphi\left(\frac{Q}{D^3 N}\right) = K\left(\frac{Q}{D^3 N}\right)^0.$$

*The internal diameter of the stator is considered to be equal to the external diameter of the rotor.

Thus $\left(\frac{Q}{D^3 N}\right)$ degenerates into a constant. That is, for a first term, $\frac{P}{\rho D^2 N^2} = K_1$

For a second term, it will be remembered that the pressure drop is proportional to $Q^2$. Then, the equation becomes:

$$\frac{P}{\rho D^2 N^2} = K_1 + K_2\left(\frac{Q}{D^3 N}\right)^2$$

For a third term, we shall imagine one between $\left(\frac{Q}{D^3 N}\right)^0$ and $\left(\frac{Q}{D^3 N}\right)^2$, that is $\left(\frac{Q}{D^3 N}\right)$, and interpret the meaning thereof subsequently. Then, if our assumptions are correct,

$$\frac{P}{\rho D^2 N^2} = K_1 + K_2\left(\frac{Q}{D^3 N}\right) + K_3\left(\frac{Q}{D^3 N}\right)^2 \tag{5}$$

The mass density $\rho = \frac{\gamma}{g}$, where $\gamma$ is the weight density and $g$ the acceleration of gravity; making this substitution, and multiplying by $\frac{D^2 N^2}{g}$,

$$\frac{P}{\gamma} = K_1 \frac{D^2 N^2}{g} + K_2\left(\frac{Q}{D^3 N}\right)\frac{D^2 N^2}{g} + K_3\left(\frac{Q}{D^3 N}\right)^2 \frac{D^2 N^2}{g}$$

$$= K_1 \frac{(D N)^2}{g} + K_2\left(\frac{Q}{D^2}\right)\frac{D N}{g} + K_3\left(\frac{Q}{D^2}\right)^2 \frac{1}{g} \tag{6}$$

$\frac{P}{\gamma}$ is the well recognized form of the "head," and is dimensionally simply a length.

$D N$ is proportional to the peripheral velocity of the rotor $= v$.

$\frac{Q}{D^2}$ is proportional to some velocity $V$ through, say, the stator vent ducts at their minimum sections. Thus, if a percentage, $\%_1$, of the inner periphery of the stator be vent ducts, and another percentage, $\%_2$, of the axial length be equal to the vent duct length, the axial length being proportional to the diameter for similar machines, the relation of $\frac{Q}{D^2} \propto V$ follows.

$g$ appearing in each term on the right hand side simply means that those terms become velocity heads

if the numerators are of the second order. The equation may then be written as:

$$\frac{P}{\gamma} = k_1 \frac{V^2}{2g} + k_2 \frac{V v}{2g} + k_3 \frac{v^2}{2g} \qquad (7)$$

Or in the usual system of $\frac{P}{\gamma}$ in in. of water and velocities in ft. per min.

$$\frac{P}{\gamma} = A \left( \frac{V\ max}{4030} \right)^2 + B \frac{V\ max\ v}{(4030)^2} + C \left( \frac{v}{4030} \right)^2 \qquad (8)$$

Here $V\ max.$ is the velocity at the middle of the machine and at the minimum section, where the radial velocities of the air are at their maximum values. When written thus, $A$ is a coefficient similar to $C\,d$ in the equation for radial discharge in vent ducts: $\frac{P}{\gamma} = C\,d\,\frac{V^2}{2g}$ as given in various papers and as used in equations for turbo ventilation.[1-3]

The second term also represents pressure drop. The meaning is that, due to the whirl generated by the poles,

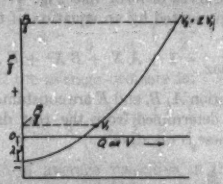


Fig. 43

it is more difficult for the air to enter the vent ducts than would be the case if the air entered from a large chamber in which the air was relatively stationary. This drop is evidently dependent upon the circumferential and radial velocities.

The poles acting as fans generate a pressure proportional to the square of the peripheral speed. This pressure is given by the third term. The coefficient $C$ is the fraction of the peripheral velocity head that appears as static pressure at zero volume. $C$ is always negative like a negative resistance drop.

The equation was not placed in the form given in (8) until a great deal of work had been done, and prior to that time it was in the form:

$$\frac{P}{\gamma} = \alpha V^2 + \beta V v + \lambda v^2 \qquad (9)$$

Now $V$ is the average of the velocities in the thousands of feet per minute at the minimum section of the stator vents. This is given by the volume in thousands of cubic feet per minute divided by the minimum section of all vents in the model in square feet. Comparing Equations (8) and (9), it will readily be seen that if all velocities are in thousands of feet per minute,

$$A = \frac{}{4.03^2} \left( \frac{V\ av}{V\ max} \right)^2 \alpha \qquad (10)$$

$$B = \frac{}{4.03^2} \left( \frac{V\ av}{V\ max} \right) \beta \qquad (11)$$

$$C = \frac{}{4.03^2} \lambda \qquad (12)$$

Here $\frac{V\ av}{V\ max}$ is the ratio of the average to the maximum ordinate of the volume (or velocity) distribution curve. $V\ av$ is the same as $V$ in Equation (9).

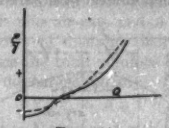


Fig. 44

The usual test curve, like that in Fig. 43, is evaluated readily by projecting the curve back to zero volume, the ordinate below 0 being $\lambda v^2$. Then select two other points such that $Q_2$ (or $V_2$) $= 2\,Q_1$ (or $2\,V_1$) For such conditions,

$$\alpha = \frac{\frac{P_2}{\gamma} - \frac{2\,P_1}{\gamma} + \lambda v^2}{2\,V_1^2} \qquad (13)$$

and

$$\beta = \frac{4\,\frac{P_1}{\gamma} - \frac{P_2}{\gamma} - 3\,\lambda v^2}{2\,v\,V_1} \qquad (14)$$

It is important to note that in evaluating these coefficients from tests, $\lambda$ is always negative, *i. e.*, the sign for the $\lambda v^2$ term must be changed.

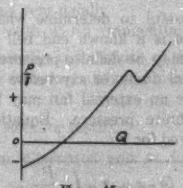


Fig. 45

The final check on the correctness of the form of Equation (8) or (9) is that it agrees with experimental results in most cases. For a few cases the curve is of peculiar form, as in Fig. 44, and an equation of the form of (8) or (9) cannot be fitted in. Then the curve is approximately fitted in. An explanation of the peculiar shape is that the radial velocities in the vent ducts are

not necessarily proportional to the square root of the difference in static pressure between the air in the air-gap and the exterior. When one considers the great complexities of the phenomenon and the very simple manner in which the form of the equation was obtained, the likelihood of the equation's being accurate for all conditions is precluded. For the most part the agreements between the form of the equation and test are so close as to leave no doubt in one's mind that the form is usually correct.

Another striking instance of departure is indicated in Fig. 45. The curve is of the form as given in the equation, up to the break, which is at a high point. The irregularity was found only for four-pole rotors and then only when 45-deg. fans were used. All those

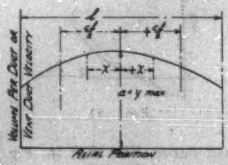


Fig. 46

fans were conical at the inner periphery, and time did not permit running with fans that were otherwise similar, but were cylindrical inside. It was apparent that the air moved in a spiral (whirl) in the end-bells below the break in the curve, and above the break, it no longer whirled, but flowed directly into the interpolar spaces, thereby reducing some of the loss. A study of Fig. 24 for conditions with and without a plate in the end-bell to break up the whirl bear out the above statements. Evidently when the character of flow is completely changed, one cannot expect the equation, based upon very simple assumptions, to agree with the facts throughout.

It is often useful to determine what volume will flow when there is a known end bell pressure. For example, there may be definite pressure drops, as in a cooler or external ducts, or say before the air reaches the end-bells; or an external fan may be used which generates a definite pressure. Equation (9) or (8) may then be solved for $V$:

$$V = \frac{-\beta v + \sqrt{(\beta v)^2 + 4\alpha\left(\frac{P}{\gamma} - \lambda v^2\right)}}{2\alpha} \qquad (15)$$

Here the end bell pressure head $\frac{P}{\gamma}$ is negative if it represents a resistance drop, and is positive if it is a supplied pressure head, and is in inches of water. $\lambda$ is always negative. Knowing $V$, with the use of methods given in Appendix II, the volume may be found.

## Appendix II

### Effect of Axial Lengths and Interpolar Areas Upon Volume Distribution and End Bell Pressure

If machines are similar, all parts are proportional one to the other. It is seldom that such is the case, and the data obtained from tests on the model must be applied to machines which depart considerably from being similar.

For many machines the shape of the volume distribution curves is like that shown in Fig. 46. This curve is nearly that of a cosine with the reference axis at the middle. It may conveniently be represented by an equation of a parabola of the form:

$$y = a - b x^2 \qquad (16)$$

Here $a$ is the same as $y\ max$. Evidently the equation may also be written as:

$$\frac{y}{Y\ max} = 1 - \frac{b}{a} x^2 \qquad (17)$$

It was found that for some constructions the shape of the distribution curve was about like that indicated in Fig. 47. Curves of form like Fig. 47 may conveniently be represented by an equation of the form:

$$\frac{Y}{Y\ max} = 1 + A X + B X^2 + E X^3 \qquad (18)$$

In this equation $A$, $B$, and $E$ are constants, the values of which are determined from the test data, and at least one of these is negative.

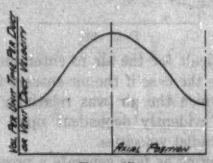


Fig. 47

These same volume distribution curves apply also to short machines which are similar to those of greater length except that the ends of the machine are removed. Thus, in Fig. 46, if $l$ is the length of a particular machine, and the length of another machine which is similar except for length is $c\,l$, then the distribution of the shorter machine is that included between the limits of $-\frac{c\,l}{2}$ and $+\frac{c\,l}{2}$. This statement holds only if the end bell pressures are the same for the same speed. The same statement holds if the speed of one is then changed, provided the ordinates of the distribution curves are plotted on the basis of $\frac{Y}{Y\ max}$, thus making the maximum ordinate unity in any case.

If in a given machine, with the volume distribution still plotted on a basis of unity for the maximum ordinate, the end bell pressure is changed, the shape of the curve changes also. The lower the end-bell pressure, the faster the curve drops off. Similarly, by keeping the end bell pressure the same, and changing the angular velocity, the distribution changes, dropping off faster, the higher the rev. per min. In order that the distribution be unchanged, the end-bell pressure should be proportional to the square of the rev. per min.

It is manifestly impossible for engineering calculations to take account of the change in volume distribution with end bell pressure. Admittedly errors may occur in calculations, owing to the incorrect choice of constants in Equation (17) or (18). A study of experimental data from models should enable the engineer to select suitable values.

Referring again to Equation (17) and Fig. 46 the average ordinate is:

$$Y\,av = \frac{\text{Area}}{l} = \frac{1}{l}\int_{-\frac{l}{2}}^{+\frac{l}{2}} \left(1 - \frac{b}{a}\,x^2\right) d\,x$$

$$= 1 - \frac{1}{3}\,\frac{b}{a}\left(\frac{l}{2}\right)^2 \qquad (19)$$

Over length $C$ the average ordinate is:

$$1 - \frac{1}{3}\,\frac{b}{a}\left(\frac{c\,l}{2}\right)^2 \qquad (20)$$

And the ratio of average velocities in the model of length $c\,l$ to the average velocities in the model of length $l$, for the same maximum velocities, is:

$$R = \text{av. vel. ratio} = \frac{1 - \frac{1}{3}\,\frac{b}{a}\left(\frac{c\,l}{2}\right)^2}{1 - \frac{1}{3}\,\frac{b}{a}\left(\frac{l}{2}\right)} \qquad (21)$$

By a similar procedure as applied to equation of the form of (18) it is found that

$R$ = av. vel. ratio

$$= \frac{1 + \frac{A}{2}\left(\frac{c\,l}{2}\right) + \left(\frac{B}{3}\right)\left(\frac{c\,l}{2}\right)^2 + \frac{E}{4}\left(\frac{c\,l}{2}\right)^3}{1 + \frac{A}{2}\left(\frac{l}{2}\right) + \frac{B}{3}\left(\frac{l}{2}\right)^2 + \frac{E}{4}\left(\frac{l}{2}\right)^3} \qquad (22)$$

In the foregoing $l$ is the total length of the model. From the ventilation standpoint, the model corresponds to a long machine. Now, choose another length of model $c\,l$, such that the model will be similar to the machine whose ventilation is to be determined. Then the distribution of volumes in the model of length $c\,l$ will be the same as in the alternator, taking the model and machine length to be 100 per cent each, and the maximum volume to be 100 per cent for both, and neglecting the influence of departure of end bell pressure from that upon which the model volume distribution was based. Then, the ratio of the average velocity in the radial ducts to the ingoing axial velocity between field coils, etc., should be the same for the model of length $c\,l$ as for the alternator. Using subscripts $a$ for the alternator and $m$ for the model, and letting $v_a$ and $v_m$ be the entrance axial velocities and $V\,a$ and $V\,m$ the radial duct velocities, then according to the above, if the two are similar,

$$\frac{v_a}{V\,a} = \frac{v_m}{V\,m} \qquad (23)$$

Let $F\,a$ and $F\,m$ represent the axial entrance areas between field coils plus air-gap, and $A\,a$ and $A\,m$ the areas in the stator vent ducts at their minimum sections. Then, since the total volumes entering axially must equal those discharged radially,

$$Q\,a = F\,a\,v_a = A\,a\,V\,a \qquad (24)$$

and

$$Q\,m = F\,m\,v_m = A\,m\,V\,m \qquad (25)$$

From (23), (24), and (25)

$$\frac{A\,a}{F\,a} = \frac{A\,m}{F\,m} \qquad (26)$$

That is, the model is similar to the alternator if these ratios of areas in the two cases are the same. The axial areas $F\,a$ and $F\,m$ are taken as the sum of the areas between adjacent field coils plus the air gap. The question then is, what number of vent ducts in the model will make it similar to the alternator? For this, the area of the stator vents is determined, and the equation combined with the foregoing.

The stator area is:

$$A = N\,W\,T\,S, \qquad (27)$$

Here

$N$ = number of vents axially

$W$ = width of one vent axially

$T$ = minimum tooth width (tangentially)

In the usual case this is the width of the tooth at the diameter of the wedges— (finger thickness + wedge projections).

$S$ = number of slots (or teeth).

(Subscripts $a$ for alternator and $m$ for model were omitted.)

Substituting back in (26), and solving for the number of vents in the model which will make it similar to the alternator,

$$N\,m = \frac{N\,a\;W\,a\;T\,a\;S\,a\;F\,m}{W\,m\;T\,m\;S\,m\;F\,a} = \frac{F\,m}{W\,m\;T\,m\;S\,m}\;\frac{A\,a}{F\,a} \qquad (28)$$

$N\,m$ is that number of vent ducts in the model which makes it similar to the alternator. Let $N\,m\,t$ be the total number of vents in the model = 11. Then the

length of the model is $l$ and that length which makes it similar to the machine is $c\,l$. Hence

$$C = \frac{C\,l}{l} = \frac{N\,m}{N\,m\,t} = \frac{N\,m}{11} \tag{29}$$

Substituting in (28)

$$C = \frac{F\,m}{W\,m\,T\,m\,S\,m} \cdot \frac{A\,a}{F\,a} \cdot \frac{1}{N\,m\,t} \tag{30}$$

The value of $R$ corresponding to $C$ may then be determined by substituting in Equation (21) for four poles;

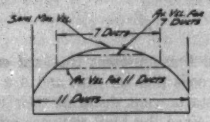


Fig. 48

or it may be read directly from a suitable curve. For four poles, $\frac{b}{a} = 0.033$ approximately, and then from Equation (21),

$$R = \frac{1 - \frac{1}{3} \times .033 \times \left(\frac{11}{2}\right)^2 \times C^2}{1 - \frac{1}{3} \times .033 \times \left(\frac{11}{2}\right)^2} = 1.50 - 0.50\,C^2 \tag{31}$$

For example, for the four-pole model, the ratio of average velocities with seven ducts to average velocities with eleven ducts $\left(C = \frac{7}{11} = 0.636\right)$ is $1.5 - 0.5 \times \overline{0.636}^2 = 1.30$. That is, with the shorter model the *average* velocity was about 30 per cent higher than for the full length model, for the same *maximum* duct velocity; or, for the same average velocity, the *maximum* velocity for the short model is $\frac{1}{1.3} = 0.77$ times the maximum for the full length model.

These statements are illustrated in Figs. 48 and 49. The pressure needed to drive the air through the vent ducts is evidently dependent upon the maximum velocity. Dividing the volume by the stator minimum vent area for all vents open gives the *average* velocity. In Fig. 48 the maximum velocity $= V\,max = \frac{Q}{A\,a} \times \frac{\text{Max. ord.}}{\text{av. ord.}}$. The coefficients obtained from tests on the model are for the model with eleven vents. We must then place the velocities on the basis of that number of vents. The equivalent of this velocity is obtained by dividing the average velocity by $R$, as $R = \frac{\text{average velocity for } n \text{ ducts}}{\text{average velocity for 11 ducts}}$ for the same max. velocity (see Fig. 48). That is,

$$V\text{ equiv.} = \frac{Q}{A\,a\,R} \tag{32}$$

Thus, $V$ equivalent is the velocity with $n$ ducts in the model that is equivalent to eleven ducts in the model, the average being given by $\frac{Q}{A\,a}$. This $V$ equivalent is the $V$ in Equation (9) in Appendix 1. We now have given all the means for determining the end bell pressure, without allowing for external variable drops or for parallel paths. Those will be covered in Appendix 3.

It is important that the machine be not so long as to cause the volumes (or velocities) in the end vents to be too low to provide suitable cooling. If the volume distribution cannot be approximated by a simple parabola, Equation (18) or a suitable curve plotted therefrom, may be used.

For four poles, take

$$\frac{q\,min}{q\,max} = 1 - \frac{b}{a}\left(\frac{C\,l}{2}\right)^2 \tag{33}$$

The value of $\frac{b}{a}$ of 0.033 used for determination of $C$ for calculating $R$ is that value which gives close agreement between calculations and test for end bell pressure. For substitution in (33) that value is usually too low, and it would be preferable to select the value of $\frac{b}{a}$ as given on the curve sheets.

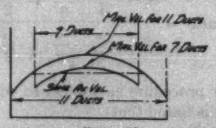


Fig. 49

The reason why the shape of the volume distribution curve approaches a cosine has been previously explained.[1,2] In the salient pole alternator somewhat similar conditions to the turbo alternator obtain, but here complications are caused by the fanning action of the rotor, and the losses are necessarily different. A simple explanation is here offered for the general shape of the curve.

In a long machine the air enters axially (between field coils and in the air-gap) at fairly high velocity. As it passes the first stator vent duct a little air is discharged through the vent due to excess of pressure in the axially moving air above that at the rear of the stator core. This abstraction reduces the axially

moving volume, and therefore the axial velocity is lowered slightly. The kinetic energy per unit volume is lowered by the difference in the squares of the axial velocities, and some of that loss in kinetic energy is converted to potential energy by increasing the static pressure. When the second vent duct is reached the increased static pressure causes an increase in radial flow above that for the first vent, and that outward flow causes a further reduction in axial volume, velocity, and in kinetic energy. Therefore the potential energy per unit volume (or static pressure) is again increased, and the flow in the third vent is augmented, etc. The relation between kinetic and potential energies is covered by Bernoulli's equation:

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + \text{losses from 1 to 2}$$

$$= \text{Total Head} = \text{Constant.}$$

The difficulties lie in the determination of the losses.*

It is believed that an explanation of the shape of the volume distribution curve like Fig. 47 may be of interest. The radial velocities increase with decreasing axial velocities so long as the gain in static pressure from one vent to the next exceeds the loss of head by eddies, and friction. When these two are equal there is no net increase in static pressure, and the outward flow remains the same. That is why with standard wedges and with great lengths the curve tends to flatten near the ends. With the four-pole rotor, the pole corners were sharp and the air contracted just after entering, and subsequently there was an enlargement. With the contraction the velocity increased, the static pressure decreased, and the end duct velocities in some cases tended to be zero. The earlier data with twelve poles were taken with square pole edges, but later with rounded corners.

## Appendix III

### Computation of Volumes through Holes Back of Core, Fans, and External Pressure Drops

1. Proportions of fans not given.

A. *Volumes through holes back of the core with solid end bells.*

It is often advisable to provide holes of suitable size back of the core through which enough air for cooling the end windings may flow. A method for determining the proportions of that part of the air circuit follows:

Calculate the losses in the end windings, and allow a suitable volume per kilowatt loss.—(Thus, for 100 cu. ft. per min. per kw., the air temperature rise is 17.7 deg. cent.)

*Mr. Sterling Beckwith has obtained a solution in which the various losses and variations in vent duct coefficients are allowed for. His solution and comparisons with experimental data were presented as a thesis for his Master's degree at the University of Pittsburgh.

Let $A_h$ = area of the holes back of the core *at one end* (*in sq. in.*), and let $k$ = coefficient of discharge through them.* The air which passes through the holes for both ends =

$$Q \text{ ends} = \frac{2\,k\,A_h \times 4030\sqrt{P}}{144} \tag{34}$$

Here $P$ is the pressure in in. of water in the end bell above the pressure back of the core where the air discharges.

Then
$$A_h = \frac{Q \text{ ends}}{56\,k\sqrt{P}} \tag{35}$$

B. *Calculation of fans.*

Deduct the air volume for the ends from the total volume:

$$Q = Q \text{ total} - Q \text{ ends} \tag{36}$$

The end bell pressure $P$ in inches of water needed to drive the air through the interpolar spaces and stator teeth and core was determined by means of Equation (9) in Appendix (I):

$$P = \alpha V^2 + \beta V v + \lambda v^2 \tag{9}$$

Before entering the fans, and after having been discharged from the stator vents, the air encounters resistance, and thereby a drop in pressure. Also, at times external ducts are used, and in a few cases an external cooler is employed. All these produce additional drops. Calling the sum of all such drops $p$, the total pressure is:

$$P \text{ total} = P + p \tag{37}$$

From the tests on the twelve-pole salient pole alternator model, the fan pressure-volume curves were substantially the same as for the earlier tests.[6] For the four-pole rotor there was disagreement, and for four-pole machines it would be best to use the fan data as given in the curve sheet in this paper.

Having decided upon the particular fan and its curve, and upon the approximate diameters of the fan (to suit the particular alternator), then reduce $P$ total from (37) to the corresponding pressure of the model fan.

$$P \text{ model fan} = P \text{ total} \times \left(\frac{\text{model fan periph. vel}}{\text{machine fan periph. vel}}\right)^2 \tag{38}$$

Then read off the model fan curve the volume ($Q$ model fan) corresponding to $P$ model fan. The width of one fan for the machine then is:

$$\frac{(\text{Per vel. x dia. x width}) \text{ of model fan}}{(\text{Per. vel. x dia.}) \text{ of machine fan}} \times \frac{Q \text{ total}}{2 \text{ x } Q \text{ model fan}}$$

II. *Estimate if the Proportions throughout are given.*

For this case proceed as follows:

*The value of $k$ may be taken from 0.62 to 0.84, the former being for holes in thin plate without guides, and the latter for holes in say fairly thick castings with guides, such as the inner surface of an end bell, leading to the holes.

(1) Calculate and plot the machine end bell pressure-volume from Equation (9) in Appendix I. Curve 1 in Fig. 50.

(2) Calculate for various end bell pressures, the volumes of air that escape through the holes back of the core, by Equation (34). Plot as curve 3 in Fig. 50.

(3) Estimate the fan pressure-volume curve from data on a similar fan. Plot as curve 2 in Fig. 50.

(4) Add abscissas for given ordinates for curves (1) and (3). This plotted as (4) and is the total volume corresponding to the end bell pressure. If there is negligible external resistance, the intersection of curves (4) and (2) is the working point.

(5) With appreciable external resistance, calculate curve (5), taking the external pressure drop to be proportional to the square of the volume.

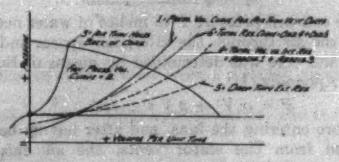

Fig. 50

(6) Add pressures for given values of abscissas on (5) to those on (4) and obtain the total resistance curve (6).

(7) The intersection of curves (2) and (6) is then the working point.

## Appendix IV

### Parabolic Distribution Equations and the Method of Least Squares

For some cases, as for four poles, the distribution of volumes axially is considered to be that of a parabola, of the form of:

$$y = a - b\,x^2 \tag{40}$$

The experimental data did not always lie on a smooth curve, and the "method of least squares" was used to evaluate $a$ and $b$ in the above equation, thereby giving due weight to the value of each point on the curve. The method as used was taken from Steinmetz's "Engineering Mathematics." Space will be given here only to the manner in which the test data were finally used.

Take first the case of eleven ducts open, the number of the central duct being 0, the first to left $= -1$, the first to the right $+1$, etc. The ordinates for each vent are $y$, and $\Sigma y$ = sum of all eleven ordinates. $x^2 y$ = square of vent duct number $\times$ ordinate, and $\Sigma x^2 y$ = sum for all eleven vents. Then the values of the constants are for eleven vents:

$$b = \frac{10\,\Sigma y - \Sigma x^2 y}{858} \tag{41}$$

$$a = \frac{\Sigma y + 110\,b}{11} \tag{42}$$

$$\text{Mean ordinate} = a - 10.08\,b \tag{43}$$

$b$ is always positive, but the second quantity in Equation (40) is negative.

When seven ducts were used, the equations are:

$$b = \frac{4\,\Sigma y - \Sigma x^2 y}{84} \tag{44}$$

$$a = \frac{\Sigma y + 28\,b}{7} \tag{45}$$

$$\text{Mean ordinate} = a - 4.08\,b \tag{46}$$

The values of mean ordinates thus calculated checked with those obtained by averaging the individual test values.

In all cases $a$ is the maximum ordinate, and the curve is defined, if $\frac{b}{a}$ is known.

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## Discussion

**Sterling Beckwith:** Mr. Fechheimer has covered fully the question of just when the ventilation paths of two alternators are "similar." However, a concrete picture of "similarity" of ventilation paths might be added, which picture it would be well for every one interested in the design of salient-pole machines to keep in mind. If an ordinary lawn sprinkler, made of a six foot length of perforated brass pipe, with one end closed, and the other end connected to an ordinary garden hose, is observed closely, it will be seen that the jets of water farther away from the hose end of the sprinkler have more force than the jets nearer the hose end. This difference in strength is the more pronounced, the longer the sprinkler pipe, or the larger the perforations: in other words, it is dependent on the ratio of the area of the perforations to the area of the pipe. In a salient-pole machine, the perforations correspond to the vent ducts, and the pipe corresponds to the air-gap plus the space between the poles, the outer end of the sprinkler being considered as the middle of the

machine. The mechanical constructions are vastly different, but the air, or water, flow conditions are the same, and in both cases the designer must see that he has the proper ratio of areas, or he will get unequal flow through the vent ducts, or the perforations, as the case may be. Thus, a salient-pole machine with large air-gap, and large spaces between poles, may be safely built much longer than the same machine with small air-gap and more copper on the poles, the question of safety being a question of getting enough air through the end vents; and changes in the ratio of slot width to tooth pitch may affect ventilation seriously on two otherwise similar machines, regardless of what fans are used.

As pointed out by Mr. Fechheimer, a parabola, opening downward, and with its origin displaced upwards a distance equal to the maximum air velocity, can be used to represent a curve of vent duct air velocities (plotted vertically), against axial distance from the center of the machine (plotted horizontally). The equation for this type of curve is $y = a - bx^2$. Mr. Fechheimer states that this form of equation does not hold for very long machines. He might add, however, that it holds for the center portion of machines of any length, but only from the center line of the machine out to a point where the vent duct velocity is approximately half that at the middle of the machine. Beyond this point the curve does not drop to zero, as the parabolic form of curve would indicate, but flattens out until it becomes horizontal.

Neglecting losses, the theoretical distribution curve is a cosine curve, which, in the region where the losses are relatively unimportant, can be represented by the parabola just described. This cosine curve was obtained as a solution of the second order differential equation of hydraulic equilibrium. If the losses are taken into account, a much more complicated differential equation for hydraulic equilibrium is obtained, but, by resorting to graphical integration, solutions can be obtained for any given set of constants. The losses to be considered may be lumped together in any convenient way. The method suggested is to consider: (1) the friction loss; (2) the loss due to sudden changes in axial velocity, occurring where the air is led off the air-gap by the vent ducts, (the same type of loss that occurs in water pipes where the pipe cross section changes); (3) the loss as the air turns a corner from the air-gap, and passes out the vent ducts. These losses must be expressed as functions of the gap air velocity and the machine dimensions. The first two losses are obtainable, approximately, from a text book on liquid flow, but the third loss is best obtained empirically, from special tests. The differential equation of hydraulic equilibrium is obtained by substituting the above losses in Berboulli's equation, and differentiating. There is not the space to here present the actual solving of the steps outlined above. However, the complete solution has been carried out for several machines, and the results check very well with test.

Mr. Fechheimer's paper is both a source book and a design manual on the subject of air flow in salient-pole alternators. Its completeness is characteristic, and it will, without doubt, become the recognized authority on this subject, as his previous papers have been on their subjects of centrifugal fan design, and turbo alternator ventilation.

**F. W. Gay:** I think we are all very grateful to the many large corporations that have freely presented at this convention a vast store of information obtained at great cost. A new record has undoubtedly been established for the volume of such information presented to any convention. The data which Mr. Fechheimer has laid before us should be of substantial assistance to machine designers, although I do not agree with him at all on how to cool large machine stators.

Twenty-five years ago a few hundred cubic feet of air per minute would cool the largest machine, and this air in its entire journey through the machine traveled not more than a few feet. In a modern large turbo generator a hundred thousand cubic feet per minute may have to be circulated and each unit of air so circulated may have to travel 30 or 40 feet in its journey from the cooler to the hot spot and back again.

Heat is a giant that has demonstrated its ability to do the work of the world and it does not seem appropriate to use a very appreciable part of the power output of the generator to assist heat in making its exit from the machine. If the heat is given half a chance it can come out "under its own steam."

A study of large stators and particularly turbo generator stators will show that a very large part of the volume of these stators is occupied by air passages. I would suggest that in these air passages a plurality of vaporization coolers be mounted and that the circulating air be led successively past a hot machine part and a vaporization cooler. A unit of air might easily be guided against a hot machine spot and a vaporization cooler twenty or thirty times in succession during a single circuit through the machine. I propose to pump to each such vaporization cooler an excess supply of liquid carbon dioxide drawn from a carbon dioxide condenser located in the condenser cooling water circuit and conduct the carbon dioxide gas back to the condenser to be cooled and condensed.

Each pound of carbon dioxide so circulated will carry approximately 150 B. t. u.'s to the condenser and the cooling carbon dioxide fluid, if it is kept saturated, will not increase in temperature materially above the condenser temperature at any point in its circulatory path. The circulating carbon dioxide will absorb large quantities of heat in the stator upon vaporizing and will give up this heat to the circulating water by condensing and will do this at substantially constant temperatures. The pump required to circulate the carbon dioxide will receive the liquid at the condenser temperature and deliver the liquid to the machine at a pressure only a relatively few pounds higher. A ten-hp. motor will deliver all the carbon dioxide required by a 100,000-kw. machine.

The described method of cooling requires the circulation of a relatively small volume of air per minute and hence relatively low velocities may be used so that the power consumed by the air blowers will only be a very few per cent of that required by the present method.

In the proposed method substantially no heat is carried from the machine by the circulating air, the air merely acts to conduct the heat from an inaccessible part of the machine to a vaporization cooler (a distance of only a few inches). All the heat is carried from the machine by the carbon dioxide.

It may be of interest to know that if all the heat is carried from a modern large turbo machine of say 100,000-kw., by air current, a cross section of the air duct required to carry this air is on the order of 20 to 40 sq. ft. If all the heat is carried from this same machine by gassifying liquid carbon dioxide, a 3-in. diameter pipe will carry the necessary carbon dioxide into the machine and a 3-in. diameter pipe will carry the carbon dioxide gas to the condenser.

It is to be noted that the modern designer in order to hold down the volume of circulating air to even its present enormous volume has allowed each unit volume of air to carry a maximum load of heat, that is, the circulating air is allowed to get very hot. It may rise in excess of 50 deg. fahr. This necessary high temperature reduces the efficiency of the air as a cooling medium. On the other hand, the temperature rise of the carbon dioxide fluid in its circulation through the machine need not be as much as 5 deg. fahr.

**G. W. Penney:** The difficulties involved in calculating the flow of air are seldom appreciated by one who has not attempted to solve problems of this type. Probably the most serious difficulty in such calculations is that the flow is determined by a combination of inertia and viscosity forces. The inertia forces are usually very large compared to the viscosity forces, but a viscous force of only a fraction of a per cent of the inertia forces may be the cause of eddies which completely alter the type of flow

and may easily double the total resistance to flow. Under such conditions exact calculations of the flow air starting from the fundamental laws of mechanics are almost hopeless in most cases.

Because of this turbulent nature of the flow of a gas most of our calculations are based on the performance of geometrically similar shapes tested at a gas velocity to give a comparable Reynold's number so that the type of flow will be similar. In the case of the flow of air through a long duct the path of the air is fairly definite and we have enough tests on the pressure drop through straight pipes, bends, enlargements, etc., so that the resistance to flow can be very closely approximated from data which may be regarded as fairly fundamental.

Unfortunately the flow of air in the salient-pole alternator is not comparable to the flow in a long duct. The exact path of the air going from the fan to the space between the poles and thence to the vent ducts is very uncertain. The flow through the vent duct is further complicated by the pulsations produced by the poles, a pulsation in the flow occurring every time a pole passes a duct as shown in Fig. 10.

To obtain any accurate solution for the flow of air in a salient-pole alternator starting from the fundamental laws of mechanics seems almost hopeless considering the complications involved. Furthermore, to be useful for engineering purposes a calculation must be simple. Therefore the method used by Mr. Fechheimer of predicting the flow through a machine based on tests on geometrically similar models imitating the major variables of machines is of great practical value, even though as Mr. Fechheimer points out such a solution cannot be expected to be accurate in every detail and for all conditions.

Using the type of analysis discussed by Mr. Fechheimer the tests can be used to predict the effect of many changes in the ventilating system and also extended to many cases of hydrogen cooling. In the case of hydrogen the type of flow at a given velocity may be different from that in air because of the higher kinematic viscosity of hydrogen. However, the type of flow will be the same at the same Reynold's number so that tests at a low velocity in air can be used to study the type of flow at a higher velocity but the same Reynold's number in hydrogen.

**S. L. Henderson:** There is one question I should like to ask Mr. Fechheimer. In describing Fig. 39, where the interpolar space was reduced, he said the curve was not parabolic because it imitated an increased length in the machine. I didn't quite see that. It would seem to me it would imitate a machine with a large number of poles. I may have got his statement wrong.

**R. L. Barns:** It appears to me that the data Mr. Fechheimer has given apply only to horizontal shaft machines which are arranged to take in air at both ends of the rotor and my experience leads me to believe that much different results would be obtained if similar tests were carried out on the ventilation of vertical-shaft waterwheel-driven alternators. Nearly all machines of this type are arranged to receive cooling air from a pit or chamber underneath and therefore the distribution of the air pressures in the air-gap and through the air passages would be quite different from that shown in Mr. Fechheimer's paper. Nor do I believe that it is possible to be guided entirely by test results on one particular vertical shaft machine in attempting to predetermine what will happen in the ventilation of another machine. I might cite an illustration or two. A recent test on a large vertical shaft alternator showed that the best distribution of the air through the stator core and over the ends of the stator windings resulted from the installation of ordinary straight blade fans at the top of the rotor. In another case tests showed that the best results were obtained with similar fan blades at the bottom of the rotor. In each case the fans were added to increase the circulation of air about the end windings, and the best results were obtained by the omission of shrouds for enclosing the fans and end windings. Personally, I believe that where it is permissible, shrouds should be omitted in order to make the windings more accessible for cleaning and maintenance even though a slight sacrifice in efficiency is made.

As I have said, the data which Mr. Fechheimer has presented are of real value in studying the ventilation of horizontal shaft machines, but I feel that they are not wholly applicable to vertical shaft alternators.

**C. J. Fechheimer:** I am indeed appreciative of the kind remarks that have been made by several men who have been good enough to participate in the discussion of this paper. I am very grateful to Mr. Beckwith, who was one of my assistants on this work and subsequently wrote a thesis for his master's degree along the lines that he indicated in his discussion in which he solved certain differential equations for the distribution of air volume.

I thank Mr. Gay for reminding me of some old-time machines. I think what he had in mind in this particular case was not a salient-pole alternator but a turbo alternator in which the air was discharged upward, as I remember it, through the two halves. I believe if we were to analyze the scheme that Mr. Gay suggests of putting in tubes at various intervals, we should find it extremely difficult mechanically, from a practical standpoint, although I have not, of course, investigated that particular scheme. There is this possibility of keeping the temperature rise of the air down to lower limits.

In general the whole thermal problem has been analyzed and we know what the temperature rises of the different parts are when the air is going through the machines, and it is not nearly so bad as Mr. Gay seems to think. In the ordinary salient-pole alternator the temperature rise of the air is of the order of 17 or 18 deg. cent., which corresponds to about 100 cu. ft. per minute per kilowatt loss. That would represent the maximum air temperature rise at discharge. At the critical part, say in the stator teeth, the temperature rise of the air is considerably less than that. The high velocities that ordinarily obtain in our large machines make for excellent heat transfer from the laminations to the air adjacent to them, so we don't have a large thermal drop from the laminations to the air; and the iron package is comparatively thin, so that the average transverse thermal drop through them is still quite low.

One more point I want to make in answer to Mr. Gay is that this paper was simply the result of investigations of particular types of ventilation, not of the general scheme, but rather of the types that are generally used; of course, not all of the schemes, nor all the possible modifications of even this one, are covered. For instance, when it was finally necessary for this work to be discontinued, we did not get tests with squirrel-cage windings, much as they were desired.

Mr. Penney has referred to Reynold's number. Any one who makes a study of fluid flow today will learn that that is the very important criterion of flow. It correlates density, viscosity, velocity, and a linear dimension. Thus, the loss of head is always the same in geometrically similar ducts if the Reynold's number is not altered. Thereby experiments can be made on models of one size, with one order of velocities, and with one kind of fluid, and the data thereby obtained can then be applied to full size with perhaps another fluid and other velocities, provided the Reynold's number for the two cases is unchanged.[1] The designer of hydrogen cooled electrical machinery may find some parts which are not adequately cooled, because the flow may be linear instead of turbulent due to the considerable difference in Reynold's numbers for air and for hydrogen, assuming that he had based his calculations upon the data obtained in an air-cooled machine.

Mr. Henderson raised a question in regard to Fig. 39. Perhaps the departure of the curve for reduced interpolar spaces from the simple parabolic form will be better understood with the aid of a physical picture.

1. The footnote near the beginning of the Appendix I bears upon Reynold's number.

In the accompanying sketch, Fig. 1, suppose the machine is long, or that the spaces between poles for axial flow are reduced. The axial velocity of the air at either end is consequently high. If the static pressure at $A$ is higher than at $B$, air flows through the radial vent from $A$ to $B$. The volume flowing axially is thereby slightly decreased, and the axial velocity lowered. If there are no losses, the static head just beyond $A$ is increased by exactly

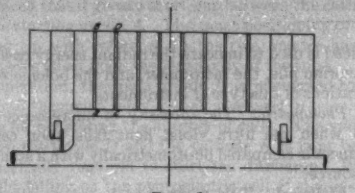

Fig. 1

the same amount as the axial velocity head is decreased. Consequently, at $C$ the static head is higher than at $A$, and the radial flow through $C$-$D$ is greater than through $A$-$B$. If the vents are very many, and very narrow, the familiar cosine (or nearly parabolic) curve would be obtained. However, there *are* losses, such as friction, and that which accompanies the reduction in axial velocity. If such losses are exactly equal to the gain in static head due to the slowing down of the air, the flow through $A$ $B$ equals the flow through $C$ $D$.[2] If the losses exceed the regained head between $A$ and $C$, the flow through $A$-$B$ is less than through $C$-$D$. It is evident that where the axial velocities are highest the losses are usually greatest; therefore it is possible in long machines for the curve to be nearly horizontal, or even bend upwards near the extremities.

By means of the mathematical solution that Mr. Beckwith obtained, he was able to check very closely experimental curves, such as shown in Fig. 39.

In regard to Mr. Barns' discussion, I do not think that the vertical alternator is any different from the horizontal shaft alternator, provided the system of ventilation is the same. As I understand it from the description he gave, there were distinct structural differences. He used different schemes of fans, and there were other differences; consequently, the distribution or the characteristics of flow were quite different from what he had obtained in somewhat similar horizontal machines. I am frequently requested to advise on various schemes of ventilation, but I cannot do so in this case because I do not know the details of the construction other than Mr. Barns outlined, and he did not make a sketch. If he wishes to do so and will submit a sketch to me, perhaps I can throw a little more light on the questions that he raised.

2. This assumes that the difference in static heads is the only actuating means for radial flow. It is recognized that circumferential velocity heads also have considerable influence.

# An Ultra Violet Light Meter

BY H. C. RENTSCHLER[1]

Non-member

*Synopsis.—An instrument for measuring ultra violet radiation is described in this paper. The general plan of the meter is explained and a description of a small portable instrument is given. By means of proper choice of cells, as described in the paper, radiations of different desired frequencies may be measured.*

* * * * *

SUNSHINE and fresh air have long been recognized essential for good health in man as well as for animals and plants. It is now well known that this beneficial effect from sunshine is in large part due to radiation from the sun which is not visible.

By passing the light from the sun through a glass prism, rays of different color are separated, producing the well-known result called the spectrum. These various colors differ from each other in wavelength only. Thus red light has a wavelength of about 6000 $\times 10^{-8}$ cm., while violet light has a wavelength of about 4000 $\times 10^{-8}$ cm., with the intermediate colors having wavelengths between these two values. By suitable means of detection it can be shown that in the spectrum so obtained there is radiant energy of wavelength longer than the red, known as infra red or heat rays. Similarly we have radiation of wavelength shorter than the violet. This latter region is known as the ultra violet.

Due to the absorption by the atmosphere around the earth, the short wavelength limit in the sun's rays is about 2950 $\times 10^{-8}$ cm. Furthermore, due to varying atmospheric conditions and seasonal variations, this short wave end of the sun's radiation is so variable in intensity that for practical applications it is a rather unreliable source of ultra violet light. Artificial ultra violet light is now extensively used in medical treatment of certain ailments, for the production of vitamines, for bringing about certain chemical reactions (a field known as Photo Chemistry) and for many other purposes. For a systematic study of the effects so produced, a practical device for measuring the intensity and quantity of the light used is evidently of great value in determining a quantitative relation between the light used and the effect it produces.

The methods which in the past been have used for measuring or estimating intensities of ultra violet light may be classed as follows:

*1. Chemical.* Here the light generally produces certain color reactions in the compounds used and the intensity is gaged by the change of color and the time of exposure.

*2. Thermal.* The radiation is allowed to fall upon the surface of a body and the temperature change produced is used to indicate the radiant energy received. The thermo pile, the radiometer, and the bolometer are illustrations of this type of instruments.

*3. Photometric.* The intensity of fluorescence produced when the ultra violet light falls upon certain substances is compared photometrically with a standard light source.

*4. Electrical.* This method is based on the phenomenon known as the photoelectric effect where an electric current is permitted to pass between two electrodes in a vacuum or a gas, by letting the light fall upon one of the electrodes. Most metals show this effect only when illuminated by light of very short wavelength; that is, in the short ultra violet end of the spectrum. The current which can be produced in this way is very small and consequently requires either a very sensitive current measuring instrument such as a galvanometer or an electrometer, or an amplifier such as is used in radio together with less sensitive meters.

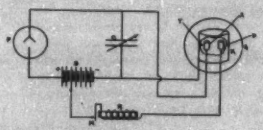

FIG. 1—ULTRA VIOLET LIGHT METER CIRCUIT DIAGRAM

None of these devices as described is really suitable where simplicity of operation and portability are essential. It is the object of this paper to show how these difficulties are readily overcome by the use of a simple device. The operation is readily understood from the following description.

In the accompanying diagram, Fig. 1, a battery $B$ charges the condenser $C$ at a rate determined by the photoelectric current produced in the cell $P$ when light falls upon the cathode of the cell. Heretofore this rate of charging of the condenser or in some cases the reverse effect, namely the rate of discharging of the previously charged condenser, was measured by means of an electroscope or electrometer. The simplicity of the scheme to be described here depends upon the substitution of a specially designed glow tube, which we shall call a "glow relay tube," indicated by $G$ in the diagram in place of an electrometer.

This glow relay tube has an iron or other suitable metal cylinder about an inch in diameter and from one

1. Director of Research, Westinghouse Lamp Company, Bloomfield, N. J.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

to one and a half inches long for cathode $K$. There are two anodes; one shown by $A$ which we shall call the starting anode, and a second anode $D$ which we shall call the main anode. The anode $A$ preferably consists of thorium metal.

A small iron or nickel wire $T$, welded to the cathode, is so placed that it gives a short gap between the cathode and the starting anode $A$. The exact positioning of this starting tip with reference to the two anodes has an appreciable effect upon the sensitivity of the tube.

In operation, the main anode $D$ is connected to the battery $B$ through a relay $R$ such as is used in telephone service for registering the number of calls. The voltage between the anode $D$ and the cathode $K$ is kept below that normally required to start the discharge. When the light falling on the photoelectric cell $P$ charges the condenser $C$ to such a potential that a discharge takes place between $K$ and $A$, the cathode resistance of the glow tube is broken down and a current flows between

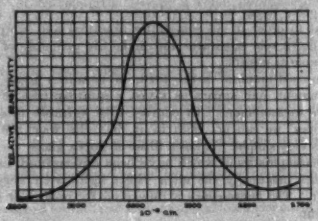


Fig. 2—Erythema Curve According to Hansen and Vahle

the main anode $D$ and the cathode. This operates the relay, pulls the armature over, registers the count and at the same time, opens the main circuit at $M$. Simultaneously the condenser is discharged. The light falling on $P$ again charges the condenser $C$ to the breakdown potential between $T$ and $A$ when the discharge is repeated. Thus it is clear that the intensity of the light falling on $P$, which is effective in producing photoelectric action, is proportional to the rate at which the counter registers and the total quantity of effective light which has fallen on the cell is proportional to the total number of discharges registered by the counter. In some cases it is desirable to use a sensitive relay for $R$ which in turn closes and opens a separate circuit which operates the counter or other recording or operating device. By means of this device, it is possible to measure photoelectric currents of the order of a thousandth of a microampere or much less with as great ease as we now measure electron emission currents by the use of milliameters.

The next question that confronts one in the measurement of ultra violet light is the use of a cell suitable for the particular problem at hand. It so happens that photochemical reactions, or the response of the human system to ultra violet light radiation, etc., is limited to a definite region of the spectrum and that different reactions require different wave bands. By the selection of the proper material for the photoelectric cell, a cell can generally be found which will not respond to light of longer wavelength than that which is effective for the

Fig. 3—Portable Ultra Violet Meter with Photo Cell Exposed in Operating Position

particular reaction. Light of wavelength shorter than that which produces the desired effect for the particular reaction can be prevented from reaching the photo cell by the use of suitable light filters. In some cases this can very conveniently be accomplished by using the proper kind of glass in the construction of the cell. In this way a very satisfactory intensity or quantity measuring device can be made by combining

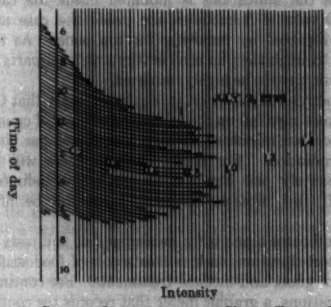


Fig. 4—Graphic Chart Recording Ultra Violet Light in Sunlight on July 2, 1929

the proper photoelectric cell with suitable filter with the scheme outlined above. To illustrate this point, for the prevention and cure of rickets, the medical profession has fairly definitely established the useful wave band of light between $2800 \times 10^{-8}$ cm. and $3200 \times 10^{-8}$ cm. The curve of relative sensitivity for different wavelength as given by Hauser and Vahle[2] is shown in Fig. 2.

2. *Vergl. Strahlentherapie*, Vol. 13, 1921, p. 41.

We have found that if uranium metal is used as the active material of the photoelectric cell, the cell will not respond to light of wavelength longer than about 3200 $\times 10^{-8}$ cm. as can readily be shown by interposing ordinary window glass between the source of the ultra violet light and the cell. Again, by using a suitable glass for the container of the cell, such as Corex *D*, only a very inappreciable amount of light of wavelength shorter than $2800 \times 10^{-8}$ cm. will reach the active material of the cell. We thus have a device which measures very well the useful radiation of the ultra violet light in the region of wavelengths beneficial for this particular use.

If the entire ultra violet region below $3200 \times 10^{-8}$ cm. is to be measured, the cell container is best made of quartz instead of this special kind of glass. If the region of wavelength below about $3700 \times 10^{-8}$ cm. is to be measured, we find metallic thorium serves very well for the active material of the cell. And again, if it is desired to measure light from blue into the ultra violet, the metal cerium serves admirably for the cathode of the photo cell.

The details followed in the construction of the cells are omitted here for obvious reasons. These are of sufficient interest and will be described elsewhere.

The indicator complete, Fig. 3, is built into a case 10½ by 12 by 9 in. The photoelectric cell is hinged on a door so that it can be set at different angles to allow the light to fall directly on the cell. When not in use, the cell folds into the case and the door protects it from being damaged. The electromagnetic counter that registers the indications is mounted inside the case. The 180 volts of *B* batteries are inside the case and can be replaced by removing the top panel. As the current through the photocell is very small, all parts of the circuit have to be highly insulated.

To operate the indicator, it is only necessary that the ultra violet rays fall on the cell. The number of counts in five or ten minutes gives the amount of the ultra violet radiation. For bright sunlight there will be approximately one hundred counts in five minutes. For half this intensity of light, there will be fifty counts.

The indicator alone is for measurements and tests of fairly short duration, such as treatments of food stuffs, testing of glass, and medical treatments. For continuous operations, a graphic meter that records the counts is attached. In this case, the electromagnetic counter is omitted from the indicator and the graphic meter operates from the contacts of relay *R*, Fig. 1. The graphic meter is the impulse type, that is, each count of the indicator notches up the pen of the recorder. The pen is automatically reset to zero every five minutes. The graphic meter gives a continuous record of the counts that occur in five minute intervals. Fig. 4 shows a chart taken of sunlight on July 2. The midday variation in ultra violet shown on the chart was due to its absorption in passing clouds.

The indicator alone is self contained and operates from the *B* batteries in the case. The graphic meter operates from a 110-volt light circuit and will give a continuous record for thirty days.

In conclusion it apears that by the combination here described we have a simple and at the same time a reliable method for measuring the ultra violet light as may be used for various purposes of application.

## Discussion

**E. Gordon:** As Dr. Rentschler explained the principle of his very interesting and useful instrument, which is in some respects new, I feel that there will be other uses beside the measurement of ultra violet to which it will be put. However, I want to mention a few things about some work which I was engaged in with the help and cooperation of the Hanover Research Laboratory during the last four or five years, in the development of an ultra violet meter which has been on the market for about two or three years and enjoys a fair amount of use throughout the world.

This meter, I believe, was not mentioned by any of the speakers tonight. It is a fluorescent meter. We considered photoelectric cells and other things in the development of this meter, and we found that in order to get something practical and simple you must cut down your apparatus and make the principle of operation as simple as possible.

We also used uranium in the form of uranium glass. Like this instrument, our apparatus gives a quantitative, but not qualitative measurement. Of course, with suitable filters and spectroscopes, we can get both in it, but the way the meter operates is very simple. It has a filter of Corex glass, the transmitting characteristics of which have been determined, and this filter admits practically the ultra violet light with very little other light. The fluorescence is measured by means of a comparison lamp.

The apparatus is extremely simple. It is operated by looking into it and comparing the color. Incidentally, the color is green. It is very difficult to make a mistake in comparison. We have tested it with many users, people who are not acquainted with the use of scientific apparatus, and we found errors of from 25 to 10 per cent with inexperienced users. The apparatus is very small. We have had some difficulty with it because we had to make a stand to protect the operator from the ultra violet light.

In addition to that, we have published curves and we have described the dosage of ultra violet light in energy doses in ergs per second per square millimeter. So far the work has been done only for the quartz mercury lamp, but there is no reason why in the future we shouldn't be able to calibrate the meter for any kind of light source.

When it comes to sunshine we have experienced a great deal of difficulty because the spectrum of the sun changes from hour to hour, the distribution changes, not only the intensivity, but even the distribution as to vapors and so forth of the air. This apparatus is a little more automatic and objective than our apparatus, which is rather subjective. You must look into it and make a comparison. It will lend itself to uses to which our apparatus cannot lend itself. We found the use of batteries and photoelectric cells involved sources of error, whereas our apparatus involves minimum sources of error.

In conclusion, I wish to state the medical people are having a great deal of trouble with the use of this simple photometer. Many laboratories are using it. They find it is not precise enough for them. They want an error less than 5 per cent. They want something which will include the use of a photoelectric as well as a very delicate measuring apparatus with a spectroscope. The doctors using this apparatus object that it is too complicated to use.

In closing, I want to congratulate Dr. Rentschler on his invention. I think it will probably be useful for x-rays as well as ultra violet, in the automatic control of x-rays.

**W. W. Winship:** Dr. Rentschler by the proper selection of photoelectric material on the one hand and light filtering material on the other definitely fixes the wavelength limits within which his meter measures any certain ultra violet light source. As all of his audience are not equally versed in the peculiarities of ultra violet light it may be well to mention again, as Coblentz (*Radiology* 10:118, 1928) has pointed out, that the comparative intensity of ultra violet light as indicated by a photoelectric cell does not necessarily mean that the same respective biologic efficiency, for example, will be obtained if different sources of ultra violet radiation are under consideration.

In these cases we are of course measuring the resultant of two factors, a qualitative one representing the effectiveness of the particular ultra violet region in producing chemical, photoelectrical, or other responses, and a quantitative one representing the intensity of that effective wavelength in the light source being measured.

Dr. Rentschler no doubt assumes that it is understood that two or several quite different ultra violet sources might give identical readings using his meter or other commonly employed means of ultra violet measurement. One light source for example might be rich in wavelengths having a small photoelectric effect, a second might have a smaller percentage of wavelengths with a much greater photoelectric power, while a third might be moderately strong in rays producing a moderate photoelectric effect, and yet the three might give the same reading on the ultra violet meter.

This paper speaks of measuring ultra violet light for various purposes of application including treatment of food stuffs, testing of glass, and medical treatments, and it is the writer's understanding that its chief usefulness lies in measuring the relative effectiveness as gaged by photoelectric effect of different ultra violet sources of the same type which had already been standardized for the particular application under consideration.

As the writer understands that curves expressing the sensitivity of a photoelectric cell to the ultra violet do not agree with those showing chemical activity, for example, and that neither of these necessarily corresponds with a curve showing the production of erythema, there seems at the moment little hope that curves showing the ultra violet effect of different light sources, as measured by different methods, will be found to bear any direct relation to one another so that a curve produced by Dr. Rentschler's meter for example could be interpreted in terms of actinic power.

As far as present data show, will it not always be necessary to measure ultra violet sources by chemical meters if required as actinic sources, by electrical methods when needed for photoelectric purposes, etc.? As regards chemical measurements, it would seem that these should always be made with the chemical involved in the investigation, the effective wavelengths required for various chemical reactions being found in such widely separated parts of the spectrum. A further complication seems to lie in the fact that according to some authorities production of erythema is apparently a matter of individual reaction and cannot be accurately measured by any form of apparatus, even if using the same wavelength and intensity as that to be applied to the human body.

**H. P. Gage:** Some of the work which has been referred to by Dr. Luckeish was performed more or less with our cooperation by Dr. G. H. Maughan at Cornell University. The first work which Dr. Maughan did was to determine, or rather redetermine a little more narrowly, about what spectral region was effective in the cure of rickets in chickens. Previous work had been done by Dr. Alfred F. Hess of this city, and I may say that his results when reviewed are entirely consistent with those of Dr. Maughan, *i. e.*, whether or not the entire effect is due to the .2968 line when working with the mercury arc, at least the difference between the relative effects obtained and the energy of the .2968 line is undetectable by biological means. That is the reason why the .2968 region is considered as being the antirachitic region.

We then wished to find something whose response would correspond as closely as possible to this region. Our first thought was to see if we had a substance whose fluorescence occurred in that region. We therefore covered a quartz mercury arc with a black Corex ultra violet transmitting filter and laid out a number of glasses to see what happened. We immediately picked on two that shine brightly; one is a uranium glass which is used I believe in a meter which has been described tonight, and the other is a potassium lead silicate of which we have manufactured tons for making cut glass tableware.

Our next experiment revealed that this glass would not fluoresce under radiation transmitted through window glass. Thus we are able to measure by photometric means the intensity of radiation of shorter wavelength than is transmitted by window glass.

Dr. Maughan recently made a test of a Mazda lamp the result of which has been included in Dr. Luckiesh's paper. He finds that the biological effect is consistent with the reading on this ultra violet photometer.

In the demonstration of the ultra violet measuring instrument we see here, we have a photoelectric cell which is sensitive to sunlight. That it is not sensitive when we use window glass has just been demonstrated. It is an instrument whose readings would be approximately proportional to the biological effect, considering the effects on rickets only. The cure of rickets is the only biological effect besides erythema which is readily measurable.

**Herman Goodman:** I should like to tell you of a very simple qualitative detector for the vital ultra violet. One uses a piece of Dr. Gage's glass and a very thin layer of salicylic acid dissolved in alcohol, painted on a piece of cloth, and one can detect the range less than 3200 Angstrom units, from a mercury vapor quartz lamp or from certain sources of carbon arc. If a piece of ordinary window glass is interposed, as Dr. Rentschler did here, the fluorescence of salicylic acid disappears. The disappointment is that if one uses very intense sources of carbon arc one is unable to wipe out the fluorescence of a salicylic acid and one is unable in actual sunlight to destroy the fluorescence in its entirety.

I believe that this is due to the fact that common ordinary window glass permits the passage of a very small amount of radiation of less than 3200 A. u., and that small amount from such intense sources as sunlight or strong carbon arc light, is such as to fluoresce salicylic acid.

**E. B. Oliver:** As a lighting man who has watched the development of the sunray lamp, and as one of the early developers of the artificial daylight, I feel that the use of this instrument will be very large. We will be able to take a room and illuminate it with artificial daylight. I have backbone enough to see that the sunray lamp is the next step in our evolution of artificial light, putting it into a room with this instrument, and detecting the sunray value in a room, or in an office.

**L. J. Buttolph:** I wish to call the attention of those interested either in the design or the use of ultra violet radiation meters to certain difficulties we have encountered in their practical use. Their sensitivity is such as to necessitate placing them so close to even the more intense light sources that the effective aperture of the device, as defined either by the construction of the photoelectric cell or of its housing, does not admit radiation from a reflector of any size. We find it necessary to measure the bare source and calculate the additional reflected component from the photometrically determined distribution curve of the reflector and the relative ultra violet reflectivity of the reflector material. Where the relative energy distribution of the total radiation must be determined the relative reflectivity

of the material must also be taken into account by evaluating the reflected component. There is a similar difficulty in the measurement of a low intensity course of extended area, such as the Cooper Hewitt lamp. The instrument generally defines all too small an element of the total source area, this area varying with the distance to the meter so as to defeat any attempt to change the intensity of the radiation received by it. The solution lies in the use of a sensitive meter and in doubling a tube source of light back upon itself to form a compact grid.

Analogous difficulties are encountered in attempts to determine the total effective ultra violet reaching a particular area from several sources or from a single source of extended area, the extreme case of the latter being the determination of the diffused ultra violet effective on a horizontal area from the total sky hemisphere. The meters do not satisfactorily comprehend a solid angle of 180 deg. and calculations from intensity measurements in various directions are complicated by doubt as to the relationship between the angle of incidence and absorption of ultra-violet. It is suggested that a wide angle, at least 120 deg. meter, to be used analogously with an illuminometer would be useful.

**B. H. Smith:** I just want to mention one point that I think might have been missed, and that is that the output of the tube itself, without any adjunct such as the secondary tube, just with an ordinary B battery, the ultra violet sensitive tube is of the order of one microampere, with a goodly amount of ultra violet source, so that even with a sensitive indicating instrument we can get a pretty fair reading. I think that will answer one of the questions asked.

**H. C. Rentschler:** Regarding the uranium glass, we have tried that and we have abandoned it for the reason that uranium glass will fluoresce even when illuminated by a 100-watt lamp. I think, as Dr. Luckiesh has pointed out, a 100-watt lamp will not be effective in producing a sunburn or an erythema dose, and consequently the uranium glass with the photometric measurements will record light which is not necessarily the particular region of the spectrum that we wish to use.

As regards the different sources of lighting being different, the position that we are in here is very much the same as what we do in photoelectric photometry. There is no photoelectric cell made that imitates perfectly the human eye, and yet it is possible by means of photoelectric cells to photometer ordinary lamps far more accurately than we can by the old method of visually looking at them. That is a consistent result.

We have very much the same problem here. I do not pretend that this cell is absolutely responding only to the wavelength that we wish to measure, but it comes within that region, and if you were to take a different source of light, as for instance an ordinary mercury arc, you would have to have a certain reduction factor for the reading here to give the same effect that you get from a carbon arc. That is, a reading of 100 clicks on the carbon arc would not necessarily give the same erythema dose as the 100 clicks on the mercury arc, and each one of the different sources of ultra violet that would be used would have to be reduced by a certain factor, which in the end can only be worked out by actual erythema tests, or whatever the purpose is that we wish to use the ultra violet light for.

# FOREWORD

# System Connections and Interconnections

## A SYMPOSIUM ON FUNDAMENTAL PLANS OF POWER SUPPLY AND OPERATING PROBLEMS OF INTERCONNECTIONS

Prepared under the Auspices of the Interconnection Subcommittee of the Power Generation Committee.

I. *System Connections and Interconnections in Chicago District*, by G. M. Armbrust and T. G. LeClair.

II. *Fundamental Plan of Power Supply in the Detroit District*, by S. M. Dean.

III. *Fundamental Plan of Power Supply in the Philadelphia Area*, by Raymond Bailey.

IV. *Operating Characteristics of Turbine Governors*, by T. E. Purcell and A. P. Hayward (p. 715)

V. *Controlling Power Flow with Phase Shifting Equipment*, by W. J. Lyman (see July Quarterly).

An interconnection may be defined broadly as a linking of power sources and load areas. Thus, interconnections include ties between power systems independently owned and operated, and also connections between different power sources and loads of a single system. It is generally recognized that local conditions and restrictions of various kinds are frequently predominant in their influence upon the type of connections and equipment used, but it is equally apparent, theoretically, at least, that with the locations of the generating stations fixed and a definite character of load to be served, there should be a single method of connection which is better than other possible methods. This method may change from time to time as improvements in equipment characteristics are made.

Assuming that a fundamental plan for a power system may be extended to include the fundamental plan for an interconnection, it is hoped that the first three of the following papers on fundamental plans of power supply will serve as the basis for the commencement of a discussion of this important subject. The committee expects to secure papers giving comparable information on other plans of power supply so that eventually it may be possible to set up a classification of ideal plans according to requirements.

The requirements of the three systems described in the present group of papers are similar to the extent that they are all large and they all have concentrated heavy load areas and relatively large light load areas. They differ in that the power sources and locations range from steam stations located near their loads to steam, hydro, and interconnection sources, some of which are near and others remote from load points. The fundamental plans of the systems were adapted to the requirements of the individual cases, as explained in the papers.

The following table lists some of the features of the systems, covering briefly both the requirements and the general plan of meeting them. A symposium on *Synchronized at the Load* appearing in the October 1929 QUARTERLY of the A. I. E. E., describes a still different fundamental plan, applying most directly to a concentrated heavy load area, but presenting considerable possibilities for more extensive lighter load areas. This plan should be considered in discussions of the papers of the present group.

In building up the art of system connection and interconnection, there are detail points involving equipment characteristics and functioning of components which must be solved, and which in some cases are of sufficient importance to influence the fundamental plan itself. Two such factors are considered in the last two papers of this group. One describes tests which were made on the operation of governors during system disturbances and the other deals with the flow of power in closed loops. These papers serve to reduce the element of speculation on these aspects of interconnection.

PRINCIPAL FEATURES OF POWER SUPPLY SYSTEMS

| Feature | Chicago | Detroit | Philadelphia |
|---|---|---|---|
| Total area | 6,000 sq. mi. | 4,400 sq. mi. | 1,300 sq. mi. |
| Metropolitan area | 209 sq. mi. | 220 sq. mi. | 136 sq. mi. |
| Peak load | 1,355,000 kw. | 550,000 kw. | 735,000 kw. |
| Major power | Steam | Steam | Steam |
| Sources | Interconnections | | Hydro interconnections |
| Fundamental plan | Close linked | Loose linked | Close linked |
| Impedance between generating stations | Low | High | Low* |
| Major transmission and distribution voltages | 132,000 | | 220,000 |
| | 66,000 | 120,000 | 66,000 |
| | 12,000 | 24,000 | 33,000 |
| | | | 13,200 |
| Provisions for limiting short circuit currents | Reactors between halves of system | Inherent in layout | Bus sectionalizing reactors |
| | Reactors on generator leads | Linkage bus reactors | Feeder reactors |
| | Feeder reactors | Tie line reactors | |
| | Segregated phase | | |
| | Neutral impedances | | |
| Voltage control | Tap-changing transformers and generator field control | Tap-changing transformers | Tap-changing transformers<br>Generator voltage regulators |

*Except one hydro station.

# System Connections and Inter-Connections

## Chicago District*

BY GEORGE M. ARMBRUST† and TITUS G. LeCLAIR†

Member, A. I. E. E. Member, A. I. E. E.

*Synopsis.—This paper outlines the characteristics of the Chicago territory and the power system which has been planned to supply this region. The extent and nature of the territory, the loads, and the service standards are outlined. There follow descriptions of the 25-cycle and 60-cycle systems, including voltages up to 132 kv.*

*Protective and control features are discussed, as well as operating procedure. Information is given on the service record and on developments being planned for the future.*

### Introduction

CERTAIN fundamental principles are necessary in any transmission and distribution system in order to maintain reliable service with a maximum output per dollar of investment. However, the fundamentals of any system are governed largely by a number of factors beyond the direct control of the engineer. A basic feature around which any system must be designed is the distribution of population, industries, and load in the territory supplied. Another important consideration is the availability of water power or of water and coal supply for steam generating plants. Between the two extremes, then, of the load at the one end and the economic location of generating capacity at the other, lies the realm for system planning. The first part of this paper therefore sets forth briefly the characteristics of the Chicago territory which are the background for the present design, and the latter part of the paper tells of the system which has been developed to meet the needs of the territory.

### I. Character of Territory

The territory included in the Chicago region is a comparatively large area with its activities centered about the city of Chicago. The city itself has an area of 209 sq. mi. which includes manufacturing, commercial, and residential sections. Immediately surrounding the city and more or less concentrated about the lines of high-speed transportation is a suburban area which is largely tributary to the city and covers approximately 1200 sq. mi. Beyond this, small towns, which are not strictly suburban and yet are apparently located near the city because of good transportation and nearness to supplies, are spread over an area of 4800 sq. mi. The total area in the region considered for this paper is thus approximately 6000 sq. mi.

The spread of population in this territory may be likened to the electrical field about a point, in that it is highly concentrated at the center and this concentration gradually tapers toward the outskirts. This distribution of population is indicated on the map of the region, Fig. 1. In the city proper the estimated 1929 population is 3,250,000, of which 1,750,000 is within the central 60 sq. mi. and the remainder in the outlying 150 sq. mi. In the near-by suburbs where a large percentage of the residents live and commute to the city, the population is about 1,000,000. The population in the remainder of the Chicago region is only 250,000, which makes a total considered of 4,500,000.

This territory is supplied from the systems of the Commonwealth Edison Company, within the city of Chicago, the Public Service Company of Northern Illinois and the Northern Indiana Public Service Company immediately surrounding the city, and the further

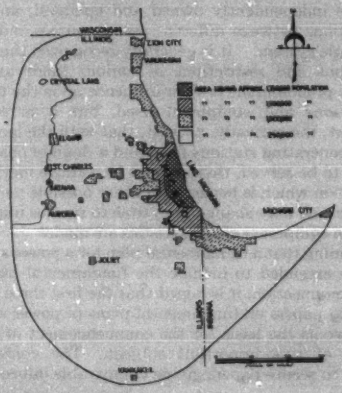


Fig. 1—Distribution of Population in the Chicago Region

outlying regions by the Middle West Utilities Company's subsidiaries. These systems are so interconnected and operated that the supply is equivalent to that from a single system.

### II. Load

In any territory of this size where the vast preponderance of power used is obtained from central stations rather than from isolated plants, there is a wide diversity between the various classes of business and some between the sections of territory supplied. Taking the region as a whole, the load is approximately evenly

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†Both of the Commonwealth Edison Company, Chicago, Ill.

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divided between these classes, and it is estimated will be as follows for the winter of 1929-30:

| | Non-coincident load | Number of customers |
|---|---|---|
| Residential | 400,000 kw. | 1,075,000 |
| Commercial Light & Power | 425,000 " | 200,000 |
| Wholesale Light & Power | 460,000 " | 5,200 |
| Railway | 350,000 " | 10 |
| Total | 1,635,000 kw. | 1,280,210 |
| Total Coincident | 1,355,000 " | |
| Diversity | 280,000 kw. = 20.7 per cent | |

Of this total load of 1,355,000 kw., 1,059,000 kw. is within the city and the remainder, 296,000 kw., in the surrounding region shown on Fig. 1.

The density of load is, of course, to a certain extent proportional to the distribution of population, except for the greater load concentration at the center of Chicago. The maximum density in the downtown area, which covers approximately a square mile, is 125,000 kw. per sq. mi. The average for the city of Chicago is about 5100 kw. per sq. mi., but for the total area in this region, it is only 230 kw. per sq. mi. These loads are the estimated maxima for the winter of 1929-30.

The annual load factor of the entire region is about 51 per cent, though the zones served by the various distribution centers (as described later) have load factors ranging from 35 to 60 per cent. However, the diversity between their maximum loads is only about 4 per cent.

## III. Service Standards

The requirements of the Illinois Commerce Commission are that the lighting voltage regulation at customers' service shall be within 4 per cent below and 5 per cent above the rated voltage (115). The standard which the Commonwealth Edison Company works for is that the pressure shall not drop below 112 volts. A recent careful survey indicates that only a very small percentage receive voltage which is below that standard. In the outlying communities it is more difficult to maintain the same regulation. On the d-c. system the load is more concentrated and the regulation problem is comparatively simple.

The voltage standard for power service is met without difficulty. The Commission's requirements are that the voltage regulation be within 10 per cent of the standard and in almost every case, the actual voltage is not outside the limits of 220 to 240 volts.

The voltage standard for the d-c. railway service is that it be maintained between 600 and 650 volts. In actual service this voltage is normally kept at 620 volts, but under heavy load swings, this voltage may go down to 600 volts and occasionally as low as 590 volts.

### 25-Cycle System

*A. General Plan.* The 25-cycle system, which constitutes the oldest part of the Chicago System and is located in the central district, evolved from the old d-c. generating stations. These were gradually supplanted by synchronous converter substations now served at 9000 volts from the Fisk Street, Quarry Street, and Northwest generating stations.

The 25-cycle system is supplied by 236,000 kw. of generating capacity located at the Fisk and Quarry Street Stations and 85,000 kw. capacity at the Northwest Station and also by two 40,000-kw. frequency changers at the Fisk Street Station fed from the 60-cycle system. No 25-cycle generating capacity has been added to the system since 1920, most of the increase in load since that time having been taken on the 60-cycle system. During the past few years the 25-cycle output has been decreased by transferring load to the 60-cycle system. The two 40,000-kw. frequency changers were recently added to the 25-cycle system supply because of the better efficiency of the modern 60-cycle generators and to provide more reserve for the 25-cycle system.

*B. Load Served.* The 25-cycle system as distinguished from the 60-cycle system has only two classes of load. One is d-c. light and power which is practically all in the central district, (and therefore, commercial). The other class is electric railway service.

At present 95,000 kw. of the d-c. light and power system load and 226,000 kw. of the traction load is supplied from the 25-cycle system. These two classes have a coincident demand of about 313,000 kw.

The substation capacities to feed this load are as follows:

| | D-C. Light and Power | Railway | Total |
|---|---|---|---|
| Substation capacity | 125,350 kw. | 245,550 kw. | 370,900 kw. |
| Number of substations | 20 | 35 | 51 |

Four of these 51 substations supply both classes and 14 also have 60-cycle equipment.

*C. Load Characteristics.* The entire load on the 25-cycle system is synchronous converters which feed either the d-c. distribution network or the 600-volt railway supply. In the case of the d-c. system, the converters are paralleled directly on the d-c. side in some cases, and in others they feed separate d-c. busses, which are in turn tied together through feeders to the low-voltage network. The d-c. system is provided with storage battery reserve which is kept floating on the system to prevent momentary interruptions to the supply which might disrupt the distribution network. These batteries have a total capacity at the 1-hour discharge rate of about 40,000 kw. The power which can back-feed from the system to one machine is considerable and is practically limited only by the impedance of the converter and transformers. The d-c. network is also supplied by other substations on the 60-cycle system, interspersed in such a manner that there can be some transfer of load from one frequency to the other, under emergency conditions through the low-tension network.

Because the load is all synchronous converters, the power factor is practically unity. In some cases care must be taken to keep enough excitation on the generators for stable operation. It has been found that the

old generators particularly are not very stable unless the power factor of their load is kept at unity or slightly lagging.

The railway load is that supplied to the surface lines and the elevated lines. This 600-volt railway load consists of a number of sections which are normally tied together through the substation busses. These sections also form a connection between adjoining substations. This load differs from the low-voltage, d-c. in that the substations are relatively far apart and not a very large interchange of energy can take place without a considerable reduction in the service voltage. The railway load is also supplied from the 60-cycle system through synchronous converters and mercury arc rectifiers.

*D. System Connections.* The 25-cycle system is

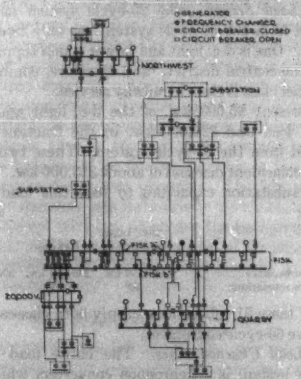


Fig. 2—General Diagram of 25-Cycle System Showing Typical Substation Supply

largely supplied at 9000 volts. (A few outlying railway substations are supplied at 20,000 volts through transformers connected to the 9000-volt system at Fisk Street.) Fig. 2 gives the general layout of this system, and its design can best be explained by referring first to the substations in the d-c. territory.

Every substation feeding the d-c. network has its converting capacity separated approximately in halves, and these halves of the converting capacity are supplied from busses which are not normally tied together, but which can be connected together by the closing of a circuit breaker. The separation between these two busses is also carried out in the lines back to the generating station, so that the two halves of any substation are fed from different sections at the generating center. The 9000-volt generating system is operated in three sections as described later. These sections are interlaced and alternated throughout the territory of the low-voltage network, in such a manner that the complete loss of one of these sections would interrupt only half of the supply to any one substation, and the overload to units on the other two sections and to those on the 60-cycle system would be reasonably well distributed over the entire area. In other words, each half substation is treated as a distinct unit and the groups of these half substations which are connected to the same network of transmission lines are interlaced with groups supplied from other sections in a manner that will come as near as possible to giving any point on the network a supply from several sections.

At Fisk and Quarry, there are three sections of the 25-cycle system, called arbitrarily, the *A*, *B*, and *C* sections as shown in Fig. 2. One of the two main busses at Fisk Street is the nucleus of the *A* section, the other that of the *B* section, and the Quarry Street busses supply the *C* section. The *A* and *B* sections are connected together through a 2.0-ohm reactor. The Quarry section is connected both to the Fisk *A* and the Fisk *B* sections through separate tie lines, each having one ohm reactors. The main bus diagram can therefore be considered as composed of three parts on the three sides of a triangle, with a high reactance at the corners. Since the installation of the frequency changers at Fisk Street it was found desirable to reduce the reactance between Quarry and each of the two Fisk Street sections to one ohm, because the generators at Quarry are not running at all times of the day, and satisfactory regulation must be maintained with a considerable transfer of energy across these tie lines.

In the early days, neither lines nor generators were equipped with reactors. Under this condition, short circuits resulted in severe shocks to the entire system and quite general dropping out of the synchronous converters. As a first step, the generating capacity was split in two groups at Fisk Street Station, then reactors installed in the generator leads and also a reactor tie between the two bus sections.

Even with the above arrangement, a severe short circuit near the generating station or at the station itself, resulted in a collapse of voltage and pulling out of step of the generator units and a general dropping of the synchronous converters. The severe abnormal conditions at times lasted as long as 15 minutes.

After two very severe short circuits experienced in 1919, all lines were equipped with current limiting reactors. The line reactors were primarily for the purpose of reducing the short-circuit current in case of line failure, and to maintain higher voltage on the bus during fault conditions. The generator reactors are to prevent complete loss of synchronizing voltage in case of a bus short circuit, and to prevent too much mechanical force on windings under short circuit.

The Northwest 25-cycle system is relatively small compared to that at Fisk, and the railway substations which constitute most of its load are more or less interspersed with 60-cycle railway substations, so that the same degree of sectionalizing in the supply is not

necessary. It is therefore connected through 9000-volt cable ties to the Fisk *B* section only.

In order to reduce further the short-circuit current, neutral resistors are used at each station. On each section, one generator is grounded through a neutral resistance; the remaining generators do not have their neutrals grounded. The neutral resistors range in value from 2 to 3 ohms. In case of a fault to ground at any point in the system, the fault current is therefore limited to less than 2500 amperes. This value of neutral current is high enough for a prompt operation of relays without being high enough to unduly stress the circuit breakers. Barriers are provided between phases throughout the generating station switchhouse, both on the switches and on the busses, but busses are not sufficiently separated to consider the switchhouse as being an isolated phase structure.

The protection of lines on the 9000-volt system is by the conventional time sequence in most cases. This time sequence is extended back to the generating station and includes relays in the supply to the line busses. Three or four substations are usually connected together in a group which is fed by several lines from the generating station. If the substations are close together, the tie lines between these substations in the group are frequently protected by a pilot wire differential scheme. These differential relays are backed up by induction overload relays at one end of the line only. Other tie lines are equipped with reverse power relays set to trip with power flow away from the bus, at each point where the relay is installed. A minimum time differential of 0.4 second is provided between adjacent sections of the network. Practically all lines from generating station direct to the substation are equipped with induction overload relays at the generating station, and a reverse power relay at the substation end, which are set to trip with power flow toward the generating station.

Each generator is equipped with ordinary instantaneous differential relays but not with overload relays. In case of a severe or prolonged overload, the operator is depended upon to open the switch, if necessary, before the generator actually fails. The machines are called upon to carry an occasional overload rather than risk unnecessary interruptions caused by operation of overload relays.

The busses do not have any direct protection against short circuit. In case of a bus failure to ground, experience has demonstrated that these faults may continue for a considerable period before an actual shutdown will occur, and the operator is expected to open the proper switches. The principal item in protection is the scheme of sectionalizing. This is not relay protection in the strict sense of the word, but is rather a precautionary measure to prevent the spread of trouble beyond the portion where it occurs as it effects a quick separation between the *A*, *B*, and *C* sections of the 25-cycle system, leaving them as independent units having both capacity and load.

*E. Operating Procedure.* The generating units are operated on a schedule which provides for the maximum fuel economy of the entire system. This schedule is, of course, changed from time to time to take into account the temporary operating limitations and outages of generators. Sufficient reserve capacity is kept running to carry the load in the event of the instantaneous loss of the largest unit, which is ordinarily one of the 40,000-kw. frequency changers. These frequency changers supplying the 25-cycle system are operated at a heavy load during the base load period since the newer 60-cycle units are more economical than the old 25-cycle units.

*F. Service Record.* With the present arrangement of the 25-cycle system, any cable fault at 9000-volts, either phase-to-ground or phase-to-phase, does not cause a serious interruption of service. When the fault is single phase to ground, the effect is usually very small. In the case of phase-to-phase, or a three-phase fault, frequently there is some dropping off of synchronous converters and resultant transfer of load to other units. Since the installation of line reactors, there appears to be no serious danger of a complete shut-down of the 25-cycle load due to any possible fault on the system.

## Sixty-Cycle System

*A. General Plan.* The 60-cycle system within the city of Chicago developed later than the 25-cycle system, and contains some similar features which have been found reliable. Some years ago the major portion of the 60-cycle system consisted of a network of 12,000-volt cables tying generating stations together through substations. This situation evolved by gradual stages rather than from a concerted plan, and after the system attained large proportions it was found necessary to adopt a plan which approaches more closely the strictly radial supply. Under the present arrangement large substations are treated as individual units fed only by direct lines from one generating station while the smaller substations are handled in groups with each supplied by direct lines and interconnecting ties. The supply to the substations is concentrated at several centers, with no interconnection at the generating voltage, but with a rigid connection between generating stations at a higher voltage.

For the outlying system in the territory surrounding Chicago, very much the same general plan of supply is used, except that it has not reached the stage in growth where it is necessary to omit the tying of large centers through the load. As a result, frequently centers are connected together through several 33-kv. lines that supply energy at several points along the way. The system is, however, reaching a point where the 132-kv. trunk line connections constitute a fairly rigid connection between centers, and the 33-kv. lines are not depended upon for interchange.

*B. Load.* The 60-cycle system covers the entire Chicago District and supplies more than three-quarters of the total load. Therefore, the load to be considered is of practically the same character and distribution as that already mentioned under the load for the entire area. The several classes of load are so distributed that there is considerable benefit obtained from diversity at each one of the centers. It is estimated the total 60-cycle load in the Chicago District during the winter of 1929-30 will be 1,073,000 kw., of which 745,000 kw. is within Chicago.

*C. Secondary Systems.* The d-c. system, which covers the downtown area in Chicago only, is the conventional type of d-c. network, with interconnected mains fused at junction boxes fed by feeders ranging in size up to a maximum of 2,000,000 cir. mils cross-section. Each of these feeders is fused at the junction box, where they are connected to the mains or to the busses of individual large customers. In the case of individual large customers, a strong tie is maintained to the network in the street, so that the junction boxes at the customer's premises practically constitute a part of the network proper.

Because this network is so closely concentrated and has such a large block of load, the problem of re-starting in the event of a shut-down would be a rather difficult one. In order to prevent such a shut-down, a considerable battery reserve is provided, but the principal dependence is placed on methods of sectionalizing in the a-c. supply, which are dealt with elsewhere in this paper.

For the remainder of the general lighting and power load, a radial system of supply is used, and the secondary system normally consists of low-tension secondary mains, which are confined within one city block. Each city block contains a secondary unit with sufficient transformer capacity near the electrical center to take care of the total load. This secondary is supplied from radial 4000-volt, three-phase, 4-wire feeders from the substations. In the case of the larger customers, such as industrial plants, theaters, hotels, etc., continuity of supply is insured by the use of either automatic or manually operated "throw-over" switches. This load is normally supplied from one 4000-volt feeder, but in event this feeder fails, the customer's electrician may transfer the load quickly to a connection from the nearest adjacent feeder. Each of these feeders or circuits is loaded only to the point where it is possible to transfer the load from any feeder to several adjoining, through pole-top disconnecting potheads or switches, without appreciably overloading the circuits.

The method of distributing to the elevated lines and surface lines has already been mentioned under the discussion of the 25-cycle system. The most modern railway system is that supplying the Illinois Central Electrification, a 1500-volt d-c. system which uses very nearly the equivalent of a solid secondary network under normal conditions. The various sections of this secondary system are connected together only through the substations and through tie stations equipped with high-speed circuit breakers. After several preliminary adjustments, the d-c. high-speed circuit breakers have been found to be selective under practically every operating condition and will clear faults without an interruption of service, except on the section where the fault occurs, and without flashing over of converters under direct short circuit. This system has been discussed in detail in the *General Electric Review*.[5]

Large wholesale customers with a power load in one plant of approximately 500 kw. or more, are supplied from independent substations fed at 12,000 volts. With the exception of the largest installation, these substations are connected to industrial rings out of company-owned substations. These industrial rings may carry from 1 to 9 customers each, and the ring is looped through a high-voltage bus at the customer's substation. The two ends of this ring come back to the same substation, but are connected to different busses across a bus tie circuit breaker which is normally open. A typical example of this system, showing the connections and the relaying used for selectivity, is indicated in Fig. 3.

*D. Substations.* Practically all the secondary system, including most of the large customers having 12,000-volt supply, is fed through substations. The relative proportion of the classes can be seen from the following tabulation of substation capacities in Chicago to feed the different classes of load:

| | |
|---|---|
| *4-Kv. distribution* | |
| Attended Substations | 452,000 kw. |
| Remote Controlled Substations | 272,600 " |
| Total | 724,600 " |
| Railway Substations | 108,700 " |
| D-C. Light and Power Substations | 158,675 " |
| 12-Kv. Industrial Substations | 421,815 " |
| Total | 1,413,790 kw. |

Number of Substations

| | |
|---|---|
| *4-Kv. distribution* | |
| Attended | 15 |
| Remote Controlled | 26 |
| Railway | 14 |
| D-C. Light and Power | 13 |
| Combination 4-Kv., Rwy. or D-C | 14 |
| Combination Rwy. and D-C | 2 |
| 12-Kv. Industrial | 219 |
| Total | 303 |

This includes 14 substations which also have 25-cycle equipment.

The supply to each major substation comes from one of the generating or distributing centers. Classified according to the source of supply the number is as follows:

| | |
|---|---|
| Calumet Station | 11 |
| Crawford Station | 13 |
| Fisk-Quarry Station | 29 |
| Northwest Station | 16 |
| Washington Park Station | 10 |
| Total | 84 |

*E. Centers.* As previously mentioned the 60-cycle system in Chicago is concentrated about five major centers. These centers are fairly well located geographically in order to get an economical distribution of the load. Fisk Street and Quarry Street are separate generating stations, but they are connected together at the generated voltage and are here considered as one station. The capacity is steam generating equipment and the loads at these centers are as follows:

| Station | Steam capacity | Coincident load |
|---|---|---|
| Northwest | 60,000 kw. | 156,000 kw. |
| Crawford | 424,000 " | 221,000 " |
| Fisk | 50,000 " | 120,000 " |
| Quarry | 28,000 " | 70,000 " |
| Washington Park | | 66,000 " |
| Calumet | 188,000 " | 112,000 " |
| | 750,000 kw. | 745,000 kw. |

In the surrounding territory the corresponding generating capacity and loads are as follows:

| Subdivision | Generating capacity 60 Cycle | Estimated maximum coincident load 60 Cycle |
|---|---|---|
| Public Service Company of Northern Illinois | | |
| Waukegan | 116,250 kw. | 20,500 kw. |
| Evanston | 250 " | 45,500 " |
| Electric Junction | 5,000 " | 8,500 " |
| Joliet-Streator | 54,850 " | 27,000 " |
| South Suburbs | 41,400 " | 36,500 " |
| West Suburbs (includes Bellwood) | 4,750 " | 60,000 " |
| Total P. S. Co. | 222,500 kw. | 198,000 kw. |
| No. Ind. P. S. Co. (Aetna System only) | 30,900 kw. | 58,000 kw. |
| Western United | 32,000 " | 26,000 " |
| Ill. Northern Utilities | 24,000 " | 18,000 " |
| Rockford Electric | 38,000 " | 28,000 " |
| Powerton (Portion of Cap. Available to Chicago) | 60,000 " | |
| State Line | 200,000 " | |
| Total | 607,400 kw. | 328,000 kw. |
| Grand Total | 1,357,400 " | 1,073,000 " |

*F. 12-Kv. Station Sectionalizing.* As mentioned briefly in the description of the 25-cycle system, those 60-cycle substations which supply the downtown or d-c. district have their capacity divided into two halves, each half being supplied from separate parts of the 12,000-volt transmission system. These two parts are arbitrarily called the red system and the blue system. This separation between parts is carried back to the generating station, as indicated in Fig. 4. The method of sectionalizing is not quite the same in all substations but the general scheme originated to supply the downtown substations and was applied more or less as indicated. This method of sectionalizing is applied only to the smaller generating stations, that is, a station

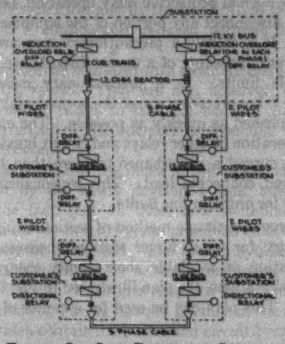


Fig. 3—Typical One Line Diagram of Supply and Relaying for Group of Large Power Customers

which has a capacity on the order of 150,000 to 200,000 kw. in generators plus transformers. No separation is, therefore, necessary purely to reduce short-circuit currents. Each outgoing 12,000-volt line is connected not directly to the main bus but to a line bus which in turn may be fed from either one or both of the main busses. Under normal conditions in a station of this

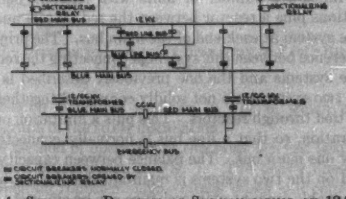


Fig. 4—Simplified Diagram of Sectionalizing on 12,000-Volt System

type, each line bus is connected to both main busses. The generators are equipped with an overload relay which operates in case of a severe disturbance, but does not disconnect the generator. Instead it operates a sectionalizing relay which disconnects each generator or transformer from one of the two main buses, leaving it connected to the other, and also disconnects each line

bus from one of the two main busses. A balance is maintained so that approximately half the capacity and half the load will be connected to each main bus, but there will be no connection between the red system and the blue system after the sectionalizing operation has taken place.

This sectionalizing operation must be distinguished from any normal protective relay operation, because it does not disconnect any portion of the equipment from service. It is merely a precautionary measure which will prevent spreading of a severe disturbance beyond reasonable limits. As a precautionary measure, it therefore takes precedence over the normal relaying and is accomplished as quickly as possible. The operation or maloperation of other relays and circuit breakers will then not spread a disturbance to more than half the station and connected load. This sectionalizing does not occur for ordinary line faults.

The foregoing simple method of sectionalizing is not satisfactory for much larger stations, because of the concentration of available short-circuit energy. For the largest stations, the plan illustrated in Fig. 5 can be applied. This plan can be used for a center of infinite

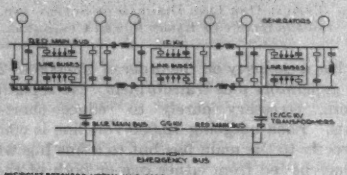


Fig. 5—Sectionalizing Diagram for Large 12,000-Volt Station

capacity simply by extending each main bus to include an indefinite number of units with reactors between sections plus a reactor between the red system and the blue system at each end of the main bus. The principal difference between this system of connecting the red and blue systems and the one previously described is that the two systems are not solidly connected together but are tied through reactors. This puts a limitation on the operation, so that a line bus is normally connected to only one main bus. The balance between capacity and load on the two systems is maintained as before, and a reasonable amount of interchange can be effected across the reactors at the end. These reactors have a relatively high ohmic value, so that a short circuit on one bus will not cause a severe reduction in voltage on the other busses. It is therefore unnecessary to open these reactor ties automatically in the event of disturbance.

The reactors between sections of each main bus are of lower ohmic value, so that there will not be a great voltage displacement between sections under load. They are required only to reduce the short-circuit current and will pass a considerable load current when generators are out of service.

For a station having a capacity intermediate between the largest and smallest, the reactors may be installed between sections of each main bus without using the end reactors, or, on the other hand, the end reactors may be used without having the intermediate reactors between sections. The reactors between sections are used in Crawford Station and the end reactors are used in Calumet Station.

*G. Short-Circuit Current Limitation.* To take account of the diversity in load, the ideal would be, of course, to concentrate all lines and all generators at one point, other factors not considered. With this concentration the short-circuit current would be enormous and the price of circuit breakers to interrupt such a current would be quite prohibitive. Rather than divide the capacity into very small units, the compromise provided is the use of reactors.

On the Chicago 12-kv. system every line consisting of 3-conductor cable emanating from a generating station or distributing station is equipped with reactors. For most lines the value of reactance arbitrarily chosen is ½ ohm, which limits the short-circuit current to about 13,000 amperes or well within the rating of the circuit breakers in case a line fails. Reactors are also used in the station buses as has been discussed previously. The use of these reactors limits the short-circuit current very effectively in the case of line failures which are the most frequent. The value of reactance chosen does not interfere with regulation on an underground system where the lines are short.

For protection against excessive values of current in the event of a short circuit in the switchhouse proper, phase isolation has been adopted for all switchhouses built in recent years and for a number of substations, particularly of the larger type. For the larger centers where high capacity circuit breakers are required, the use of phase isolation does not greatly increase the cost of the switching equipment and it does permit the use of circuit breakers with smaller interrupting capacity, so the net result is an economy. As a typical example, the station may have a calculated short-circuit current, three-phase, equivalent to 2,000,000 kv-a., but the risk of having a three-phase short circuit is sufficiently rare that 1,000,000 kv-a. circuit breakers can be considered satisfactory for this service. The equivalent short circuit current in the case of a fault to ground would be only about 40,000 kv-a., since the ground current is limited by the use of neutral resistors. Each station is equipped with at least two neutral resistors or their equivalent having a resistance of 3 ohms. These resistors may be connected to the neutral of any generator. Where the station normally operates in parallel, the practise is to operate with only one resistor connected but with the control arranged to throw a second resistor in service on the opposite half of the system in the event that the station splits into two sections. This, then, establishes

a neutral for each part of the system without ordinarily having two neutrals paralleled in the connections which can feed any given short circuit.

In all the newer generating stations, that is, Calumet, Crawford, and the 60-cycle switchhouse at Fisk Street, phase isolation is used throughout. The circuit breakers for isolated phase switchhouses of this type have been standardized at approximately 1,000,000-kv-a. interrupting capacity. For the new distributing station at Washington Park, experience has indicated that the possibility of between phase failures in the switchhouse

Fig. 6—Switch Structure Supported on Insulators for Fault Bus

is extremely remote. Therefore, instead of purchasing all circuit breakers with the highest interrupting capacity, the line circuit breakers have an interrupting capacity of 550,000 kv-a. while the transformer and group switch breakers have an interrupting capacity of 1,000,000 kv-a. The purpose of this arrangement of switching equipment is that normally the fault current is limited by reactors or neutral impedance to a low value, but in the event of an unforeseen emergency which would cause a three-phase short circuit the transformer and group switch circuit breakers will act as backup protection to clear the trouble in case the line breaker does not. This arrangement makes further use of the isolation of phases in reducing the cost of switchhouse with concentrated energy.

*H. General Protection Scheme of the 12-Kv. System.* The protection of industrial loops fed from substations has already been discussed. The remainder of the protection for lines is comparatively simple. The standard procedure is to use an inverse time induction overload relay at the source end of the line to the substation and to use a reverse power relay at the substation end set to trip with power flow away from the substation. These reverse power relays have a low current setting and also a low time setting, since the wattmeter element has its contacts open under normal conditions. Each line is equipped with three relays which will take care of either single- or three-phase faults. The value of current which will flow through the neutral resistance is high enough to insure tripping of the reverse power relay at the substation end under the condition of minimum fault current.

A few of the direct 12-kv. lines are equipped with overload relays at the generating station end and pilot wire relays at both ends instead of using the reverse power relays at the substation end. This is used on lines which are short and by this application the time of operation is considerably reduced without increasing the cost.

Generators are equipped with sensitive instantaneous differential relays. They are not, however, equipped with overload relays to trip the machine in case of severe overload. The operator is depended upon for this protection.

The protection of the buses in the newer stations is provided by the newly developed fault bus system. From the fact that all these new switchhouses are designed on the isolated phase principle, all faults must necessarily be to ground. The fault bus takes advantage of this condition by actually conducting the fault current through the proper relays to clear the trouble. This is done by having no solid grounds in the compartments which contain the busses and circuit breakers, but having in place of the solid ground connections, branches of the fault bus, which are insulated and are connected to the main ground bus through current transformers and relays. The method of mounting the

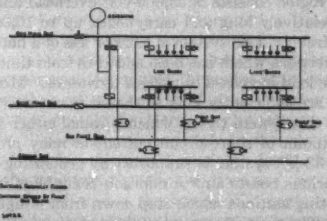

Fig. 7—Diagram to Illustrate Operation of Fault Bus in 12,000-Volt Station

switches on insulators is shown in Fig. 6, which is a photograph of the latest installation.

The method of operation of this fault bus can best be explained by reference to Fig. 7. The heavy lines in this diagram represent high-voltage buses and connections and the dash lines represent fault bus connections which are insulated but operate practically at ground potential. As an illustration of the method by which the protection is obtained, we may assume for example that a ground occurs on one of the switches connected to line bus $X$. The fault current then passes through the branch of the fault bus, the current transformer, and relay at $H$ in going to ground. The operation of the relay opens all the line circuit breakers connected to this line bus and also the circuit breakers $A$ and $B$. This

operation clears all the faulty equipment. If the fault should be on the line side of one of these breakers, the backfeed will, of course, be cleared by the line relay at the substation.

A slightly more difficult condition arises from the failure of one of the switches supplying the line bus. We may assume, for example, that a failure occurs on switch *B*. In this case the ground current goes to the branch of the fault bus in this compartment and is conducted through the current transformer and relay *J* to the main fault bus, thence through the current transformer *K* to the ground bus. The relay *J* is given a very short time setting and the operation of this relay opens the same circuit breakers as were opened by relay *H*. In case the fault in this compartment is on the side of the breaker toward the line bus, this operation clears the fault; if on the other hand the fault is on the side of the breaker toward the main bus, the fault current continues and operates relay *K*. This relay opens additional switches *C*, *D*, *E*, *F*, and *G* and kills the main bus in addition.

In its effect, this system is somewhat similar to the conventional bus differential relay. Actually, it has a considerable advantage because it does not add the hazard of additional current transformers in the buses. In these installations there are no bus current transformers.

*I. 33,000-Volt System.* The transmission system supplying substations in the outlying parts of the Chicago region consists of 33,000-volt overhead lines which are relatively long and carry loads up to 10,000 kv-a. per circuit. This system is more or less of a heterogeneous network which has been added to from time to time as the load increased in various territories. Most of the lines are sufficiently long so that it is not necessary to limit this system to one which is radial either from the standpoint of short-circuit current or relay protection. This 33-kv. system is supported by generating stations at various points and in addition is supplied from distributing stations which step down from a higher voltage. The most important of these stations are Chicago Heights and Belvidere, where power is supplied from the 132-kv. system, and at Bellwood where an interconnection is made with the underground 66-kv. system from Chicago. In the future this system will become a number of small groups centered about points of supply as shown in Fig. 13.

This 33-kv. overhead system is also used to a limited extent for interconnections between the Commonwealth Edison Company and the Public Service Company of Northern Illinois. These connections are at the Crawford Station and Northwest Station.

There is also in existence within the city of Chicago an inter-station tie system originally designed for 33,000 volts, but now operating at 22,000 volts. The tie lines are three-conductor, 33-kv. underground cable each connected directly through a transformer at each end to the 12,000-volt buses. This system is rapidly being discontinued and replaced by the 66-kv. system. This voltage was chosen as the highest practicable for underground cable at the time and as the one which would permit the largest unit of line capacity.

*J. 66,000-Volt System.* This system within Chicago is somewhat unique in several respects. As contrasted with the system synchronized at the load or by "loose linking" the system established by these 66-kv. lines constitutes a rigid tie or the equivalent of a sectionalized high-voltage bus extending from Northwest Station at the north to the State Line Station at the south and as far west as Bellwood in the Public Service Company territory. The system is shown geographically in Fig. 8. Because this system concentrates such a large amount of capacity the first essential of this system is phase isolation throughout. Single-conductor cable is used so that faults in the lines themselves must all start from one phase to ground, and, in addition, transformers are

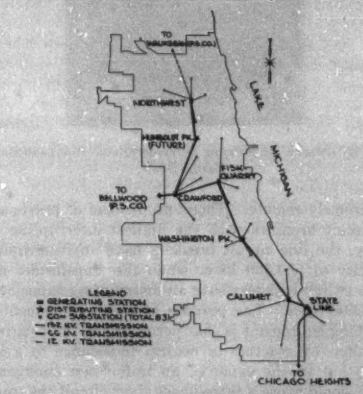


FIG. 8—LOCATION OF CENTERS AND 66,000-VOLT CONNECTIONS IN CHICAGO

single phase with barriers between units. The terminal bus structure is also isolated phase. This is accomplished by having the phases widely separated, with separate single-pole circuit breakers on each phase and by erecting a grounded metal barrier between phases to prevent flashover. By the use of this phase isolation it is practicable to use circuit breakers of approximately 1,000,000-kv-a. interrupting capacity. Short-circuit current is limited by the use of 30-ohm neutral resistors, one of which is installed at each high-tension terminal. Each resistor may be connected in the neutral of any one of the transformers at a 66-kv. terminal. The arrangement of the resistors under various conditions is adjusted to keep about the same number of resistors on the red and blue systems.

The reason for choosing the bus plan at this high

voltage is primarily for economy in the use of transformers. As this system includes both old and new generating stations, it is desirable to shift the load from one station to another at different times of the day in order to obtain base load operation for the most efficient plants. Under these conditions energy may be required to pass by one station to another beyond. As a typical example, energy is normally being supplied from State Line to Washington Park, and farther north, passing through the bus at Calumet Station. At Calumet Station the generating capacity is nearly equal to the load so that a considerable saving is made by not having the transformer capacity equal to that of the lines. It is also possible to feed out from Calumet Station to the high-tension bus during the peak, and receive energy from this system at times of light load without affecting the conditions at other stations. The Calumet Station might also be completely disconnected from the high-

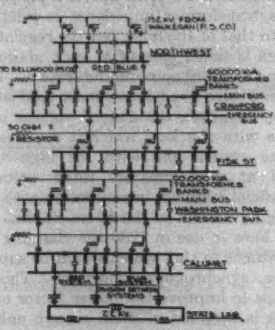


FIG. 9—GENERAL DIAGRAM OF 66,000-VOLT SYSTEM IN CHICAGO

voltage system without disturbing the normal flow of power.

A distributing station such as Washington Park can also receive its supply from two directions and is not dependent upon the reliability of a single source.

Sectionalizing at 66,000 volts is carried out to correspond with that at 12,000 volts, that is, the major division between the red system and the blue system also applies to the higher voltage. Fig. 9 shows the interconnections and scheme of sectionalizing. The circuit breakers in the busses at each station which are indicated as on a vertical line through the center of this diagram, are normally operated open and there is no tie between the red system and blue system at this voltage. In the layout of the high-voltage system, each half is considered separately and the lines and transformers arranged accordingly for proper loading. The balance in loading on the two halves is improved by having transformers paralleled on the low-tension side which allows some shifting of load automatically from one system to the other. Because of the large capacity of each unit in this system whether lines or transformers, a further sectionalization is accomplished by the use of the additional bus tie circuit breakers. These circuit breakers are, however, normally operated closed and are operated only by the fault bus relays. These additional circuit breakers are installed in only one of the two busses at each station because the intention is to operate ordinarily with all lines on the main bus, with the emergency bus used only under special conditions such as during cleaning, repair, etc.

Based on experience at 12 kv., the fault bus system is utilized at 66 kv. and is effective. With phase isolation, practically the only possible fault current must be to ground and the steel supporting structure is used as the fault bus. The supporting steel for busses is installed as a unit between adjacent bus tie circuit breakers. There is no connection between the steel from one side of this bus tie circuit breaker to the other. The establishment of a fault bus is accomplished simply by insulating the steel structure from ground and providing a relay in the connection from this steel structure to the main ground bus. The relay trips all circuit breakers connected to the section of the bus supported on this part of the steel structure.

An additional relay is required to provide proper fault bus protection in case any of the lines or transformers should be connected to the emergency bus instead of the main bus. This additional relay with a longer time delay than the one previously referred to, trips all breakers which can be connected to the same emergency bus and usually includes breakers on more than one unit of structure. If the operation of the first relay does not clear the trouble, the source must be some switch which is not on the unit of structure where the fault occurred and this is cleared by the second operation. For illustration, we may refer to the portion of the 66-kv. diagram showing Washington Park. Let us suppose, for example, that the two lines and the transformer at the left end of the bus at Washington Park were operating connected to the emergency bus and the remainder of the lines and transformers were connected to the main bus as usual. If a failure should occur on the switches or the bus at the left end of this structure, four circuit breakers would be opened and the fault would be cleared promptly. If, on the other hand, a fault should occur on the emergency bus near the section breaker which is between the red and blue systems, the first relay operation would clear all the switches between the center section breaker and the left section breaker. This operation will not clear the fault and the second relay with time delay is required to trip out the remaining switches which feed the fault.

The lines are protected by a pilot wire scheme which gives practically instantaneous protection against either ground or between phase failure. This pilot wire method of protection is found desirable for two reasons. One reason is that the ordinary impedance type relay

or directional relays cannot be made properly selective under various operating conditions when the current is limited primarily by the neutral resistors and very little by the line impedance. The other reason for using the pilot wire relay is that for a system of this size much better stability can be obtained with practically instantaneous clearing of faults.

Transformers are equipped with differential relays and since most of these transformers are three-winding units and are equipped for tap changing under load, the protection scheme is somewhat complicated. A diagram indicating the relays used is shown in Fig. 10. In this diagram three-coil or four-coil percentage differential relays take care of the normal differential protection. With the use of neutral resistors the fault current which would flow in case of a failure near the neutral end of the 66-kv. winding, is not great enough to trip the differ-

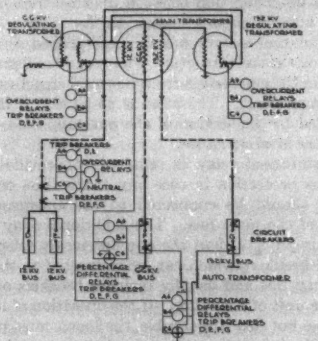


FIG. 10—DIAGRAM OF RELAY PROTECTION FOR LARGE THREE-WINDING TRANSFORMERS

ential relays. Therefore, generator type differential relays are used across the two ends of the 66-kv. windings. In such large transformer installations the most probable point of trouble, as indicated by past experience, is in the tap changing unit. In this tap changing unit the capacity is only 10 per cent of that of the main unit; therefore, the fault current in case of a flashover between taps would not be sufficient to trip the over-all balanced relays. Additional relay protection is therefore installed on the tap changing unit.

On the 12,000-volt side of the transformer, the neutral resistance at the station bus limits the short-circuit current to a value which is below the full load current of the unit and an additional ground relay is connected to this circuit which will trip off the unit in case of a failure to ground on either the 12,000-volt winding or on the single-conductor cable between the transformer and station bus.

Both the 12,000-volt side of each transformer and one end of each transmission line are equipped with overload relays having a relatively long time setting for back-up protection in case the proper relays fail to function. These back-up relays cannot be made selective for all conditions, but they would ordinarily not be called upon to operate except when some other protective equipment has failed.

Such a system as this, using transmission lines which are electrically very short and which form practically a high-voltage bus, contains very great inherent stability. The synchronizing power required to pull these lines out of step would be far beyond the limits of the ordinary fault currents. For this reason no special consideration need be given to the stability problem as it would be on a system containing long overhead lines.

The voltage regulation of the 66,000-volt bus system did not offer any design problems. These lines are so short that under the maximum expected operating variations, the greatest difference between voltage at any two points on the system is from 2 per cent to 7 per cent. The transformer impedance is relatively high compared to that of the lines, but the regulation on the transformers is taken care of at each station without reference to any other point on the system. The setting of transformer taps is adjusted under load so that each station may maintain the desired voltage on its low-tension bus with the load which it requires from the high-voltage system and with the high-voltage bus maintained at approximately rated voltage. One rather beneficial influence in connection with regulation is the charging current of the 66-kv. cables. With the number of lines in use in 1930 the charging current is about equivalent to that which would be supplied by a 50,000 kv-a. synchronous condenser. This charging current helps to improve the power factor on the generators, but is supplied in small enough units that no disturbance is caused by its connection or disconnection.

*K. 132-Kv. Interconnections.* The interconnections of the Commonwealth Edison Company with the adjacent companies, are made by means of 132-kv. overhead lines. The impedance of a 132-kv. line is comparatively high when the line covers an appreciable distance. This feature permits a considerable displacement of phase-angle between voltages of two interconnected systems, where there is an interchange of power over the line.

Up to the present time, the stability feature of 132-kv. lines did not appear as a serious operating problem, partly because the loads carried on the lines were considerably below the probable stability limit and partly because the important lines were comparatively short. However, when an attempt was made to operate in parallel with another large system of a size comparable to that of this group, it was found impossible to keep the two systems together without an undue amount of regulating at generating stations. The amount of power which could be transmitted through this comparatively weak tie, was not sufficient to prevent the systems from drifting apart in phase-angle, even when running in

synchronism. It is evident that in spite of all the efforts of the operator, during an emergency switching on either end of this line, the line is likely to trip out, separating the systems.

Lightning storms are quite frequent in this territory and most lines are protected by both lightning arresters and ground wires. Some lines are also protected by arcing rings. At the Devon Avenue Terminal which is the junction between the overhead line and the six miles of underground cable, the absorptive effect of the cable is relied upon to take the place of lightning arresters.

The general arrangement of the 132-kv. system is shown in Fig. 11.

VI. *A. Load Control.* For the most economical operation of the system, accurate control of load division between separate stations of the network is of great importance. The Commonwealth Edison Company is using a system by means of which the load of each generating station is automatically indicated at the Load Dispatcher's Office and, at the same time, an indication of the total load is sent back to each generating station. With this scheme, each station operator has before him the total system load as well as his own load. With the aid of special charts showing the division of load between individual stations for any given total system load, the operator at each station knows his responsibility for the allotted portion of system load without telephone instructions. These charts are prepared by the Load Dispatcher in cooperation with other departments in such a way as to take into account individual station performance, availability of generator capacity, etc. Departures from these schedules take place only when one station is unable to meet its individual responsibility. The same scheme is used on both 60-cycle and 25-cycle systems.

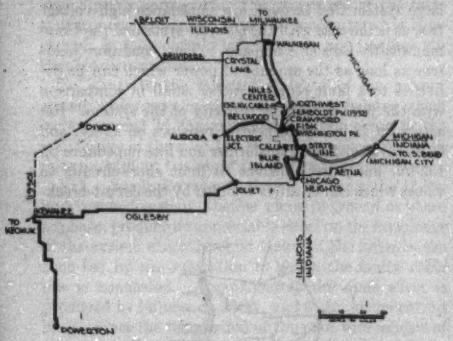


FIG. 11—MAJOR TRANSMISSION SYSTEM IN THE CHICAGO AREA

Legend

- Future lines
- Lines—132 or 66 kv.
- Lines—33 kv.
- Present generating station
- Future generating station
- Present substation
- Future substation

The system for transmitting meter readings is that of electric impulses, the number of which is proportional to the station load. These impulses are transmitted to the Load Dispatcher's Office over a leased telephone circuit where the impulses are totalized and converted into meter readings by a series of special relays and differential gears.

The same telephone circuit is also used to transmit the totalized load back to the individual stations.[6]

*B. Frequency Control.* Until a few years ago there was no other method of frequency control but manual regulation. A fairly satisfactory performance was obtained which was considerably better than the official limits imposed by the Illinois Commerce Commission. The permissible variation in frequency is 3 cycles, while with the manual control the usual departure did not exceed ½ cycle.

With the advent of synchronous motor-driven clocks, and more rigid interconnections in this region, the question of uniform and accurately measured frequency became of great importance. Recently a very accurate graphic recorder of the frequency appeared on the market and, at the same time, several schemes of automatic frequency control were tried out and some of them found fairly satisfactory. The Commonwealth Edison Company developed an automatic frequency control scheme which has some features of its own. With this scheme it is not only possible to keep the instantaneous frequency of the system within about 1/20th of a cycle, but also to correct any cumulative error which might result from a slight instantaneous error and therefore affect the time reading of the synchronous clocks. With this time correction feature, it is possible to hold the time on synchronous clocks normally within two or three seconds of the correct value.

*C. Reserve Capacity.* It has been commonly said that, on any power system, a cold reserve is no reserve at all. For this reason, it is the practise to keep running at all times sufficient generating capacity to permit the instantaneous loss of the largest single unit. With the very close interconnections which exist in the Chicago region, it is not necessary that each company maintain a reserve at its own stations. The practise is to pool the capacity for all the stations in this district and maintain at least sufficient running reserve in the district to allow for the loss of the largest unit. The approximate total reserve which can be called upon, as indicated in the tabulated loads and capacities, is 285,000 kw. This total reserve is not ordinarily called upon and may not be running, but in the event of any unit tripping out in an emergency, sufficient additional capacity is immedi-

ately started to restore the condition of having running reserve equal to the largest unit.

*D. Abnormal Conditions.* The design of the transmission system should be such that an instantaneous loss of generating capacity will not seriously overload the transmission lines under the abnormal conditions. In this particular case, such a problem is not at all difficult to solve. The newer stations and the ones having the largest units are also both the largest and the most efficient, so that the normal flow of power is from the large stations to the small. Hence the loss of one of the large generating units effects a reduction rather than an increase in the load to be transmitted through the high-voltage system. This tends to increase further the stability of operation.

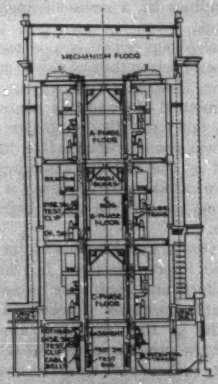


Fig. 12—Cross Section of 12,000-Volt Isolated Phase Switchhouse

Legend

- Present line operated as part of a loop
- Proposed line operated as part of a loop
- Present line not operated as part of a loop
- Proposed line not operated as part of a loop
- Present major distribution center
- Proposed major distribution center
- Present distribution center to be given loop service
- Proposed distribution center to be given loop service
- Present distribution center not to be given loop service
- Proposed distribution center not to be given loop service

*E. Voltage and Control.* As distinguished from systems where the greater proportion of energy is transmitted over long distances, voltage does not fluctuate appreciably with normal changes in load. In fact, it has not been found desirable to supply any of the generators with automatic voltage regulation. In the generating plants, practically all the voltage control is accomplished with manual adjustment of the field on the generators. By this adjustment it is possible to maintain a higher voltage during load periods to partially compensate for line drop. In a station where there is little generating capacity compared to the load requirements, such as at Fisk Street, this field control must be supplemented by the operation of tap-changing units on the transformers connected to the high-voltage system. All of the transformers connected to the 66-kv. system, as previously mentioned, have tap changers for the control of voltage under load, and these tap changers maintain steady regulation for all practical purposes.

*F. Stability of Operation.* The problem of system stability under normal and emergency conditions does not appear to be of great importance for a very compact, large system tied through low impedance high-voltage ties, as is the case with the 60-cycle system of the Commonwealth Edison Company. This condition holds true as long as the amount of power which can be delivered to a fault remains rather small in comparison with the total generating capacity of the system. Reactors on 12-kv. lines, neutral resistors on 12-kv. and 66-kv. systems, and transformer and line impedance on 132-kv. lines, are sufficient to limit short-circuits to values which can be safely handled by the circuit-breakers and which are well below the instability condition for the system.

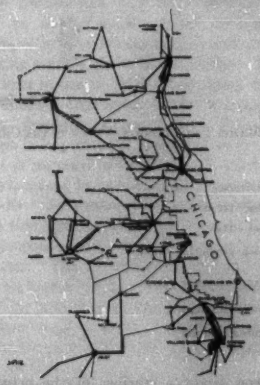


Fig. 13—33,000-Volt Transmission System in Region Around Chicago

An ample synchronizing power between the individual units and between generating stations, and well damped governors on the prime-movers, insure stability of generators connected to the 60-cycle bus bar. With the frequency changers in operation between the 25-cycle and 60-cycle systems, there is an oscillation of power between these systems. This oscillation amounts to approximately 5000 kw. above and below the average

load. It is merely a series of momentary swings and shows no indication of instability.

Until the present time, no consideration has been given to the installation of high-speed excitation on the generators or to the improving of governor response, as there has been no apparent need of these refinements for a system in the Chicago area proper. The problem of stability of future transmission lines will depend largely on characteristics of the outside generating stations from which the energy will be transmitted and upon the characteristics of transmission circuits rather than upon the receiver end, that is, the Chicago system proper. The 66-kv. network which is likely to receive this energy from outside may be considered as a very large bus, with both generators and load directly connected. The proportion of the total synchronous equipment which is concentrated is large enough so that outside influences do not produce noticeable disturbance.

To illustrate the inherent stability of the present system, cases may be cited of main bus failures which have occurred in the generating station prior to the installation of the fault bus and continued as long as 15 minutes without the loss of any generating capacity.

VII. *Service Record—60-Cycle.* Faults in the 12-kv. underground system, whether phase to ground or phase to phase, produce no appreciable effect on the remainder of the system except a slight flicker of the lights in the zone fed by the substation to which the faulty cable line is connected. Approximately the same effect is produced by failures on 33-kv. and 66-kv. underground lines. Since the installation of the pilot wire scheme of relay protection on 66-kv. lines, there were two failures of underground cable caused by mechanical injury to cable sheath. In both cases the relays and switches cleared the faulty line in a small fraction of a second, causing no interruption of the service at any point on the system.

A failure at the station itself, both on the 12-kv. and 66-kv. systems, is cleared by means of the fault bus. Since the installation of the fault bus there were several operations under actual service conditions on the 12-kv. system. In some cases, the action was so prompt and the resultant burning so slight that considerable difficulty was experienced in locating the point of fault. Until the present time there have been no service operations of the 66-kv. fault bus installed on the outdoor structure; however, tests made under actual service conditions with a solid ground applied and full service voltage on the 66-kv. bus, gave perfect protection, clearing the fault in about ½ second, with no disturbance of any kind to the remainder of the system.

Failures of generators at the station are not frequent but when they occur, the effect of the failure upon the system is not sufficiently severe to cause any interruption of service, since there is enough generating capacity kept running on the system to take care of any additional increase in load, comparable to the size of the largest unit in operation.

A large number of short-circuit tests has been made with currents ranging up to 30,000 amperes, three-phase at 12,000 volts during the past two years. The disturbance to the system was negligible so long as the time of short circuit was kept to two or three cycles.

VIII. *Prospective Development.* The future development of this transmission scheme is based on load estimates for the entire region projected from five to ten years in the future and a survey of the possible and desirable sites for generating capacity to meet this demand. Within the city of Chicago it is planned to extend the 66,000-volt underground system which constitutes a duplicate bus extending through the city and interconnecting the generating stations. This will be of sufficient capacity to transmit the output of large efficient stations to load centers where it is not feasible to provide such generating capacity. This will permit the free transfer of reserve capacity and most economical use of efficient units.

In order to improve efficiency of transmission and as far as possible to limit concentration of energy at distribution points additional 66-kv. distribution stations similar to the Washington Park station will be provided. These will be supplied from the 66-kv. transmission system and distribute energy at 12,000 volts to substations.

Surrounding the city is an outer ring of 132-kv. overhead lines which will tie into the 66-kv. system at several points and extending outward to interconnect stations more remotely located.

As the future increase in generating capacity within the city is limited an increasing proportion of the energy required will come from stations outside, some located at considerable distances. Transmission of large amounts of energy from the more remote sources into Chicago will be by means of overhead lines at 132 kv., 220 kv., or higher voltage and stepped down to 66 kv. at points as near as practicable to the load centers.

The basic conditions of the system will be changed in the future as a larger portion of the energy comes from more distant sources instead of from sources near the load center. The reliability of service required for this metropolitan load must still be maintained. Stability of long lines and lightning protection, two influences which have not heretofore been a factor, will become major problems when these heavily loaded long circuits are relied on as a continuous source.

With the development of generating stations of the order of 1,000,000 kw. outside the load center and with limited rights of way for tower lines, circuits must be designed for and operated at the maximum loading. This will require much research and study, to develop both overhead lines and underground cable for higher voltages and greater loads, also to apply the proper facilities for load and voltage control.

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## Discussion

For discussion of this paper see page 612.

# The Fundamental Plan of Power Supply of the Detroit Edison Company*

BY S. M. DEAN†

Member, A. I. E. E.

*Synopsis.—Experience indicates that if electric light and power systems are to expand indefinitely without enormous obsolescence charges a carefully coordinated engineering plan must be adopted and, as far as practicable, system extensions fitted to it. This paper sets forth the principles involved and the plan adopted by the Detroit Edison Company.*

*The description of the area served and the classification of customers indicates that the system is essentially of the metropolitan substation type supplemented by a 120-kv. transmission system.*

*The importance of selecting proper circuit voltages and arrangements and their bearing on service reliability, system simplicity, and cost is discussed.*

*The underlying principles and the "Loose Linked" Power Area Plan adopted to accomplish those principles is set forth. This is supplemented by the plan for short circuit and stability control and the resultant classification of substations, power sources, and protection schemes.*

*Those characteristics of major electrical equipment affected by the plan are outlined.*

*Operating procedure and results are given.*

## I. Service Requirements

THE territory served by the Detroit Edison Company comprises 4400 sq. mi. in the southeastern part of the State of Michigan with a population of 2,190,000 people. The east central portion of the area is the city of Detroit which comprises some 2 per cent of the areas served but in which are concentrated 76 per cent of the people and 80 per cent of the power requirements.

Along the eastern boundary of the district is a series of great water ways, the St. Clair River, Lake St. Clair, the Detroit River, and Lake Erie, which furnish an abundant source of cooling water and on which are located the four steam power plants operated by the company. The general topographical character of the district is featureless, the country is flat and level, and there is no water power of consequence available. In addition to the city of Detroit, there are located in the district 20 smaller cities and 66 villages.

The city of Detroit may be divided, for purposes of studying the electrical load requirements, into three classes of districts: (Fig. 1)

1. The general business and commercial area at the center of the city in which is concentrated the business life of the district and which shows an average load density of 25,000 kv-a. per sq. mi. and requirements of 100,000,000 kw-hr. per sq. mi. per year with maximum values in smaller areas of double that.

2. Industrial areas occupied by the manufacturing companies which are distributed in a rough circle around the heart of the city and at some distance from it, with a marked tendency to stick very closely to the railroads. This industrial area has an average load density of 17,000 kv-a. per sq. mi. and average requirements of 50,000,000 kw-hr. per sq. mi. per year.

3. The residential districts which fill in the gaps between the downtown commercial area and the industrial districts in the outskirts of the city and which extend beyond into suburban or country areas. Load densities and requirements in residence districts are small in comparison with the density encountered in commercial and industrial areas running from 60 kv-a. per sq. mi. and 200,000 kw-hr. per sq. mi. per year to 4500 kv-a. per sq. mi. and 12,500,000 kw-hr. per sq. mi. per year in the thickly settled districts. These latter densities occur where the residential areas include rather

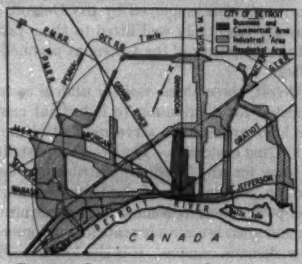


Fig. 1—Classification of Load Areas

large amounts of commercial lighting in the form of stores and shops and also apartment houses.

Much of the transmission within the city of Detroit is by underground cable placed in conduit, and all lines, both transmission and distribution, are underground in the more congested portion of the city by requirement of municipal ordinance and public opinion. In the residential areas of the city, distribution is by overhead lines, and outside of the city area both transmission and distribution are overhead.

The system peak load is about 550,000 kw. and the output of the power plants on the order of 2½ billion kw-hr. per year. The annual load factor for all classes of service is about 55 per cent, whereas the daily load factor often runs as high as 70 per cent. The entire

†Senior Engineer, Engineering Division of the Detroit Edison Company, Detroit, Mich.

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system area lies within the same time zone. The load carried by the power houses is characterized by the fact that half of the energy is delivered to less than 500 very large industrial and commercial power customers ranging in size from 100 to 15,000 kv-a. In direct contrast to this, is the fact that only 12 per cent of the energy is delivered to 450,000 residence customers. The company has only a small street railway load amounting to less than 7 per cent of the total. Fig. 1 shows the character of the area served.

It is evident at once that an electrical system to serve such a territory will be essentially a substation system by reason of the many large industrial customers and the large proportion of low density residential and commercial area which can be well served by overhead lines. Since most of its load lies within the city area, it will be in large part a metropolitan underground system. Also, since power plants are of necessity located along the waterways on the edge of the territory served, and there are relatively large blocks of load located some distance from them it will be, in part, a transmission system.

## II. Selection of Voltages

The importance of the selection of proper voltages and circuit arrangements early in the development of a system cannot be overemphasized. The voltages and circuit arrangements employed by the Detroit Edison Company are essentially well fitted to their tasks and much of the simplicity of the system as planned is due to that fact.

A 4800-volt, three-phase, *isolated neutral system* was early selected for distribution to industrial customers and was later extended to serve residential and commercial lighting customers. That voltage is sufficiently high to care for any overhead distribution densities likely to be encountered in residential, commercial, and small power areas for some time to come and in the underground areas is quite adequate for customers up to 10,000 kw. demand or more. It is also low enough to be reasonably safe for overhead construction in streets and alleys and switchgear and regulating requirements are not burdensome. Also, the fact that the circuit is isolated neutral and the further fact that ringed primary mains are employed makes it quite possible to operate without more than momentary interruption to service with a wire down on the ground, that is, grounds do not usually cause short circuits. This is most important from the service point of view.

A 24,000-volt, solidly grounded neutral system is employed to feed substations; 24,000 volts was selected as being low enough to be safe for the three-conductor cables used within the city and high enough to serve reasonably the outlying substations through overhead lines. That voltage is also high enough to serve for some time to come, any probable power requirements over any distances likely to be encountered in the underground district. It is also high enough to permit the transfer of large blocks of power between generating centers by operating a reasonable number of cables in parallel (see Fig. 2). This eliminates for some time to come the necessity for a higher voltage step for bulk power transfer underground with all that that means in the elimination of costly and hazardous switchgear and in added transformations.

The two generating plants located within the city load area (Delray and Connors Creek) deliver energy at 24,000 volts.

For the two generating stations more remotely located from their load areas (Marysville and Trenton Channel) 120 kv. solidly grounded neutral transmission is employed. This transmission system also serves as a backbone for the outlying portion of the area served. Again this voltage is sufficiently high to give convenient bulk transfer of power, both within the system and for interconnections. Fig. 2 illustrates the general transmission layout.

## III. Fundamental Plan

*Principles.* The underlying principles which served as guides in the Detroit Edison Company's system plan are as follows:

1. It is not necessary or advisable to operate the Detroit Edison Company's electrical system as a single unit, but rather to operate it as a group of power areas each served at 24,000 volts, by its own power house or large step-down substation.

These power areas shall be loosely connected for purposes of synchronizing and interchange of power, but so arranged that, when an uncontrollable disturbance breaks loose in any power area, that power area shall disconnect itself from the others, taking with it only its own load area. The boundaries of these power areas shall, where necessary, be flexible to permit of reducing the size of an area while reconditioning generating equipment.

2. Any acceptable system plan should be capable of indefinite expansion without recourse to major changes of switchgear or other electrical equipment, that is, without unreasonable obsolescence. Practically, this means the system must be designed for a maximum short-circuit duty consistent with available switchgear and still be stable under operating conditions.

3. The plan adopted shall result in a simple system, in order that it may be practically operative and less likely to fault through sheer mass of equipment involved.

4. Substations and generating stations should be reduced to a minimum number of standard types and sizes employing, as far as conditions permit equipment essentially standard with the electrical manufacturers.

5. Since the greater part of serious electrical operating troubles arises from the malfunction of switchgear or its accessories, it is good business and good engineering to eliminate (particularly on those parts of systems having grounded neutrals) as much switchgear, bus work, and accessories as possible. This tends toward the use of added cables and transformers to secure

reliability of service, but added cables, and to a lesser degree added transformers, result in reduced losses, and what is equally, if not more important, in reduced duct heating. Cables also have a relatively high salvage value. Cable faults, being underground and away from substations, are not likely to result in a general shutdown of a substation or power house. Also transformer fires are very rare, and if reasonably simple precaution is taken, this hazard can be controlled.

6. As far as practicable, it is better to avoid the use of current limiting reactors in feeders, using them rather for sectionalizing purposes.

*General Plan.* The general plan which has been adopted to carry out the principles set forth is illustrated by Fig. 2. It consists of a number of 24-kv. generating stations or 120-kv. step-down substations (Class "D") each of which feeds what is termed a "power area."

Within the city these Class "D" power sources are connected together by what we have termed "interlinking cables." These "interlinking cables" are so relayed that, should an uncontrollable disturbance occur in any one of the step-down substations or generating stations, or their connected 24-kv. cables, they will, as a last resort, open, leaving the power area in trouble to go its own way rather than unduly disturb the rest of the system. This is what is technically known as "loose linking." It is evident at once that those cables may be of any reasonable number and still be "loose linked," that is, "loose linking" is a function of relaying and not of power transfer. These "interlinking cables" are used for day to day transfer of power between power sources to get best over-all operating economy. The only stipulation is, that with the largest machine down for repairs, the size of the power area as determined by the "pull apart" points in the "interlinking cables" shall be such that the loss of the largest running generator in that power area, or the loss of its "interlinking cable" ties with one neighboring power area, shall not leave that power area with load in excess of its ability to carry it.

The "pull apart" points referred to above are essentially at the points marked *PA* on Fig. 2. The separation is accomplished by proper settings of the inverse time overcurrent "back up" protection and gives sufficient time for first and second line defense relays to clear the fault, if that is possible.

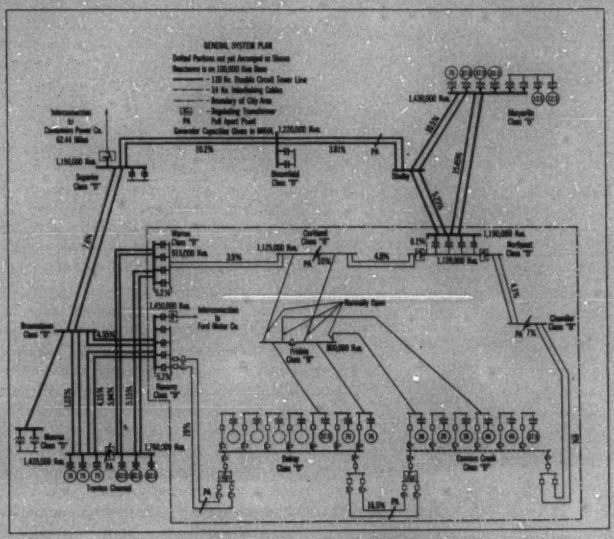


FIG. 2—GENERAL SYSTEM PLAN

In the suburban areas, the Class "D" power sources largely feed into a network of 24-kv. overhead lines where short-circuit duty is a relatively simple problem. This network constitutes so loose a tie between Class "D" substations as to be negligible and entire dependence is placed on the 120-kv. lines for holding the system in synchronism.

With one exception, the control of voltage and wattless kv-a. between power areas is to be accomplished by tap changing regulating transformers installed in the "inter-

linking cables" between power areas and between the halves of the 120-kv. bus at Trenton Channel. That exception is Northeast Substation (Class "D") where synchronous condensers are required because of the longer transmission distance.

It is evident at once that such a system can be extended indefinitely by connecting additional generating or step-down stations into the ring of "interlinking cables," provided the through impedance of the sections of "interlinking cables" between stations is kept up to the same value. For this system the maximum value is approximately 20 per cent on 100,000 kv-a., which is reasonable from the standpoint of stability.

*Short Circuit Duty.*—After considerable study, the following criterion for short circuit duty was adopted:

For 4800 volts—250,000 kv-a. maximum
" 24 kv. —1,250,000 kv-a. maximum
" 120 kv. —The nature of the 120-kv. system does not lend itself so readily to maximum short-circuit control, but it seems reasonable to assume that we can keep within 2,000,000 kv-a.

In arriving at these allowable short-circuit duties, it was necessary to take account of the types of generating

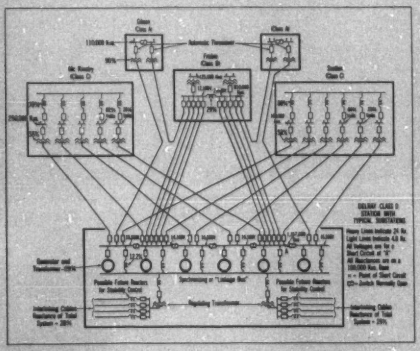

Fig. 3—Delray—Class D Station with Typical Substations

stations and substations, as well as the methods of interconnecting them. To meet those limits, and to reduce high-voltage switchgear to a minimum, the following types of substations were adopted. (These types are illustrated in Fig. 3.)

Class "A" Substations serve areas of essentially residential and small commercial character. Each transformer is fed by a 24-kv. cable going directly into its tank. The 4800-volt buses are not interconnected. When a cable or its transformer fails, its load is automatically thrown on to the spare transformer capacity with an interruption of about one second. As far as practicable, each transformer is fed from a separate Class "D" or Class "B" Substation. Their interesting features are: they have no 24-kv. switchgear, they do not interconnect Class "D" power sources, and they have *permanent maximum short circuit duty* on the 4800-volt side.

Class "B" Substations are equipped with 24-kv. switchgear and serve as feeds to Class "A" Substations, feeds to transformers located on the premises of large industrial customers and feeds to their own complement of 4800-volt subtation equipment. They also serve as blocks of load which may be transferred from one power area to another as required, ormay, as is usually the case, be the connecting link between two power areas. Fig. 2 shows the three Class "B" switching substations now planned for the metropolitan area. These Class "B" substations are so designed that, at a later date, they may be converted into points at which "bulk power" at high voltage may be fed into the 24-kv. system, that is, into Class "D" Substations.

Class "C" Substations serve industrial or metropolitan underground areas where it seems inadvisable to have even one second interruptions in the event of transformer or 24-kv. cable failures. The 24-kv. cables run directly into the transformer tanks and the transformers are connected together on the 4800-volt side through a star connected synchronizing or "equalizer" bus. Each transformer is connected to a separate bus section in the same Class "D" source of power. The interesting features are: they have no 24-kv. switchgear, they do not interconnect Class "D" power sources, they have a *permanent maximum short-circuit duty on the 4800-volt side*, and by reason of their high "through impedance" they do not invalidate the generating station bus section reactors.

Class "D" Substations are the sources of feed to the 24-kv. system and are either power-house switch houses or 120-kv. step-down substations. In the case of the 120-kv. stepdown substations a single 24-kv. bus has so far been employed without sectionalizing reactance of any kind. In the 24-kv. generating stations sectionalizing reactance is required, and again the star connected synchronizing or "equalizer" bus is employed. It is between these "equalizer" buses and the 24-kv. buses in the 120-kv. stepdown substations that the "interlinking cables" are connected.

Within the metropolitan underground area where short-circuit control is the real problem, the Class "A" and Class "C" Substations constitute the great majority, there being at present only the three Class "B" switching stations planned. It is quite essential that the number of Class "B" switching stations be kept at a minimum as they do materially short circuit the generating station bus section reactors. This also results in confining the costly and hazardous 24-kv. high duty circuit breakers to the comparatively few Class "B" and Class "D" substations and *reducing the number to something like half those that would be required if 24-kv.*

*switching were used in all substations.* This is an important consideration from the point of view of reliability and economy.

Having adopted these types of substations and applied them to the existing system, the distribution of reactance between the Class "D" Substations, and within the 120-kv. system, and the resultant short circuits obtained, became those shown for the general system in Fig. 2. This might be termed the distribution of reactance between power areas throughout the system.

The distribution of reactance within the power areas fed by Class "D" 120-kv. step-down substations is not of particular interest in that so far the 24-kv. buses of these substations are solidly connected together, the Class "C" and Class "A" Substations representing the only attempt at a short-circuit control.

The distribution of reactance within those power areas fed by Class "D" generating stations is of especial interest because the large power concentration will not permit of solidly connected buses. Fig. 3 illustrates the combination of such a power plant with typical substations and "interlinking cables" showing the distribution of reactance, the short-circuit duty for the most serious typical fault, and the approximate voltage conditions during that fault. The interesting features of such a layout are multiple synchronizing paths through the substations and the synchronizing or "linkage buses," the means of connecting the power area into the system through its generating station synchronizing bus, (note that this is simply done with standard 24-kv. cable and switchgear) *the reduced amount of 24-kv. switchgear, and the total absence of duplicate 24-kv. buses and switching.* This absence of duplication is possible because each substation transformer is connected to a separate generating station bus section. It is possible, therefore, to lose any one generating station bus section without losing more than the normal reserve of feed to each substation which seems a fair chance to take considering the rarity of bus faults.

The star connected synchronizing bus was deliberately chosen with the full realization that it inevitably created a high short-circuit point on the system. Accordingly, its reactors were made integral with it so that no circuit breaker is exposed to the high duty. See Fig. 3. It was chosen because every generator or group of tie cables is made equally available to every other one and power transfer between them can be accomplished with a minimum of voltage variation. Also, the synchronizing bus creates a "back bone" by which the power plant is connected into the system.

The star connected synchronizing buses with their reactors in the Class "C" Substations and the automatic throw-over equipment which permits straight radial operation of each transformer in the Class "A" Substations are the devices by which short circuits are kept down on the 4800-volt system. Fig. 3 illustrates these arrangements.

The general use of Class "C" Substations with the transformers paralleled on the 4800-volt bus through reactors results in a much higher average short circuit duty on the 4800-volt system than would be the case if the Class "B" substations were employed in which the 24-kv. bus eliminates the necessity for 4800-volt paralleling. This condition was deliberately chosen in preference to 24-kv. switching for five reasons. First, it is very difficult to keep permanent control of short circuit duty if 24-kv. switching is generally used in substations and its use results in duplication and complication of switchgear and buses in the generating stations. Second, it is better in principle to have the higher short-circuit duty on the lower voltage isolated neutral system rather than on the high-voltage grounded neutral system, since grounds usually do not result in short circuits. Third, the cost of suitable 4800-volt circuit breakers for this higher duty is not enough greater to be a ruling consideration and is much less than the added cost of 24-kv. switchgear. Fourth, operating experience over a period of years indicates almost no trouble from 4800-volt circuit breakers, even where the duty is much in excess of the breaker rating. Fifth, the high short-circuit duty area is relatively small. Even on cable feeds this duty drops within a half mile length of cable to the rating of the smallest breaker we would recommend for master switches on primary customers' 4800-volt installations.

In laying out this plan, the advantages of isolated phase construction were recognized but it was not practicable to adopt the principle for the following reasons. First, with a system employing generators having two to one step-up auto-transformers neutral impedance exposes the generator and cable system to over-voltage during short circuits. Earlier generating equipment was not designed for that duty and it also did not seem wise to expose the rather large 24-kv. cable system (then some 700 mi. of all ages and conditions of cable) to over-voltage. Second, it seems desirable to avoid, if possible, the general use of 24-kv. feeder reactors because of the cost of the reactors, their losses and ventilation, the increased hazard, and the somewhat poorer voltage regulation. However, with one exception the new indoor Class "B" and Class "D" switching substations are laid out to accommodate future feeder reactors because they may be needed to protect the switchgear of possible future customers served at that voltage, because of the inherent uncertainty of the best available switchgear and the possibility that future loads may demand reducing voltage fluctuation during faults to the minimum.

*Protection Schemes.*—The relaying methods adopted are as follows:

Instantaneous relaying for 120-kv. line faults. (Double circuit tower lines relayed differentially. Single line operation over-current, for lack of suitable faster method.)

Instantaneous relaying for 120-kv. transformers.

Inverse time overcurrent protection for 120-kv. bus faults and as "back up" protection for line faults (for lack of suitable faster method).

Instantaneous relaying for all 24-kv. line or cable faults over approximately 250,000 kv-a.

Instantaneous relaying for all 24-kv. transformers, if the fault is in the high-voltage winding.

Instantaneous relaying for all generators and their step-up transformers.

Inverse time overcurrent protection for 24-kv. bus faults in outdoor switching substations and also as "back up" protection for line faults. (For lack of suitable faster method.)

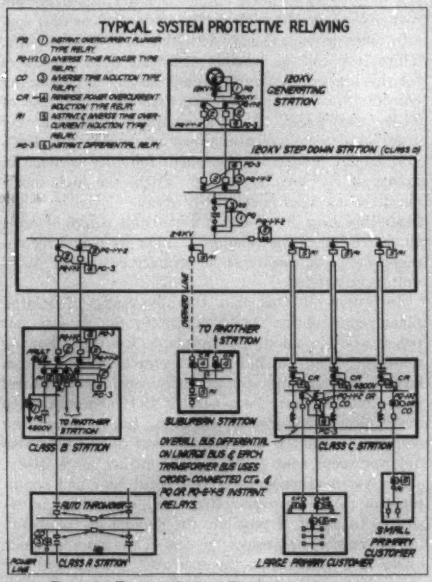


FIG. 4—TYPICAL SYSTEM PROTECTIVE RELAYING

Instantaneous fault bus relaying on all indoor 24-kv. switching substations.

Approximately ½ second inverse time delay on 4800-volt line faults which have 250,000-kv-a. ultimate maximum. (To permit transformer fuses and customers breakers to clear first.)

Instantaneous bus differential relaying for all 4800-volt equalizer buses in Class "C" Substations.

Fig. 4 illustrates each of these applications translating these general statements into specific applications and relays. With the exception of fault bus protection, each relay and method has been employed on the system for a number of years.

The fault bus scheme employed in the newer indoor 24-kv. switching stations is of interest. The complete 24-kv. bus and circuit breaker structures are made of metal, each phase being in its own separate compartment throughout. This metal bus and circuit breaker enclosure is set on insulators and is sectionalized and grounded through current transformers for fault current relaying. This gives complete grounded enclosure for safety purposes, definite paths for fault current quite independent of the building steel or reinforcing and, for all practical purposes, phase isolation. While phase isolation is not depended upon for short-circuit control on the machine buses (Fig. 3) it is of very real value on the synchronizing bus where it is important from the point of view of stability that we do not have three-phase faults.

While the instantaneous protection outlined has served its purpose excellently, further careful study of the system as well as some operating experience indicates the necessity for faster and more reliable relay protection for the outdoor 24-kv. and 120-kv. buses as well as single line operation of the 120-kv. lines. The ideal would be reliable instantaneous protection that cannot be invalidated by the taking out of commission of lines or equipment for repairs or maintenance. Careful study is being given to defining the requirements more exactly and to the possible solution.

*Stability.* In arriving at any system general plan giving the desired distribution of reactance for proper short-circuit control, the opposite horn of the dilemma must be faced in the form of stability under operating conditions and the final solution must be a balance between these two considerations.

In the system plan outlined above dependence is largely placed on fast relaying and switching for protection against instability. Consolidating relay times with their corresponding circuit breaker times, the following total fault durations are obtained on faults over approximately 250,000 kv-a. (60-cycle basis)

120-kv. circuit breakers—20 cycles (new) 25 cycles (old)
24-kv. circuit breakers—13 cycles (new)

Studies, based on these fault current durations and the magnitudes previously stated, together with the reactance distribution given in Figs. 2 and 3, have, so far, been largely confined to limiting cases of three-phase faults on major buses (both 120-kv. and 24-kv.). The assumptions made for these studies are rather pessimistic in that they assume all machines fully loaded and a perfect three-phase fault.

Under the above assumptions, three-phase faults directly at the 120-kv. buses at Trenton Channel or Marysville generating plants theoretically approach instability in the case of some of the older and slower circuit breakers. However, taking account of the difference between the theoretical and the actual operating conditions, and the fact that we have for several years operated the 120-kv. system under essentially

the present conditions without any evidence of instability, there is reason to feel that the situation is satisfactory. Further study is being given to a more accurate evaluation of the limits of stability on the 120-kv. system as well as to the available means of dealing with it should it arise.

All studies so far made indicate that there is a reasonable margin of safety in the case of the 24-kv. system, even under three-phase fault conditions. The one exception is the synchronizing or "linkage buses" of the Class "D" generating stations (already mentioned under Protection Schemes) and possibly the interlinking cables. On the "linkage buses" three-phase faults are made practically impossible by the enclosure of each phase in a separate grounded metal compartment. Line to ground faults should cause no trouble.

While calculation indicates that it will probably not be necessary, the design of the switch houses is such that a reactor may be installed in each end of each interlinking cable, thereby preventing a three-phase fault in those cables from completely cutting off the synchronizing power between power areas by reducing the voltage between them to zero. There is no evidence to indicate that individual generators within the same station will become unstable or fall out of step.

## IV. Equipment Characteristics

The characteristics of equipment are determined to varying degrees by the general type of system employed. The essential equipment characteristics as determined for this system are as follows.

*Prime Movers.* The last nine turbo-generator units have been designed with a nominal rating of 50,000 kw., a best point rating of 43,000 kw., and with good vacuum conditions and extraction could probably carry somewhat over their nominal ratings. A plant group of six units can be loaded on average days to 250,000 kw. with maximum economy, with one unit down it can still carry 250,000 kw. reasonably, and care, if necessary, for somewhat greater short time peaks. With two units down it can carry somewhat over 200,000 kw. Such a plant has an excellent running reserve and requires a minimum of transfer lines and cables.

Governor response does not appreciably enter into the question of system faults because of the short durations employed. Its principle interest, therefore, is the question of how a suddenly imposed load caused by the loss of major units will be distributed among the remaining units. So far we have not had particular difficulty from this source since the governor characteristics of all the larger units are quite similar.

*Generators.* All generators whose output is at 24-kv. or 120-kv. have the generators and step-up transformers arranged as a unit. The reactance of the combined generator and transformers is kept at from 20 to 25 per cent. So far no trouble has been experienced due to instability of machines under suddenly applied loads and therefore no particular short-circuit ratio has been specified. No one generator constitutes a large proportion of the total running capacity and its loss therefore does not impose extreme loads on the remaining machines. Also the like governor characteristics tend to cause even division of load.

*Excitation System.* Hand controlled excitation by means of throttled pole exciters, without main generator field rheostats, has been employed so far with entire satisfaction. It is planned that, if automatically controlled, quicker response excitation should later be required, it can be to some degree obtained by replacing the throttled pole pieces with normal ones and adding regulators.

*Circuit Breakers.* The following speeds of operation and interrupting duties are required.

| Service | Time | Rating |
|---|---|---|
| 120 kv. | 15 cycles | 2 million kv-a. |
| 24 kv. | 10 cycles | 1¼ million kv-a. |
| 24 kv. | 10 cycles | ½ million kv-a. |
| 4800 volt | 7 cycles | 250,000 kv-a. |
| 4800 volt | 7 cycles | 150,000 kv-a. |

The above circuit breaker times are from the energizing of the trip coil to the parting of contacts on a 60-cycle basis.

All 120-kv. and the 1¼-million kv-a., 24-kv. circuit breakers are applied on a single CO basis. The remaining circuit breakers are applied on a 2-OCO basis. This is because the 120-kv. faults are of such magnitude and lines of such importance that a brief inspection of equipment is made before reclosing. On 24-kv. cable faults, no reclosure is made until the fault is repaired.

The voltage ratings are 132-kv., 37-kv., and 7500 volts respectively.

The 24-kv. circuit breakers for indoor use are the live pot variety having a minimum of oil, and have air clearance to ground.

## V. Interconnections

The company has four interconnections and two throw-over fringe connections. The interconnection with the Consumers Power Company was made to profit by the diversity between the combined hydraulic-steam system of that company and the all steam system of the Detroit Edison Company, and for mutual reserve. The interconnection consists of a single 132-kv. solidly grounded neutral circuit on double circuit towers. It is about 62 mi. long connecting to the 120-kv. system of the Detroit Edison Company at Superior Substation (Fig. 2) and to the Consumers Power Company's system at Jackson, Michigan. The capacity of the interconnection is 30,000 kv-a. It is connected to the latter system by a bank of delta-delta tap changing transformers to avoid grounding the neutral as that system operates at 140-kv. isolated neutral. It is connected to the Detroit Edison Company's 120-kv. system through a bank of delta-Y tap-changing transformers, the *Y* point being used to ground the interconnection line neutral. The line was designed to interconnect three systems and

therefore regulating transformers installed at each end but, as yet, the third connection has not been made.

The line is protected by inverse time overcurrent relays for line to line faults, instantaneous ground current relays for line to ground faults, and over-all differential for the transformers.

Lightning protection is by arresters at each end and a single ground wire on the tower tops.

Rough calculation indicates that the power limit of the line and transformers is about 80,000 kw. Swings as high as 60,000 kw. have been carried without evidence of difficulty.

The momentary power required between the two systems is of the order of 2000 kw. ±.

The interconnection with the Ford Motor Company is for mutual reserve. The initial installation of 30,000-kv-a. capacity has been operating for a few months and the second installation of the same capacity will shortly be made.

The connection is from the 120-kv. bus of the Detroit Edison Company's Navarre Substation through a step-down transformer bank and regulating transformer to five 13,200-volt cables operated solidly connected together as one cable. Connection is made to the Ford Motor Company's 13,200-volt bus through suitable reactors.

Over-all differential relay protection is provided for the transformers and regulator and inverse time overcurrent relaying for other faults.

Interconnections are also established with the University of Michigan and the Packard Motor Car Company to equalize steam heating load and power requirements. One feature of technical interest in the interconnection with the University of Michigan is the use of impedance relaying to permit the safe operation under night time steam heating conditions at the University Power Plant of a single unit so small that its short-circuit current is not sufficient to operate the usual form of overcurrent relays with settings correct for day time use. By taking account of the voltage as well as the current this condition was met.

Two throw-over fringe connections have been established with the Consumers Power Company along the mutual boundary line at points too remote for duplicate feeds. Each consists of means for manually disconnecting the load from one system and connecting it to the other without interconnecting the systems. In neither case are voltage regulators provided.

## VI. Operating Procedure

Load control is accomplished by the load dispatcher assigning to three of the four power plants a definite load as determined by plant economy and instructing the fourth plant to hold frequency. Each plant load and the total are continuously indicated in the system operator's office to insure prompt action on the part of the load dispatcher and as a check on the compliance with his orders.

Frequency control is manual and the Warren Clock Method of indication is employed as a guide.

It is possible that, as the system approaches more nearly the planned condition, it may be necessary to modify the present load control arrangement as far as Connors Creek and Delray are concerned on the basis of holding interlinking cable loads rather than holding a fixed load. Such a modification does not appear to be difficult of accomplishment.

The general rule is that sufficient running reserve is maintained at all times to permit dropping the largest machine in any one plant on the system. Even with one machine down for overhauling the plant must be able to carry its own load if it loses a second machine or loses its ties with one neighboring power area, thus meeting the requirement of the general rule. If there is sufficient machine or tie capacity to meet this condition, no change need be made in the power area but if not, then the boundary of the power area must be adjusted to meet the new conditions.

## VII. Results as Determined by Operating Experience

The 120-kv. system has been operating in essentially the form shown in the plan for about a year and has given entire satisfaction. There has been no evidence of stability disorders or malfunction of switching or relay equipment. During that period faults have been confined to the lines.

The first of the 24-kv. Class "D" power plants has just gone into commission and as yet no experience has been obtained. It is the Delray Plant shown in Fig. 2.

Quite a number of Class "A" and Class "C" Substations have been in commission a year or more and during that time have functioned under line faults, giving very satisfactory results.

The 120-kv. step-down substations (Class "D") have been in satisfactory operation a number of years. A recent fault involving a section circuit breaker and two bus sections in the 24-kv. bus of one of these substations resulted in a fault which was sustained for eight seconds. No evidence of instability was shown by the Trenton Channel Plant feeding it through the 120-kv. system. However, the machines in the solidly tied Delray Power House dropped their loads. That was to be expected under the conditions. The completion of the synchronizing bus equipment in the new Waterman Class "D" substation should correct that condition.

The performance of 4800-volt equipment under fault conditions has given full satisfaction.

## Acknowledgment

The writer wishes to express his appreciation of the valuable suggestions and assistance given by Messrs. R. E. Green and I. S. Mendenhall in the preparation of this paper.

## Discussion

For discussion of this paper see page 612.

# Fundamental Plan of Power Supply
## In the Philadelphia Area*

BY RAYMOND BAILEY[1]

Member, A. I. E. E.

***Synopsis.***—*This paper describes the service requirements for the various kinds of load demands in the Philadelphia area. The territory served and the distribution of load in it are also given.*

*The fundamental plan of the system of the Philadelphia Electric Company is outlined, including information on the location and capacity of the principal stations and elements of the transmission system. The various reasons and conditions which have led to the development of the system are explained.*

*The major equipment, such as generators, transformers, synchronous condensers, etc., are described, with particular reference to the adaptability of their characteristics to the conditions to be met.*

*Interconnections with other electric utilities are briefly outlined.*

*The operating procedure, relating particularly to allocation of load to the various generating stations, reserve capacity, and frequency control, is discussed. Operating experience, including information regarding unstable operation at times of line faults, is presented.*

*There are also presented, in conclusion, the more important basic principles which are followed, as far as practicable, in the development of the Philadelphia system.*

### Introduction

It is a well recognized fact that there are many differences in the essential features of the fundamental plans of electric utility systems, some of which apparently may be attributed to different solutions of much the same problem, although many of the differences are due to the wide variation of conditions which largely determine the development of a system. It is the intention of the author to describe in this paper the fundamental plan of the system used for the supply of energy to the Philadelphia area, and to give the reasons which have led to the development of the system in the particular form in which it exists. It is rather difficult to set forth clearly in a paper all of the factors, both tangible and intangible, that influence the development of a system, but it is hoped that the reasons that are given in this paper will prove sufficiently clear to show the logic of the various steps in the development of this system. It is hoped in any event that this paper will prove helpful either in arriving at conclusions as to the best fundamental plan of system for any particular combination of conditions, or else in pointing out definite parts of the problem that need further study. The interconnection of electric utility systems leads to problems, the solution of which it is believed will be greatly facilitated by an increase in knowledge of the fundamentals of system planning.

It is important to recognize that plans for future development of electric utility systems may have to be revised to meet changed conditions relating to requirements for service, development of equipment, or the economic situation. Even though there is this possibility of having to revise plans for future development, it is apparently true that best results can be obtained by having such plans.

On account of the necessity for preparing this paper in October, 1929, the data for 1929, such as peak load demands, kw-hr., etc., are estimated.

### Service Requirements

*Character of Territory.* Electricity is supplied by the Philadelphia Electric Company in the territory shown by Fig. 1, having an area of approximately 1300 sq. mi., of which 136 sq. mi. is metropolitan Philadelphia. The

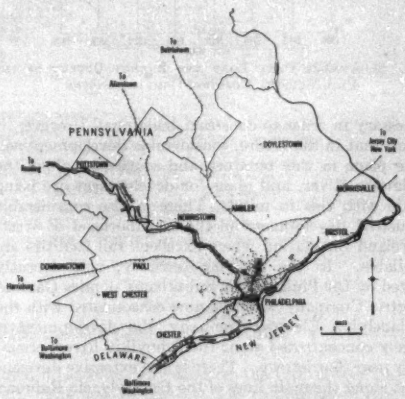


Fig. 1—Territory of the Philadelphia Electric Company System Showing Estimated Distribution of 1929 Peak Load

distribution of load throughout the area is indicated by the dots on Fig. 1, each dot representing 1000 kv-a. of substation peak demand as estimated for 1929, excluding the 25-cycle street railway and railroad electrification load and 46,000 kw. taken by other utilities. The character of the territory is urban, suburban, and rural. The mos dense load development is in the central business district between the Schuylkill and Delaware Stations. The major industrial development lies mainly

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1. Assistant Electrical Engineer, Philadelphia Electric Co., Philadelphia, Pa.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

along the Delaware River. Along this river, particularly in the Kensington district adjacent to both the Delaware and Richmond Stations, is a very extensive mill district. At the southern extremity of the territory along the river in the vicinity of Chester is also a large industrial development. Along the Delaware River near the mouth of the Schuylkill the industrial development has not been so rapid as the soil in this district is swampy in character and costly foundation work is

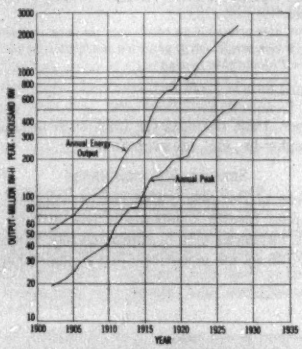



Fig. 2—Annual Peak Load and Energy Output of the Philadelphia Electric Company System

necessary in order to construct buildings. However, it is felt that in the future, considerable development will take place in this territory and southward along the Delaware River, and plans for development are being made with this in mind. There is also considerable industrial development in the neighborhood of Westmoreland Substation where excellent rail facilities are available. In the outlying territory, until recently served by the Philadelphia Suburban-Counties Gas and Electric Company which is now consolidated with the Philadelphia Electric Company, the development is largely concentrated along the Schuylkill River, principally near Norristown. There is also extensive development along the main lines of the Pennsylvania Railroad and Reading Railroad.

The population of the entire area is approximately 2,800,000, of which 2,200,000 are in the city of Philadelphia. The average density of population is 2160 per sq. mi. for the entire area with a density of 16,200 per sq. mi. for Philadelphia and 515 per sq. mi. for the outlying territory.

*Nature of Load.* The estimate of the peak load of the system for 1929 is 735,000 kw. There has been a steady growth resulting in the peak load being approximately doubled every five years and it is expected to continue growing although at a decreasing rate. Fig. 2 shows the yearly peak loads and net guaranteed kw-hr. since 1902 plotted on semi-logarithmic scale. The total number of customers is approximately 610,000, of which approximately 125 (including utilities) are supplied at 13.2 kv. or above. The consumers supplied at 13.2 kv. or above, including railways and utilities, however, take approximately 50 per cent of the total energy sold, with the railways and utilities taking 32 per cent of the total.

The average load density for the area excluding the loads of railways and utilities is about 480 kv-a. of individual substation demand per sq. mi. with an energy consumption of about 1,300,000 kw-hr. per sq. mi. per year. The highest load density occurs in the central district with a demand of 22,000 kv-a. per sq. mi. and an energy consumption of 68,800,000 kw-hr. per sq. mi. per year. The city residential district load density is approximately 2000 kv-a. per square mile, taking about 7,000,000 kw-hr. per sq. mi. per year, and the suburban districts around Philadelphia have a demand of approximately 600 kv-a. per sq. mi. and 2,000,000 kw-hr. per sq. mi. per year. In the least developed rural territory the density is as low as 0.3 kv-a. per sq. mi. with about 1000 kw-hr. per sq. mi. per year.

The yearly load factor is about 46 per cent, the average monthly load factor is approximately 58 per cent, and the average daily load factor approximates 68 per cent. The inherent power factor of the load referred to the generating station bus, at the system peak, is about 90 per cent. This decreases to approximately 82 per

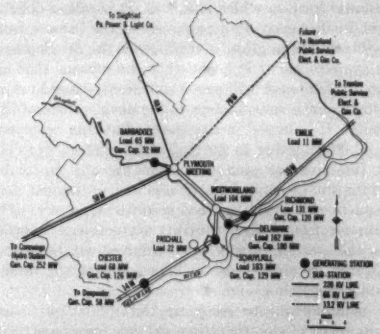



Fig. 3—Main Transmission System and Stations of the Philadelphia Electric Company System

cent during the off-peak daytime period and decreases further to about 72 per cent during the early morning minimum load period.

There is about 60,000-kw., 25-cycle load used exclusively for railroad and street railway service. Most of this load is supplied through frequency converters, but some is generated at 25 cycles by steam driven generators. The street railway load is being gradually changed over to 60-cycle supply and all new railroad load is supplied by frequency converter stations so that no

additional 25-cycle steam generating capacity is planned.

## Fundamental Plan of System

*Design of System.* The fundamental plan of the system for supplying the Philadelphia area provides 13.2 kv. and 33-kv. major distributing centers at generating stations and at high-voltage step-down transformer stations from which energy is transmitted to substations for re-distribution or distributed directly to large customers and these major distributing centers are normally tied together with relatively high capacity lines in order to utilize the power from the more efficient steam plants, hydro stations and 220-kv. interconnection. The inherent advantages of a system so planned that there is sufficient generating capacity at various large load centers to carry the load under emergency conditions, in the event of opening of generating station lines, are recognized, and this is carried out in so far as it is practicable, taking into account the economics of the situation, including both investment and operating expenses.

Fig. 3 shows the main transmission system and principal stations in the area supplied by the Philadelphia Electric Company system. The distributed peak loads and the local generating capacity as of 1929 are indicated for each major distributing center. The location of the various stations is, of course, determined by load requirements, together with suitable conditions for a generating station or connection with the high-voltage system. The spacing of these centers is such that all large substations are within the limit of economic transmission for the voltage and type lines involved. The tie lines between most of the distributing centers consist of two circuits operating at 66 kv. and provision is made for more circuits when necessary. High-voltage underground cable is used where the lines pass through the central section of the city and aerial lines are used in the outlying sections. This voltage is used since it was the maximum voltage practicable for underground transmission at the time the lines were put in service and studies showed it would be the most economical for transmission of large blocks of power for the distances involved. The transmission from Conowingo is at 220 kv. This voltage was selected rather than some lower voltage for the following reasons:

1. At Conowingo it was found to be impracticable to locate the high-voltage switching station on the river bank, and the 220-kv. layout was the only one that could be satisfactorily used on the roof of the station.

2. The use of 220-kv. for Conowingo permitted tying directly in with the interconnection system, which system required this voltage on account of the large capacity requirements and the distances involved.

3. The cost of 220-kv. transmission for Conowingo was substantially the same as that of other voltages considered.

*Scheme of Connections.* The connection scheme for the present system is shown by Fig. 4. The general plan of each station is to have double high-voltage and low-voltage busses with sectionalizing and space provision for reactors. This is to provide reliability and means of operating with any degree of sectionalizing that operating conditions may require for the service involved. The present practise is to operate normally

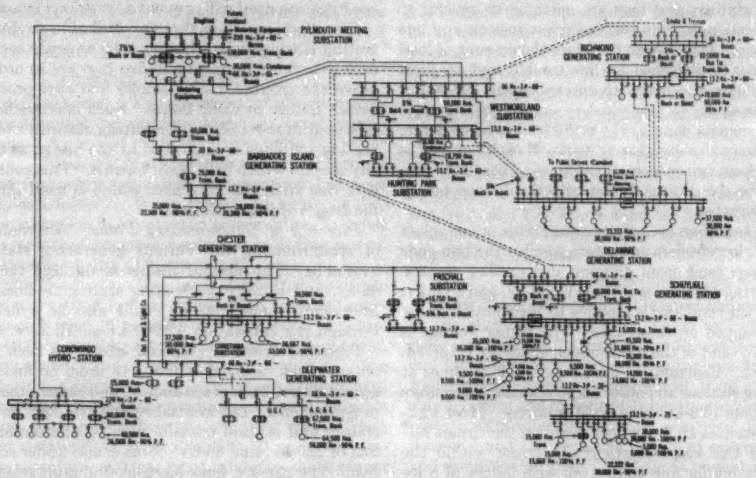



Fig. 4—Major System Connections of the Philadelphia Electric Company, 1929

with solid 220-kv. buses, solid 66-kv. busses except where limited current interrupting capacity of oil circuit breakers requires splitting the 66-kv. bus and with most 13.2-kv. buses sectionalized by reactors.

*Method of Distribution.* The greater part of the load is supplied through substations where it is distributed at 13.2-kv. to the consumers having the larger demands or transformed to 2300 or 4000 volts for general distribution. In the urban section all substations are supplied by multiple underground lines direct from one of the major distributing centers. In general, tie lines with 12,000-kv-a. capacity are installed between the city substations fed from different distributing centers in order to provide emergency service for the substations in case of failure of one of the distributing centers. Double busses with sectionalizing breakers are used in all large substations and they are operated in general so there are no more than two incoming lines on any one bus section. This is done to reduce the amount of load which may be disturbed by line trouble and to limit bus short-circuit current to approximately 300,000 or 400,000 kv-a.

In the central district where the load is most dense, low-voltage a-c. networks are used and each network is supplied from two or more substations. These networks replace the d-c. Edison system which will soon be entirely eliminated.

In the suburban area many substations are supplied by 33-kv. loop feeders and where possible the two ends of the loop come from different distributing centers. The outlying territory is covered by 33-kv. and 13.2-kv. lines and the rural load is supplied by distribution transformers tapped on these lines. The higher voltage is used on account of the transmission distances involved.

*Reactors.* Reactors are used on all 13.2-kv. lines at generating stations and other major distributing centers and on some 13.2-kv. lines at substations. Most 13.2-kv. line reactors are 3 per cent based on the circuit rating, since this keeps short-circuit current within the breaker rating for line faults even with failure of a reactor in one phase, and voltage regulation under normal operation is not seriously increased. So far no 66-kv. reactors have been installed but space is provided for them if necessary to limit short-circuit current when the system is further developed.

*Neutral Impedance.* The 220-kv. and 66-kv. systems have solidly grounded neutrals so as to limit the voltage stress on cables and other equipment and on the 220-kv. system permit the use of graded insulation on the transformers. The 13.2-kv. system is grounded through 4-ohm resistors in the generator neutral or with grounding transformers in case no generators are available. The neutral of the 13.2-kv. system is grounded in order to avoid excessive voltage stress on insulation, and resistors are used to limit the ground fault current.

*Means of Synchronizing.* Generators in each station are synchronized on the main bus which is normally sectionalized with reactors. The size and rating of the bus reactors is such that load equal to the rating of one generator may be transferred from one bus section to another without excessive voltage drop, but of sufficient reactance so that a bus fault will not lower the voltage on adjacent bus sections to less than 50 per cent normal, which is thought to be sufficient for the generators on the adjacent bus sections to remain in synchronism.

*Isolation of Phases.* There is only one isolated phase switch house on the Philadelphia Electric Company system. This station, Richmond, is only partly developed and when extension is necessary it is planned to consider alternate types of construction. The most recent major distributing center, Westmoreland, has been built with outdoor 13.2-kv. switching structure. All 66-kv. and 220-kv. stations are, of course, outdoor and it is expected that the liberal spacing and heavy construction used will prevent any serious trouble.

*Fire Barriers.* It is thought desirable to divide generating station switch houses into separate sections for each generator by means of fire barriers in order to localize the trouble due to smoke and soot produced by switch failure or other cause. Such barriers have been provided in most of the generating stations and disconnecting switches are installed in the bus so as to isolate any section which may be in trouble. This construction is in line with the unit plan which is used throughout the design of the stations.

*Diversity of Synchronizing Paths.* Alternate means of synchronizing the various generating stations are available. The normal means is through the various 66-kv. and 13.2-kv. generating station tie lines. In an emergency some stations could also be synchronized through the substation 12,000-kv-a., 13.2-kv. tie lines.

*Protective Schemes.* Special effort has been made to obtain quick clearing of faults in order to limit system disturbances, improve stability, and reduce the damage to equipment. Differential relays are used on all generators and station transformers. Differential protection of 220-kv. and 66-kv. buses is also under consideration. The 220-kv. lines have ground fault relays which are expected to clear most of the faults and in addition directional impedance type relays for protection against phase faults. The 66-kv. lines are protected with directional impedance type relays which protect against both phase and ground faults. Pilot wire protection was considered but it was doubtful if satisfactory operation could be obtained and the possible gain in speed was not deemed sufficient to justify the additional cost. Balanced ground relays are also used on the 66-kv. Plymouth Meeting-Westmoreland lines to obtain quick clearing of faults which is necessary under heavy load conditions in order to improve stability. The 13.2-kv. and 33-kv. lines in general have overcurrent protection at the source end and reverse power protection at the load end.

*Means of Regulating Voltage.* Voltage is automatically maintained at each major distributing center by means of voltage regulators on the generators, condensers,

and frequency converters. Bus voltage is increased during the heavy load period in order to provide more uniform voltage at the load. Generators supplemented by condensers are used to carry reactive kv-a. so as to secure satisfactory power factor for transmission from Conowingo and other generating stations. It is the policy of the company to encourage power factor improvement by the consumers and contracts provide appropriate rate adjustment. Tap changing under load equipment is provided for the 220/66-kv. transformers and practically all 66/13.2-kv. transformers. Induction regulators are used on the 13.2-kv. Delaware-Westmoreland and Delaware-Richmond tie lines. This equipment provides means of controlling reactive load distribution as well as adjusting voltage. Most of the 2.3-kv. and 4-kv. distribution circuits are equipped with automatic induction type voltage regulators and there is provision for the installation of induction regulators if required on some 13.2-kv. distribution lines.

## Equipment Characteristics

*Governor Response.* The governors of all steam turbines are adjusted for approximately the same regulation of about 3 per cent while the hydro units are set for 5 per cent. The operating experience with these settings as far as frequency regulation is concerned has been generally satisfactory. While there is no evidence that governor operation has increased power surges, it is felt that the matter of governor performance during system disturbances is worthy of further study.

*Generator Reactance.* The large steam turbine driven generators are all of normal design with transient reactance ranging from 14 per cent to 30 per cent, synchronous reactance ranging from 82 per cent to 135 per cent, and short circuit ratio ranging from 0.75 to 1.25. The hydroelectric generators are slow speed and special effort was made to keep the reactance as low as possible consistent with high efficiency and low cost. Their transient reactance is approximately 30 per cent, synchronous reactance 90 per cent, and the short circuit ratio ranges from 1.25 to 1.45.

*Excitation System.* Practically all steam turbine driven generators have shaft end exciters with the customary speed of response. The hydro-generators have high-speed excitation with separate motor driven exciters and pilot exciters, giving a rate of response of approximately 600 volts per second. The synchronous condensers at Westmoreland Substation have high-speed excitation with a maximum rate of response of 3000 volts per second and a maximum excitation voltage of about 500 volts, while the Plymouth Meeting condensers have high-speed excitation with a maximum rate of response of approximately 6500 volts per second and a maximum excitation voltage of 900 volts. The high speed provides greater stability during transient disturbances and calculations indicate that one condenser equipped with high-speed excitation is as effective during transient disturbances as several such condensers with ordinary excitation.

*Circuit Breakers.* The speed of operation of all circuit breakers in use on the system is the usual value because in most cases this is satisfactory and at the time the installations were made high-speed circuit breakers had not been sufficiently developed. High-speed circuit breakers are considered very desirable, particularly in places where stability of operation is affected, and tests of new high-speed designs have recently been made on the Philadelphia Electric Company 220-kv. system in cooperation with the manufacturers with the idea of possible increase in the speed of operation of the high-voltage circuit breakers now in use.

The 220-kv. circuit breakers have interrupting capacity of 2,500,000 kv-a. and the maximum duty with the present system is approximately 1,800,000 kv-a. The circuit breakers most recently installed on the 66-kv. system have interrupting capacity of 2,000,000 kv-a., while some of the older breakers are rated 1,500,000 kv-a. and 1,000,000 kv-a. The maximum duty on these breakers is very close to their rating and various plans are being considered to keep the duty within the switch rating with further development of the system. The 13.2-kv. circuit breakers in the most recent generating stations have interrupting capacity of 1,500,000 kv-a. for the generator and transformer switches which is sufficient for the duty in case of equipment failure or bus fault, and 750,000 kv-a. for the line switches which is ample capacity for line faults since they are limited by reactors to a maximum value of about 500,000 kv-a.

## Type of Interconnections

*Trunk Ties.* The principal interconnection is a 220-kv. tie with the Pennsylvania Power and Light Company, (see Fig. 3). Although the Pennsylvania Power and Light Company load is somewhat smaller than the Philadelphia Electric Company load, there is considerable diversity and consequently heavy interchange takes place. This interconnection is also used for reserve diversity and the exchange or sale of economy power and dump hydro power. The tie at present consists of one circuit, but an additional 220-kv. line is planned for the near future which will connect with the Public Service Electric and Gas Company System of New Jersey and complete a 220-kv. transmission ring joining the three systems. Considerable economies in operation have been obtained with this interconnection and it is expected that still further savings in operation and investment will be possible after the tie is completed with the Public Service Electric and Gas Company of New Jersey. This interconnection is described in greater detail in the paper: *The Conowingo Hydroelectric Project of the Philadelphia Electric Company's System—with Particular Reference to Interconnection,* by the late W. C. L. Eglin, (see A. I. E. E. Quarterly Trans., Vol. 47, April 1928, p. 372).

Another incidental interconnection is the proposed tie with the American Gas and Electric Company System in southern New Jersey. This is to be accomplished by a 66-kv. bus tie at the new 1200-lb. pressure Deep-

water Steam Generating Station. This station is controlled jointly by the American Gas and Electric Company and the United Gas Improvement Company of which the Philadelphia Electric Company is a subsidiary. The initial installation at Deepwater consists of two 58,000-kw. units and it is planned to take the entire output of one unit into the Philadelphia Electric Company System. This station will be connected to the Philadelphia Electric Company System by two 66-kv. circuits and a substation belonging to the Delaware Power and Light Co.

*Fringe Ties.* One other interconnection which is of relatively light capacity and normally open furnishes reserve interchange for a remote part of the system. This consists of a 13.2-kv. line connection and a 2250-kv-a. 33/13.2-kv. transformer tie with the Chester Valley Electric Company 13.2-kv. system at Downingtown, Pa.

## Operating Procedure

*Load Control.* The system connections as outlined allow ample flexibility for loading the generating stations most efficiently. The control of the load for the entire system is centralized in the Load Dispatcher's office, where recording wattmeters, automatically controlled from the generating stations, record the power generated at each station. The totalized system load is also recorded. The Load Dispatcher is in constant telephone communication with the operator in each generating station and instructs him as to what load his station shall carry.

In allocating the load most efficiently to the various generating stations, the Load Dispatcher is guided by several load allocation charts. One of the charts enables him to load the Conowingo hydro-station, the loading of which is predicated by the river flow. Another chart determines the most economical allocation of steam generated load to the various steam generating stations. In the preparation of the latter chart, consideration has been given not only to the increment efficiencies of the various generating stations but also to the intervening tie line losses. The loading of Conowingo must be determined before the load generated by steam can be allocated to the individual generating stations.

By means of the charts and instruments in the Load Dispatcher's office, it is possible to load each station so as to obtain the best over-all economy. The attainment of practically ideal loading has been due in part to the flexible plan of system connections and has resulted in obtaining unusually high over-all system economies.

*Frequency Control.* The regulation of frequency is assigned to the Pennsylvania Power and Light Company when water flow conditions at their Wallenpaupack hydro-station are such that the frequency can be regulated at this station, where automatic frequency regulation is installed. At other times, the frequency control is assigned to one of the Philadelphia Electric Company stations where it is regulated manually. In general, the regulation of frequency is assigned to that station which is normally scheduled to have the greatest variation in load during the particular period involved.

Satisfactory frequency regulation has been maintained by hand control on the Philadelphia Electric Company system up to the present time, although the installation of automatic frequency control may be necessary with the growth of the system and the interconnections. Successful manual frequency control has been due in part to the cooperation between the load dispatcher and the operators in the various generating stations and also between the load dispatchers or system operators of the individual interconnected systems.

The instruments installed in this connection at the various generating stations and in the Load Dispatcher's office are an instantaneous frequency recorder and a Warren master clock. This latter is used to check the frequency recorders and the accumulated frequency error.

The regulation of frequency is, of course, closely interlinked with the control of the load. The station regulating frequency is told what approximate load it will carry and the other scheduled load stations are also instructed as to their loads. If the load on the scheduled load stations is scheduled to change in a given interval, these stations must vary their load at a constant rate. In making this change, the scheduled load stations are instructed that the change must not be made contrary to the prevailing frequency. In other words, if a scheduled load station is designated to increase its load a definite amount, the load increase must not be made at a time when the system frequency is above normal, as this might impose too much variation on the station regulating frequency. The scheduled load stations are not required to maintain their scheduled load exactly, as too much manipulation results in poor frequency regulation.

There is always a constant periodic variation of approximately 3 per cent in the system load, which causes the frequency to vary about 1/20 cycle from the normal. The regulating station makes no attempt to correct for this variation as the general effect would probably be to cause greater deviation from normal frequency. There are, however, constant changes which are not periodic in character and it is for these changes that the regulating station is continually on the alert. In regulating the frequency, the regulating station must correct for time deviations from the standard as shown by the Warren master clock. The Load Dispatcher, by means of the instruments in the central office, maintains a close supervision of frequency. It has been possible in this manner to maintain the frequency within 1/10 cycle of the normal most of the time.

*Reserve Capacity.* Enough reserve generator, transformer, and line capacity is maintained on the system at all times to meet the local and general load demands in the event of the failure of any single piece of equip-

ment. During periods of low river flow, Conowingo is operated for the greater part of the time at reduced power output, thus making some hydro capacity available for reserve in case of emergency. As the hydro units can be brought up from standstill and put on the line in approximately one minute each, this provides increased reliability at practically no additional standby cost. By means of the system connections as outlined, the reserve capacity requirements have been maintained at an economical minimum.

*Abnormal Conditions.* During electrical storms since

Fig. 5—Record of System Disturbance Showing Unstable Operation of Conowingo Due to Fault on 220-Kv. Line

1928 it has been the practise to split the 220-kv. system if four or more generators are in operation at Conowingo and operate Conowingo in two separate sections so there will be less chance of losing the entire station through instability in case of lightning flashover of either 220-kv. line. With the possible increase in the speed of the 220-kv. circuit breakers on the Conowingo lines, it is felt that this practise will not be necessary.

## Operating Experience

*System Performance During Faults.* The performance of the system during the several stages of development including the present has been very satisfactory. There have been no general service interruptions although many faults have occurred on the lines and equipment. Several faults have occurred on generating station buses, but in each case the load interruption was confined to the station where the fault occurred. Four cases of actual instability occurred during 1928, which is the first year that Conowingo was in operation. In each instance some or all of the generators in operation at Conowingo pulled out of step and tripped on overspeed, but the steam turbine driven generators picked up the load so that no consumer's service was interrupted except in one case when about 30,000 kw. of synchronous load was lost. This latter case was caused by a very severe fault on the Chester-Schuylkill 66-kv. line, involving two or more phases and tripping both circuits. The other three cases of instability were caused by lightning flashovers of the Conowingo 220-kv. line and each case involved two conductors and ground. The two-wire-to-ground fault is, of course, very severe from the stability standpoint and the system was not designed for stable operation with full load under that condition because experience on other 220-kv. lines had indicated that practically all faults would be one wire to ground. All four cases of instability of Conowingo occurred before the installation of synchronous condensers was complete and before the high-speed excitation system was working satisfactorily. During the second year of operation up to October 1929, there has been no case of instability but all flashovers during this period have occurred when Conowingo was carrying little or no load. There are also frequent lightning flashovers on the Pennsylvania Power and Light Company system and the 220-kv. tie line trips out occasionally, but this has caused practically no disturbance on the Philadelphia Electric Company system. The high-speed excitation is very effective in holding voltage so

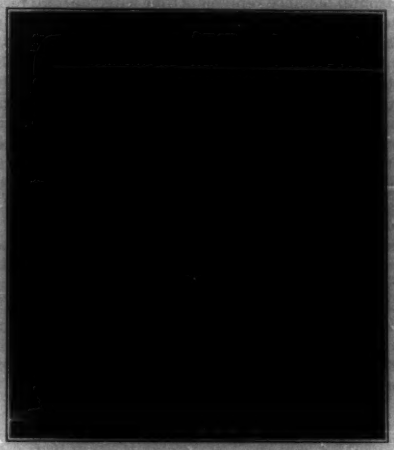


Fig. 6—Record of System Disturbance Showing Effect of 66-Kv. Line Fault
Westmoreland Substation 9:20 p. m. 5-5-29
6603 line pipped

that most disturbances on the high-voltage system are scarcely perceptible in their effect on the lights of the Philadelphia Electric Company system.

Automatic oscillographs are installed at each end of the Conowingo line to record system disturbances and Fig. 5 is the record obtained at Conowingo for one of the cases of instability. The voltage was taken from the 220-kv. bus and the variation in amplitude is characteristic of instability. The first minimum point on the envelope of the voltage wave shows the time when the generators are 180 deg. out of phase with the system,

and since only approximately 14 cycles are lost before the first visible record is obtained, this shows the station was out of synchronism in less than one-half second. The record of *C* phase line current shows two phases were initially faulted and that the arc on one phase was extinguished when the envelope of the voltage wave reached the first minimum value. The arc on the other phase continued until the line switches tripped as shown by the record of neutral or residual current. The voltage reached a steady value after the last Conowingo generator tripped on overspeed. Previous to the trouble four generators were in operation at Conowingo carrying 140,000-kw. load.

An automatic high-speed recorder is also installed at Westmoreland Substation to record disturbances on the 66-kv. system. Fig. 6 is a typical record showing the effect of a 66-kv. cable failure of one phase to ground close to Westmoreland on the Westmoreland-Richmond line. The height of the records made by the various elements shows the residual current in some of the lines and the voltages to neutral on the 66-kv. bus. The horizontal distance represents time with the total record covering ten seconds. Before any switches open the voltage is practically zero on the faulted phase and 75 per cent of normal on the other phases. When the line switch opens at Westmoreland, there is a sudden rise in voltage on the faulted phase to about 50 per cent normal and the next sudden increase is when the line switch opens at Richmond. The effect of high-speed excitation on the Westmoreland condensers may be seen by the rapid increase in voltage and fault current during the fault. The fluctuations in voltage after the fault is cleared are the result of power surges on the system.

*Service Record.* An analysis of interruptions of service to consumers in the Philadelphia Electric Company territory since the beginning of 1928 shows that troubles on the 220-kv. and 66-kv. systems have been responsible for less than 5 per cent of the total interruption time. The remainder of the interruption time is due to troubles on the distribution circuits and customers' equipment, errors, accidents, etc.

## General Summary

In order to bring out the basic principles used in developing the Philadelphia Electric Company system, there are enumerated below several ideals which were followed so far as permitted by the economics and practicability of the situation:

1. The various elements of the system, such as generators, transformers, lines, feeders, etc., should be arranged, as far as practicable, so that the failure of any one of them will not interrupt service, or lead to a severe widespread disturbance. This, in the case of distribution feeders, of course, is not practicable, except in those cases where the load densities are high enough to warrant the use of a network.

2. The various generating centers as far as practicable, should be located with respect to the loads, so that in the event of opening up of tie lines each generating center will be self-sustaining. The increased need for transmitting large blocks of power from a distance, and the relatively high economy of recently constructed steam generating stations, makes it impracticable to carry out this principle fully.

3. The arrangement of the system should be such as to permit sufficient transfer of power throughout the system so that generating stations can not only be loaded so as to secure the maximum economy, but also so that minimum generating capacity need be provided for emergency use.

4. The general plan of the system should be such as to permit expansion to take care of increased load demands satisfactorily without retirement of certain existing equipments due to increased duty, or sacrificing operating flexibility.

## Acknowledgment

The author desires to thank Mr. C. C. Baltzly, operating engineer of the Philadelphia Electric Company, who furnished the material on operation, and Messrs. J. W. Jones and H. Estrada for their helpful assistance in the preparation of this paper.

# Discussion

## POWER SYSTEM PLANNING

(Armbrust and LeClair, Dean, Bailey)

New York, N. Y., January 28, 1930

**A. H. Kehoe:** Two of the systems described in the symposium are designated as "close linked" and the third one "loose linked." It is becoming increasingly difficult to indicate by fundamental plan whether a system is close linked or loose linked. The Philadelphia plan, I believe, is very definitely close linked, there being ties made at almost every point where circuits come together. However, in the Chicago system (Chicago paper, Fig. 9) the 66-kv. system departs somewhat from being strictly close linked. Nevertheless, it cannot be designated as loose linked since it is operated as two separate systems tied at another voltage and must remain in synchronism to supply load. The Detroit system (Detroit paper, Fig. 3) may be operated as a group of independent areas without being in synchronism. I suggest that our definition for type of system connection should be "that to be close linked all parts of a system must remain in synchronism for proper operation, while a loose-linked one may be split up and operated in several independent groups."

The Chairman has mentioned the symposium on systems synchronized at the load, presented at Swampscott last summer, which described a method of eliminating concentrations of power without loose linking. Such an arrangement also reduces switch duties and maintains ample system stability.

It is evident that nearly everyone is endeavoring to render service that is complete and continuous. Such questions as relaying, protection, stability, and other similar features can be equated in terms of over-all reliability. In considering reliability, one fundamental seems to have been omitted in all of the papers; that is, whether there is maintained in service a fixed percentage of reserve to load, or whether the principle of having a spare, or hot, unit in operation is the one followed. Such differences have an important bearing upon system design. I believe it is universal practise on metropolitan systems to have at least one hot unit in reserve. Such a unit is usually carrying load on the system. However, in case the system is to split up on a fault, the design must be such that the loss of a unit in any one area

would not affect the capacity required by that area; otherwise, 100 per cent reliability would not be assured. If the system design is such that reliability is assured with the loss of one unit, the required reserve capacity may be taken as one spare unit; otherwise, each section which may be separated from other parts of the system should have sufficient spare capacity in operation to carry its load in case of a break-up of the system as a result of a machine failure. Excess feeder capacity also should be maintained in some definite percentage of reserve to load. The amount of such reserve has a very marked effect upon the type of design. For instance, the amount depends upon whether there are two circuits supplying the load, which requires a 100 per cent reserve, whether there are three elements with a 50 per cent reserve, or whether more units are used with still a further reduction in required reserve capacity.

It appears to me that until the minimum operating reserve is stated as a fundamental, it is very difficult to explain the differences in system connections or the differences in methods of supply to any particular load area. If such reserves are taken into account and the expected reliability is stated—and in most cases it will be 100 per cent system reliability that is required—then I think the reasons for the many differences in our present Metropolitan system connections would be made evident.

**System Development Committee of The Edison Electric Illuminating Company of Boston:** Detailed discussions of papers of this type are difficult to prepare, due to the inability of persons outside the organization of a company to appreciate, or be familiar with, the many local factors dictating a decision which superficially would appear unwise and not in accordance with conventional engineering policy.

Papers of this general character, however, are very much worth while as they serve to keep other organizations in close touch with the solutions to problems of System Planning as worked out to meet specific conditions in other areas.

The situation with respect to varying local conditions is undoubtedly responsible for the development of the several rather well-defined and diverse points of view on the principles of System Planning. There are numerous fundamental factors which may differ greatly for each particular locality. Some of the more important of these are:

1. The geography of the area to be served.
2. The location and availability of suitable generating station sites and the relation of these sites to the area to be served.
3. The type of supply stations, whether steam or hydro.
4. The distribution and character of the load.
5. The topography of the territory and its effect on the use of overhead or underground transmission lines.
6. The effect that existing plant equipment must have on any plan of future development. This is determined by the policy of the management with respect to obsolescence of equipment.
7. The views of the operating organization with respect to provisions for necessary spare equipment such as boilers, generating units, transmission lines, and substation apparatus.

The local treatment of and relative importance attached to the many variables mentioned, leads inevitably to diversified plans of System Development.

Perhaps the most helpful contribution which we can make to this discussion will be to describe briefly the general principles which are used as a basis for the development of the system of the Edison Electric Illuminating Company of Boston.

The Boston Edison system is being divided into separate power zones, each fed from a major source of supply, such as a generating station or large capacity step-down substation served from one of the generating stations. These stations correspond quite closely to the Detroit Company's Class D stations. From the large capacity step-down stations, energy is redistributed to other and smaller stations and to large industrial customers by means of cable loops.

Each of the generating sources is to be interconnected by means of direct tie lines which are installed primarily to provide means of interchanging spare generating capacity as needed to meet a deficiency at any point. Tie lines once installed for this purpose are thereafter used to maximum advantage in the interchange of power between generating station busses to effect maximum overall system economy. The tie cables are operated tightly linked at present.

The power zones into which the system is being divided are to be kept independent of one another for normal operation, but provision is to be made for a certain number of relief cables crossing zone boundaries to provide emergency capacity in the event of failure of normal supply cables into a zone. The tying in of these outside cables between power zones is not considered to be desirable on our system at the present time. Trial operation has developed disadvantages in complicating the network in the control of wattless kv-a. and voltage, and in relaying as well as in the stressing of circuit breaker equipment in substations which may lie intermediate between generating sources. This method of operation also requires at specific points in the various closed loops which involve more than one generating source, adequate tap changing regulating transformers, or other apparatus for the control of wattless kv-a. and voltage.

Loose linkage, if applied to tie cables, would require greater available reserve generating capacity on the bus for each zone, as at any time a zone may be instantaneously isolated.

In general, the Boston Edison system will have three steam generating stations on the seacoast to serve an area of approximately 650 square miles, roughly semi-circular in form. Current is generated at 14,000 volts, three-phase, 60-cycle and distributed at generator voltage to power zones immediately adjacent to each generating station.

The central and original steam station at L Street supplies downtown Boston and the downtown d-c. system. Energy is supplied over radially operated lines from the L Street Station to sectionalized busses in the substations where converters are paralleled on the d-c. side. Storage batteries are floated in reserve on the d-c. busses. The separate bus sections at substations are served by lines originating at the generating station bus. This bus can be sectionalized so that in the event of the loss of any one section the substation will be supplied from other sections.

A double-circuit 120-kv. overhead transmission ring now practically surrounds the area. Large capacity step-down substations on this ring reduce the voltage to 14,000 for the supply of power zones associated with each substation.

A section of the 120-kv. transmission ring is a part of the New England Power Company's hydroelectric system, supplementing and supporting the steam supply at the seacoast.

There is a central area, or core of the territory, which is beyond the economic 14,000-volt transmission distance from any of the generating stations or large capacity substations. This area is being served at 24,000 volts direct from the generating stations by step-up transformer units.

The 14,000-volt supply in the various areas is stepped down in local substations to 4000/2300 volts, three-phase, four-wire, for local distribution.

The Boston Edison development plan is similar to that of Chicago and Detroit. We are at present adhering in operation to the closely linked plan of Chicago, rather than the loosely linked system of Detroit.

System planning should, wherever possible, provide for flexibility so that a change may gradually be made from one system of operation to another, as circumstances may dictate in the growth of the system, without the necessity of having to rebuild the system to meet changing conditions.

**E. G. Allen:** The transmission and distribution systems usually constitute over half of the fixed investment of a light and power company. It is in some respects the more important half, for, while there have been more opportunities for effecting

economies in the generating plant, the character of service is usually determined by the distribution system. In it originate the majority of interruptions to service and faults of operation. It is then obvious that the transmission and distribution system should receive as much care and attention in design and construction as the power plant itself.

These papers present three different standpoints and three somewhat divergent methods of obtaining the same object, which is efficient and reliable transmission and distribution of electrical energy from the power plant to the consumer. Although the standpoints are somewhat different, the final resulting systems are essentially similar.

The situation in Chicago differs from that in Detroit and Philadelphia in that the central portion of the city is served with direct current. This is the result of the evolution of the art and is the common heritage of several of our large cities. Although it is a solution to the problem of concentrated power which would not be adopted today, it was probably the best solution at the time of its inception and is now an actuality which must be reckoned with where existent.

All three cities have adopted the obvious general plan of concentrated power generation in a few stations, transmission at comparatively high voltage to main centers, and distribution at a medium voltage from these centers to local substations so situated that they can economically serve the consumers at voltages which are desirable for local distribution. This is the same solution that has been found best for commodity distribution, involving wholesaler, middleman, and retailer.

The difference in the details of the solution of the problem appears in the different schemes for relaying, providing reserves, and eliminating faulty lines and equipment.

Detroit looks upon each district as a unit complete in itself but forming an alliance with other districts to improve economy and severing these ties at the slightest appearance of contagious trouble.

Philadelphia considers its entire system as an entity but provides reserves at every point so that any member of line or equipment can be eliminated instantly in case it should develop a fault.

Chicago splits its system into duplicate parts, either of which can carry on the functions of the whole in an emergency.

The points of view are different but the resulting systems are essentially similar. There are technical considerations of short circuit, capacity functioning of relays, and the like which render a detailed comparison of the three systems far too complex for a brief discussion. Each has been developed to a point where its service record may be a matter of pride, but the engineer, never satisfied until perfection has been achieved, may well study the three solutions of the distribution problem as set forth by these papers to eliminate the weaknesses which still exist.

**H. R. Woodrow:** The outstanding feature that has been presented in these three papers this morning is the indication that real system planning is under way. Three points of view have been shown and at the last Summer Convention a fourth was presented. It is evident that each one of these systems is laid out on the basis of a definite plan and that is a large step in advance over much of the work that has been done during the past years.

Systems are now being planned not only for the next two or three year period but with vision into the future for at least ten years. In looking ahead ten years some rather essential features are discovered. A forecast into the future ten years indicates a load three to four times that of the present and in laying down the proper plan for a system of this load radical departures may be made on a comprehensive scheme and much of the inadequate system can be expected to be removed within this period.

Much of the material today which is not economical for production is too valuable as peak capacity to scrap immediately, but a comprehensive program will show that future systems should not be laid out on the basis of the present equipment and that much of the equipment can be retired during the period of development without an undue burden on the company.

The question of loose linkage or tight linkage is one that has been grossly misunderstood. For instance, the New York companies have been classed as having a tightly linked system, whereas Detroit has been considered to have a loosely linked system. A careful review of the two systems would show that from some angles the Detroit system is more heavily connected than the New York system, since the New York stations are subdivided and these tie together through a multiplicity of paralleling circuits via substations and load centers. In general, these circuits have comparatively high reactance, giving good stability conditions, and although each one is of relatively small capacity the total approximates the capacity of the section. The relays are so set on these interconnecting ties that a short circuit on any one of the connecting links has very little effect on the system or interconnections, and the only kind of disturbance that will pull the systems apart is a short circuit on the generating station busses.

In the above analysis it may be seen that the system is tightly connected so far as being sectionalized in case of troubles, but loosely linked from the standpoint of having a disturbance on any one of the connecting lines, affecting the combined system. The Detroit system, on the other hand, has all generating units within a station connected through heavy busses, and the ties between generating stations are of comparatively low reactance. The relays are so set that the stations are automatically segregated in case of the more usual short circuit troubles. The low reactance ties do not give the same stability for interconnections as a large number of relatively high reactance ties and consequently require the lower relay settings, as two generating stations are more apt to be pulled out of step in case of system troubles.

I concur in Mr. Dean's statement of the desirablity of eliminating as much high-tension switching as possible. The plan that he has shown as *D*, where high-tension switching is eliminated and all switching handled from the low-tension side of the transformer, is very good. If it were possible, however, to have the separate feeders run from distinctly separate generating units in a station or separate generating stations, the continuity of service would naturally be more reliable.

**A. F. Bang and L. G. Smith:** It may be of interest to describe briefly the layout of a somewhat smaller system, to point out how many of the principles and operating methods outlined also find application here and how some of our arrangements differ and may be worth mentioning in so far as we believe them to be of value.

The system is the combined systems of the Consolidated Gas Electric Light & Power Company of Baltimore and the Pennsylvania Water & Power Company which supply Baltimore and surrounding territory, and in addition the cities of Lancaster, Coatesville, and in part York.

The Baltimore (and Lancaster) systems are mixed frequency systems with 25-cycle supply to industrial customers and street railways, and 60-cycle supply for commercial and residential distribution and some industrial. The main sources of energy supply in Baltimore are two steam generating stations, located on the water front, one of which is mixed frequency, and 40 miles away the hydroelectric development at Holtwood of the Pennsylvania Water & Power Company. Holtwood also has mixed frequency and is combined with a small steam plant using largely local river coal as fuel.

The combined capacity of these plants is about 360,000 kw. and the annual output for 1929 was 1,200,000,000 kw-hr. 44 per cent in hydro energy. Work has now been started on a new hydro station higher up the river (Safe Harbor) the initial development of which will be about 160,000 kw., 60 cycles, and which again will make Baltimore a city largely supplied by hydro energy.

All of these systems are operated in parallel through standard

type frequency changers where necessary. In Baltimore these are at present scattered in different substations, though it is planned to replace these smaller units with a few larger ones of about 30,000 kw. capacity each.

The main distributing and transmission voltages are 4000 volts, 13,200 volts, 26,000 volts, 66,000 volts.

*Reclosing Device on 4000 Volt Feeders.* The 4000-volt, 60-cycle distribution system consists of all radial feeders; each one is equipped with a reclosing feature which differs from those generally used, in that the opening and reclosing of the oil circuit breaker is made as fast as in any way possible (approx. 0.7 sec.). If a feeder is successfully reclosed in this way the lights will not go out but merely flicker, and motors will keep on running. If the feeder is permanently bad it will stay out after the third opening. In 1929 such reclosing operations took place over a thousand times and 78 per cent were entirely successful, the feeder not being permanently injured. This device has been described previously in the A. I. E. E. Transactions, 1916, by F. E. Ricketts. For the past few years this device has also been used successfully on a 66,000-volt radial line.

*Feeder Reactors—13,200 Volt System.* Previous to the installation of feeder reactors on the 25-cycle system, it was not an infrequent occurrence that when a two- or three-phase short circuit occurred on a tie cable between two generating or main substations in Baltimore, the generating station at Westport would fall out of step with Holtwood, due to the momentary disappearance of synchronizing power when such a heavy cable short circuit took place. Since the installation of such feeder reactors at both ends on practically all underground cables, a similar short circuit never produces an out-of-step condition, as the reactor does not merely limit the short circuit but also maintains the voltage on the rest of the system. To quote figures: In the three years 1921-23, 120 cable failures occurred producing seven out-of-step conditions, while after this installation was practically completed the three years 1926-29 showed 92 cable failures with no evidence of any out-of-step conditions. This experience entirely parallels the Chicago experience on its 25-cycle system.

*Operating Transformers and Circuits as a Unit.* The system we are considering contains many short transmission lines from 15 to 40 miles long, where the impedance consequently is relatively small in the line itself, and often greater in the transformers at each end. As a result we have found it of great advantage to use the transformers at either end as reactance coils for the short overhead lines. This is done by operating all transmission circuits separately on the high-tension side and only paralleling on the low-tension side, in other words, switching circuits and transformers as a unit. This arrangement, in our opinion, has been very successful and will clear a disturbance on these circuits with a minimum amount of disturbance. It has also the advantage that the expensive high-tension oil switches can be omitted and at the generating end it gives the simple and very reliable ground relays an excellent chance to work as they can be set at very low current settings and as a ground on one circuit does not affect more than one relay. On the 60-cycle system in Baltimore it is planned in the future to tie the main generating stations and the terminal substations from the new hydraulic development at present under construction, with 33,000-volt underground cables. These cables too will be operated in a similar way without high-tension oil switches and switched only on the low-tension side of the transformers (13,000 volt).

Bus reactors are used at the Holtwood plant for limiting the short-circuit current on this bus. They serve, however, another important purpose also. On a river of variable flow like the Susquehanna River the hydro plant will in low flow periods be used to carry the peak and be shut down at night time to store the water. During such periods it is necessary to send an appreciable amount of energy back from the Baltimore steam plants to the Pennsylvania customers. As there is no means of changing transformer taps under load and the power flow is in the opposite direction of normal, full voltage is maintained on the Pennsylvania customers by inserting sufficient of these bus reactors between Baltimore and the part of Holtwood bus from which the Pennsylvania customers are fed and by floating one generator as a synchronous condenser with the vacuum broken in the draft tube of the turbine. In this way from 14,000 to 18,000 kw. can readily be sent in the reverse direction with an increased voltage of some 20 per cent.

*Grounding of Generator Neutral.* In a power house like Holtwood where there are no feeders or transmission lines directly connected to the bus, but all power is sent out through transformers, it has been found to be desirable not to ground the generator neutral at all. If an accidental ground occurs the capacity current will be the only current flowing, and this is so small that it does no harm. In other words, accidental contact or "grounding" or even the accidental opening of a disconnector under load, does not necessarily result in a flashover between phases. On a rather old-fashioned bus construction this has been of great advantage in the 20 years it has been in operation,—there has been no short circuit on this bus in 17 years.

To leave the generator ungrounded, we do not consider practical when many feeders, overhead and underground, leave directly from the bus. At the Westport station, which has a modern switch-house with vertical phase separation, the arrangement is that that neutral of all the 25-cycle generators is carried to a neutral bus which is again grounded through a reactor of about ¾ ohm and of sufficient size to withstand a dead ground for four minutes carrying 10,000 amperes. Using a reactor instead of the more common resistor for this purpose has been done for about two years without any difficulty developing. The neutral of the 60 cycle generators, on the other hand, is dead grounded.

*Operation of System.* Operation of a system like Baltimore, which relies for about one-half of its energy on hydro power some distance away, must necessarily be as a rather close linked system during periods of high flow in the river. During such periods it has been found an advantage to split the busses not only on the high-tension side but also on the low-tension side at the terminal station of the incoming hydro power and (especially when these busses for some reason must be tied) to split the generating capacity at the main steam station at Westport in two or three sections. Paralleling, in other words, takes place only on the low-tension bus at Holtwood and at the different substations, in this way somewhat approaching the synchronizing at the load arrangement now used successfully in New York. Such a scheme distinctly keeps down the tendency for severe disturbances, such as a short circuit on a substation bus, from spreading to the remainder of the system. It also helps to get the proper division of load between the different groups of cables.

In spite of the many improvements that have been made in late years, overhead transmission lines are, of course, still subject to various troubles unknown to underground transmissions, notably lightning and sleet. On the Holtwood-Baltimore system, disturbances from lightning are kept at a minimum by using four circuits in parallel. Experience indicates that more than two circuits are very rarely hit at the same time. Nevertheless, for full protection of the more important downtown city and lighting load, arrangements are made to carry extra steam in Baltimore when a storm approaches, and this section of the system is then arranged with quite a loose tie with the remainder of the system and such a tie will promptly open up on severe transmission disturbances. This is similar to the loose linkage of the Detroit Edison system.

The other serious trouble on transmission lines is sleet, but this difficulty seems to have been overcome on the Holtwood-Baltimore system entirely by means of melting any sleet off by current from the power house as soon as it appears. Thus there has been no outage on these lines due to sleet for the last 12 years, while in the previous seven years, about twelve disturbances from this

took place—some of them resulting in broken cables. It is, therefore, the Pennsylvania Water & Power Company's policy now to arrange for sleet melting on all its important 66,000-volt circuits.

*Division of Load Between Substations.* By virtue of the fact that in Baltimore a substation may be fed from two generating stations, and with a number of such stations fed in this manner, an interesting problem of control of energy between the various groups of cables from the same generating station is introduced. It was found that it was necessary to check the phase angle shift from generating station to each of the substations so that the proper loading of cables and the desired distribution of load is obtained with the same phase angle difference between the two generating station busses. When the 33-kv. generating station tie system is completed the necessary phase angle correction has been calculated and phase shifting transformers must necessarily be used, such as described by W. J. Lyman.

*Rural Load.* In order to supply the rural distribution load in the neighborhood of Baltimore, a 66-kv. steel tower line has been installed around the city. This line is designed for future operation at 110 kv. From the substations on this ring 13.2-kv. lines have been installed to supply small pole-type step-down substations for feeding rural distribution lines. The voltage on these 13.2-kv. lines may be raised at a future date to 33 kv. and they have been so designed. Due to the fact that the step-down substations from the ring will never be of very great capacity, it was desired to make them as cheap as possible and at the same time render reasonable reliability of service. To this end all of the switching, both on the supply stations to the ring and on the step-down substations, is accomplished on the low-tension side of the transformers so that there will be no 66- or 110-kv. switching. Oil circuit breakers of 110-kv. have been installed at the mid-point of the ring to sectionalize it automatically in case of trouble.

*Influence of Relays on Layout.* As brought out in the discussion of the Chicago system, the system layout has a material influence upon the method of relaying used. However, the converse may be true, that is, the system of relaying adopted might influence to some extent the layout of transmission cables. In Baltimore all of the transmission cables are relayed by current differential protection backed up by straight overload protection. In order to obtain selective action of relays in the current differential scheme a minimum of three cables to each substation is required. As a rule, four cables are preferred so that one cable out of service will still permit selective relaying among the remaining three. In some cases where a new substation has been started and not more than two cables justified, a scheme of potential differential relaying has been devised. This is obtained by inserting reactance coils or step-down transformers between the pothead and bus in each incoming cable. The potential transformers are installed on the pothead side of the reactances and differentialed through a special voltage relay, so that when the voltage on one cable is higher than that on the other, a definite rotation of the relay disk is obtained. In order to keep potential off the voltage relays under normal conditions, an instantaneous current relay is provided which connects the voltage relays to the two potential transformers only during short-circuit conditions.

**E. C. Stone:** I was interested in Mr. Moultrop's comment on the method of handling system planning in Boston by a committee made up of representatives of the interested departments. Since 1922, in Pittsburgh, we have had a system planning division whose business was to do nothing except plan the development of the power system. The engineers in this division are specifically trained in the problem of system planning for the purpose of getting the best possible system.

In passing, I want to call attention to one point that was brought out by one of the discussors—the similarity of the various systems that have been described. Considerable emphasis has been placed on the difference in the size of the territory and the character of the territory, and the details of the system, but I think we should bear in mind that the three systems described in the three papers, and the system described by Mr. Moultrop, and to a certain extent the system commented on by Mr. Bang, are in principle exactly the same. That is to say, a few large generating stations are connected together by high capacity lines, with direct feed to the load, both from the generating stations and from substations on these trunk lines. These groups of distribution, so to speak, are centered around the various generating centers and more or less isolated electrically. This, by the way, was the system we adopted in Pittsburgh in 1916 and we have been deliberately and consistently working toward the development of it since then. However, in my opinion, this is not the ultimate answer and I believe that we will see changes in these fundamental principles in the next ten years.

I think our present systems are too complicated. I think the intermediate voltages are too low, and I think the substations are too elaborate. There are probably other things that will suggest themselves to you.

In power system design during the past few years attention has been centered on the problem of minimizing the severity and reducing the extent of system disturbances, the principal causes of which appear to be short circuits which do not clear before the stability of the generators is affected, and incorrect operation. Analysis discloses that there are two fundamental conditions to be met, as follows:

(a) Adequate transmission of energy from the power sources to the load.

(b) Stable synchronous operation of the various generating units under abnormal as well as normal system conditions.

In the systems just described the second condition has been recognized by the installation of additional special circuits set up for the purpose in the form of reactors between generator busses and tie lines between power stations. In the "synchronized at the load" scheme now in operation in New York, however, the second condition is complied with in the arrangement of the main transmission circuits without any special equipment such as reactors and station ties. The system connections are so arranged that the impedance of the regular load-carrying lines and transformers takes the place of the special reactors and tie lines in the other systems.

Another general characteristic of the systems just discussed appears to be the grouping of generators and loads in several sections with only one or two connecting links between the sections, so that if the system protective apparatus fails, the section in which the fault has developed may be promptly isolated from the rest of the system. In the New York system, feeders are interlaced between stations so that the isolation of a section becomes more complicated.

In all of these systems a major purpose has been to interpose sufficient reactance between generators so that if a dead short circuit occurred at the terminals of one machine, the voltage on the other machines would be sustained at a high enough value to hold them stable. If, however, it should become possible always to isolate short circuits by means of high-speed circuit breakers before instability could develop, it might be possible to do away with the insertion of high reactance between generators, thus accomplishing substantial simplification in many cases.

Improved continuity of service has clearly been the principal aim of the past few years in system design. It is significant that all of these systems are built up around the central fundamental that failures must be expected in all parts of the system, and that provisions must be made for meeting such failures without interruption to service or overloading of plant. This is true in electrical transmission to a far greater degree than in the transmission of energy in other forms, such as water or gas. If this necessity of providing for breakdowns was greatly reduced or

eliminated, there would be substantial changes in our principles of design.

Nevertheless, the tremendous advances of the past few years in this direction must be recognized. The developments of the past few years have given to us apparatus and equipment much better for our purposes. Obviously, the extent to which we must guard our continuity depends upon the reliability of our apparatus, and as the reliability of apparatus improves the system design will become more simple.

Much more is known now about the theory of the behavior of insulation under voltage stress. Progress in this direction must of necessity be slow, but may be expected to be steady. Already we are feeling the effect of it in the development of high-voltage lead-covered cables, which are revolutionizing power distribution in congested districts. Developments in selective relaying and circuit interrupting devices are also very important. The low-voltage network protector offers a principle in relaying which may be of great value in power systems of the future. High-speed circuit breakers, thoroughly reliable, and of ample interrupting capacity, will undoubtedly very much simplify the fundamental power system schemes. Studies in lightning protection will revolutionize the reliability of overhead transmission systems. The result of these developments, together with many others which might be mentioned, will be greatly to reduce the probability of electrical failure by making the various parts of the system more reliable, which in turn will undoubtedly lead to greater simplicity and economy. Studies of breakdown experience in the various parts of the system and of future expectation of breakdown, based on the theory of probability, should be of substantial value in analyzing this problem.

While undoubtedly most serious attention has been given to the economic aspects of the systems under discussion, it is disappointing that more emphasis is not placed on them in the papers presented. Some of the more important of these factors appear to be as follows:

Ratio of installed generating capacity to system peak load (size of largest unit).

Proportion of spare capacity for emergency in lines and substations.

Flexibility of system connections and number of circuit breakers—ability to concentrate system spare capacity at any needed point.

Closeness of relation between loads carried and operating capacity as system grows.

Cost of synchronizing circuits, including reactors and generating station tie lines.

Required interrupting capacity for circuit breakers—use of reactors.

Closeness of adaptation of rated capacity to actual loads carried (operation on total temperature basis).

Economics of interconnections or tie lines.

Of particular importance is the necessity of giving extensive study to the ultimate capacity of all parts of the system for relatively short periods of time under those unusual conditions of abnormal operation which occur only perhaps once in five or ten years.

In the struggle for more system capacity per dollar of investment, which is bound to be intensified in the next decade by the nearer approach to load saturation, and probable competitive conditions, we shall undoubtedly hear more of the economic side of the power system problem.

**H. L. Melvin:** The descriptive papers on the New York, Chicago, Philadelphia, and Detroit systems outline basic plans for serving four great metropolitan areas. In each situation the problems are somewhat different and the fundamental plan adopted has been varied. Interrupting capacities of oil circuit breakers, stability, load distribution and relation of power plants to the loads, together with service requirements seem to be controlling factors in selecting the schemes of connection. It is interesting to note that a voltage or voltages above those commonly used for primary distribution have been required in each case for the transmission of larger blocks of power and for interconnection purposes. With developments in underground construction for the higher voltages and improvements in overhead line designs, it would be expected that there will be more extensive use of the transmission voltages even to the extent of using them for purposes for which distribution voltages are now being used and planned.

The basic principles and lessons which have been learned, particularly that of the necessity for careful system planning, can well be applied to the newer and growing situations. On systems of the type which cover extensive low load density areas and distances of many miles, either within the system itself or between systems contemplating interconnection, a different group of factors become predominating. On such systems the locations of power sources are determined by the availability of hydro and economic location of thermal plants. Relatively long high-voltage lines are usually required which are routed from power sources to load centers, through territory being served and as interconnecting lines between systems or between parts of a system. The selection of suitable nominal voltage or voltages for the transmission system, which takes into account service to the entire territory which may logically develop into an interconnected network, is of prime importance. Economics, service, voltage control, and stability are important considerations in the planning of such a system, rather than oil circuit breaker interrupting capacities, and some of the other major problems peculiar to metropolitan systems.

Improvements in the performance of governors both steam and hydraulic, automatic system speed control, improved excitation schemes, increased interrupting capacities of oil circuit breakers, decreased duration of faults on the system by increasing the speed of oil circuit breakers and relaying will all have their influence on system planning in the future. These improvements are coming about largely due to the urge and necessity for their development as they have presented themselves in working on system planning problems. Continued encouragement should be given to development and research which will aid in further improvements to existing equipment and operating procedure, thus effecting improvements to service and greater utilization of facilities.

The design and selection of load control equipment present many problems; however, it is unfortunate from the economic and operating standpoints that phase shifting equipment and transformers for making minor adjustments in voltages seem to be necessary in many of the interconnections under consideration.

Reviewing developments during the past few years, it can now be seen where many of these conditions might have been avoided and construction which has been done might be functioning more effectively if more foresight had been exercised. Systems will continue to expand and interconnections will, no doubt, be made in increasing numbers, so we may well profit from present experiences, particularly in territories where two or more utilities may be operating. Cooperative planning and study of the fundamental problems involved, between the various engineering groups interested in a given situation, also engineering influence in contractual relations should be fostered with the expectation that economies will be effected and service improved.

**D. K. Blake:** This problem of system planning seems to me to turn around one point which has been emphasized by Mr. Kehoe, namely, reserve capacity. If it were not for the question of the failure of equipment, if we could always be sure that the equipment worked perfectly, we would not need to provide any reserve capacity. So it is my opinion that the real problem of system design is to provide economically that reserve capacity.

It is to be regretted that all of the authors did not include a series of underlying principles, as Mr. Dean did. Inasmuch as the time is short I will not take them up in detail but will just

make two brief statements. First the problem in the abstract and then the problem in the concrete.

Considering the problem in the abstract, that is, not considering any local conditions whatsoever. It would be difficult for any advocate of the low-voltage a-c. network system to provide a better set of specifications in order to influence a selection of that system than Mr. Dean has in his first five points as to what are the principles to serve as guides. It is my opinion that, considered in the abstract, there is no system that will meet these points as fully as will the conventional low-voltage a-c. network system.

Considering the problem in the concrete, that brings in the question of your local conditions. Of course I have no local conditions of my own and am not so well qualified to talk upon that, but I will point this out; that you are now in a locality where the local conditions vary considerably. Can you imagine any spot upon the face of the earth that has a wider range of conditions than Manhattan Island on one hand and Flushing and Queens and Brooklyn on the other, with their differences in load density. Four or five different groups of engineers studying this problem and using the principles similar to those that Mr. Dean has outlined as guides, with the addition of the reserve capacity mentioned by Mr. Kehoe, and the continuity at the consumer mentioned by Mr. Woodrow all come to the same conclusions as to what type of system it ought to be, namely, the low-voltage a-c. network.

**W. J. Lyman:** One of the most important features of any fundamental system plan is the manner in which future increases in load are to be handled. Very often, the only way this is taken into account in the master plan is a general provision that more circuits will be added when required and substation space may be reserved for the future equipment.

This continual addition of circuits sometimes leads to undue complication, causing annual changes in system layout and making the systems which we are actually operating today only a temporary step toward an ultimate goal which may never be reached. One solution to this problem is a somewhat different general scheme which may find application in many cases, especially in high load density areas requiring underground cables. The basic principle involved is that the number of circuits required for supplying a given area depends primarily upon the spare capacity required and standard of service to be rendered and should be to a large extent independent of the amount of load. Thus it might be that six feeders to a certain area would be required for a flexible, economical, and dependable system. In the event that the load in the same area doubles, six feeders of double capacity probably would be about as satisfactory as twelve feeders of the original size.

With this in mind a definite transmission system could be laid out from the power source to the load centers providing terminal equipment for the desired number of circuits. As the load grows new cables (or overhead lines) would be installed and connected in parallel with the existing cables on the same breakers. In this manner the feeders would develop in two, three, or four cables paralleled at both ends, preferably with disconnecting devices so that a faulty cable could be isolated quickly and the feeder returned to service at reduced capacity.

During the development, if higher capacity circuits prove feasible they could be readily accommodated, relieving some of the smaller cables to reinforce other feeders. If the limit is sometime reached for the particular voltage used, a feeder could be replaced with a higher voltage cable with transformers at both ends.

Thus by making the capacity of the transmission units keep pace with the increase in load density, the system would remain unchanged over a long period of time in its essential layout, would be easy to operate economically in switching, and would avoid the confusion attendant on frequent changes in system connections.

**J. W. Bennett:** (communicated after adjournment) Factors of primary importance in the development of any system of power supply, are simplicity, flexibility permitting growth without excessive obsolescence, and the selection of the proper voltage for the various parts of a system. As is, I believe, quite well understood, the design of any system is a compromise among a number of contradictory requirements. It is therefore very important that the whole system be considered in the design of any of its constituent parts.

The three systems described in the papers presented here, reveal two fairly distinct types of systems of power supply for metropolitan areas, namely the so-called close linked system as used in Chicago and Philadelphia, and the loose linked system in Detroit. Papers presented by Messrs. Kehoe, Griscom, Searing and Milne, Volume 48, A. I. E. E. Quarterly TRANSACTIONS, October 1929, describe another method of power supply to a similar area, that of a system synchronized at the load. It is to be hoped that an exchange of ideas on this rather broad subject will ultimately lead to the development of a system which, with some modifications due to local conditions, can be generally used.

There are two points in connection with power system planning to which I would like to call special attention. First: A power system should be simple. The use of complicated switching and protective equipment, while apparently justified in a great many cases, often causes more faults than it prevents. Second: Any plan for power system development should take into consideration the distribution as well as the power generation and transmission divisions. A great many of our systems are well planned, and efficient in operation, up to the secondary bus in the distribution substation. From this point on, they have been permitted to grow with scant regard for any system plan, with the result that the losses in distribution lines on many systems more than overcome the savings made in other parts of the system. There are probably more opportunities for savings through improvements in the distribution system of the average operating company than in all other parts of the system combined. It is to be hoped that operating engineers and executives will in the future, give the distribution division of the system the attention it should have by virtue of its importance as compared to the other parts of the system.

**G. M. Armbrust:** Referring to the diagram, Fig. 9, the 66-kv. system is cited as an example of part of a solidly interconnected system which may not have the degree of stability generally ascribed to such a system. However, the difference between the terms "solidly interconnected" and "loose-linked" is more or less relative. Not all the parts of the solid system need have the same degree or absolute maximum of stability, but it is intended that they be made stable under all conditions that may be imposed on the system. In the other type of interconnection, Mr. Dean does not want his linking too loose. The various degrees of stability desired are those required to meet the condition imposed by the requirements of the individual systems described and by the policy of the management regarding service standards in each system.

Mr. Moultrop brought out a good point regarding flexibility in the system design to provide for variations which may become necessary in the future. An example of this is the operation of a 220-kv. line from Powerton Station to Chicago. Referring to the diagram, Fig. 11, a 220-kv. line is to be superimposed on the 132-kv. connection between Powerton and the 66-kv. bus in Chicago. Preliminary studies of the stability of this part of the system indicate that parallel operation of these lines will be unstable and it will be desirable, at least until more lines are added, to split the bus at Powerton and operate this line "synchronized at the load" somewhat according to the principles outlined by Mr. Woodrow and used on the New York systems.

It is generally agreed that the elimination of high-tension switching equipment is desirable. However on a high-voltage system

which constitutes a bus receiving and distributing energy at various points, switches and busses may be justified by the reduction in transformer capacity otherwise required. Also on long high-voltage lines forming part of a general interconnection carrying considerable amounts of energy, the addition of high-tension switches and busses may increase the stability limit of the system by an amount sufficient to justify their use.

Regarding the reserve capacity in generators and feeders required for the system, as Mr. Kehoe says this is one of the fundamentals of reliability and system design. The requirements for reserve capacity may vary somewhat with the type of system design. In the closely linked system, such as used in Chicago, reserve capacity at any one point is available at any other point on the system without special provisions in transmission line capacity, and therefore the amount of running reserve capacity need only be equal to the largest unit in the entire interconnected system. When the system reaches considerable proportions, it may be even desirable to have reserve capacity which is more than equal to the largest unit, and this may be accomplished without the percentage reserve being unreasonable. It also becomes practicable, with the closely linked system, to install relatively larger generating units, as the capacity is available at all points rather than in any one area.

One of the principal differences between systems which has not heretofore been mentioned is that, with the loosely linked system or with the system synchronized at the load, it is either necessary to increase somewhat the capacity of transmission lines or to distribute the new and efficient generating units proportionately between the various areas. With the rigid system of interconnecting lines, one station may contain entirely efficient turbines and another station, which is the center of a different area, may contain inefficient turbines, while still permitting the maximum operating economy by the use of the best equipment at all times.

**S. M. Dean:** The opinion seems to be that "loose linking" is a kind of "touch and go" thing that may fall apart if somebody sneezes inadvertently. It isn't at all. It consists of good solid ties. These ties may be increased to something like 100,000-kv-a. total capacity if necessary. The important thing is that the reactance of the "interlinking ties" is sufficiently high so that, with a short circuit on a feeder bus, the neighboring generating stations can continue to supply their portion of the short-circuit current without serious disturbance to themselves for a period long enough to permit the switchgear in the faulty power area to clear the trouble if it is going to do so.

The matter of system reserve has been mentioned. It seems to me there are two considerations there. One is the size of generating units and the other is the number of generating units. It so happens, to speak again of Detroit's condition, we have some 24 generating units. There are enough of them so that we must assume one out for maintenance work at all times. We must therefore be ready to drop a second unit. With our 50,000 kilowatt units, that means 100,000 kilowatts total reserve plus a little more because it is not all equally available to all parts of the system. The actual total load is something over 500,000 kilowatts, so a little over 20 per cent is the minimum reserve that we can safely carry. It is evident at once that it is unwise to have too large a proportion of the total generating capacity in any one unit as it increases the necessary reserve to an abnormal amount.

I was much interested in the comments on where you synchronize the units of your system. We would do it at the customer's service voltage, if we had enough load at that voltage. Unfortunately we do not, so we must go higher in voltage to where we do have enough load and consequently enough tie facilities to hold the system together. In principle you tie together at the lowest voltage level at which you have interconnected load enough to do so. If one has enough interconnected load at a-c. network voltages to permit tying at that level, one is very fortunate.

Someone mentioned 100 per cent continuous service. That is a nice thing to talk about, but the Detroit Edison Company recognizes that there are certain classes of our load, particularly residential, which can endure an occasional one-second interruption. The Class A substations are predicated on that fact. If your lights go out when you are reading your paper the first thing you do is to sit still for a moment until you can readjust your faculties to the new condition. If your lights come on again before you can readjust yourself to the extent of falling over a neighboring rocking chair you will probably consider that as good enough service. You can trade in an occasional interruption of that kind for switchgear, and that is precisely what we did. We cut out the high-voltage switchgear and used the automatic throwover.

I heartily agree with what Mr. Stone had to say about substations being too expensive and complicated. While we first do the things which we must do to prevent general blow ups, thereafter we should do the rest of it as economically as possible. That is where electrical engineering becomes an art as well as a science—the art of making our reserve in transformers, cable capacity, etc., do two or three things instead of one.

You will note the total absence of duplicate busses and switchgear in the Detroit Edison Company's system. We spread our substation cables over the generating station bus in such a fashion that we can lose any one bus section without subtracting more than the normal reserve of cable and transformers from any substation and thereby avoid duplicate busses and switchgear.

Mr. Woodrow spoke of substations and generating stations becoming obsolete in ten years. If the substations built in the last three or four years on the Detroit Edison Company's system become obsolete in ten years I am sure a number of us will have to put on our hats and start running and I shall be one of them. If properly designed, they should have a useful life of much more than ten years. It is also a serious matter in a loosely linked system to allow generating stations to run down to a condition where they are valuable only as reserve because such reserve is not equally available to all parts of the system. There is a real urge to develop what might be called an "open end" generating station design wherein you may add a large unit at one end and remove a couple of small obsolete ones from the other end and thereby maintain a reasonably economical station continuously and one which can grow with the load in its power area.

Mr. Melvin spoke of the use of higher voltages to serve customers in the future. If you look back over the history of any of our systems, you will find we started with only 2300 volts. Some of us went to 4000 volts. Others were fortunate enough to have picked out higher voltages such as 4400 or 6600 volts to serve the customers. Gradually the loads became so big that the number of feeders became a burden, and the next thing we were serving them at 12,000 volts, 24,000 volts, or higher. We must be ready to serve our bigger, newer customers, at higher and higher voltages. That is one of the reasons why Detroit has built a few 24,000-volt switching stations throughout its system as sources of feed to very large voltage customers.

**Raymond Bailey:** I think the two authors who preceded me in closing their papers have very ably answered most of the questions brought up in the discussion. On account of the limited time, I will just make one or two remarks.

In my opinion, the terms loosely and closely linked systems are largely relative. It would appear that as a closely linked system grows it may be desirable to sectionalize large capacity transmission centers, so as to limit the magnitude of the short circuit currents, and minimize the effect of disturbances at times of faults without sacrificing the desirable characteristics of closely linked systems.

I was very much interested in Mr. Stone's remarks regarding simplicity and reduction in investment. It seems to me that these two things will logically go hand in hand. Referring to his remarks concerning operation on a temperature basis, I should

like to give two examples. In the case of our Plymouth Meeting transformer banks, which have a rating of 130,000 kv-a. when operated with forced air cooling, we carry loads as great as 150,000 kv-a. when the ambient temperature conditions are such that this can be done without exceeding the allowable transformer oil temperature. The 7500-kv-a. transformer banks in our distribution substations would be operated with loads as great as 9500 kv-a. in the event of one bank being out of service.

I note that there were no questions concerning the size of generating units and of generating stations. It seems to me that both of these matters, especially the size of the station, are very important in their relation to the over-all system investment and economy. For this reason I feel that comprehensive studies of this matter in the future are well worth while.

# Transoceanic Telephone Service—General Aspects

BY T. G. MILLER[1]
Associate, A. I. E. E.

*Synopsis.—The extent of transatlantic telephone service and its growth since its inception in 1927 are outlined in this paper.*

*It is pointed out that at the present time 85 per cent of the world's telephones are included in the area served and about 50 calls are made per business day. Analysis is given of the calls with respect to distribution by countries, by time of day, and by kind of message. The volume of calls, the rates, and a general indication of the quality of transmission are given. Plans for future extensions of the service are outlined.*

* * * * *

COMMERCIAL telephone service between the United States and Europe was initiated January 7, 1927 over one radio circuit, using long waves (about 5000 meters) and with the circuit terminals at New York City and London, England. Two papers[2] were presented at the Winter Convention of the Institute in February, 1928, on the subject of Transatlantic Telephony, and these outlined the situation as it stood then, after one year's experience with this new telephone service.

There has been a rapid and consistent growth in both the scope and volume of this overseas telephone service, which has clearly demonstrated that such service has a permanent and important place in international communications. It is the purpose of this paper to review briefly the changes in the character and extent of the service that have been made since the presentation of the papers referred to and to consider certain general aspects of the service as now furnished.

The initial long-wave radio circuit has now been supplemented by three radio circuits which operate at short wavelengths ranging from approximately 12 to 50 meters and which terminate at New York and London. In addition to the European service, arrangements have been made for establishing telephone service early this year between the United States and points in South America by the use of a short wave radio telephone circuit with terminals at New York and Buenos Aires. These new short-wave systems are discussed in three papers to be presented at this meeting by Messrs. Bown, Oswald, and Cowan.

The whole of England and Scotland, Dublin and Belfast in Ireland, most of the important cities and countries in Europe, and one point in Africa, are now within reach of telephone users in the United States, Canada, Cuba, and Mexico. The number of points between which the service is available is continuously increasing, as new points and even whole new countries are added from time to time as the necessary arrangements are made. Very soon after the inauguration of the telephone service between New York and London, this service was made available to telephone users in all parts of the United States. Soon thereafter extensions were made to Canada, Cuba, and Mexico. In Europe the extensions have closely followed the development of the continental connections centering at London, which is still the European terminal of the transatlantic telephone circuits. Among the more important European extensions was the opening of service to France and Germany. The shaded areas on the map shown in Fig. 1 indicate those sections of the overseas world which could be reached by telephone from the United States, Canada, Cuba, and Mexico at the end of 1929. Twenty countries, with a population of about 400 million and with eighty-five per cent of the world's telephones, were included within the area served on both sides of the Atlantic. The next major development expected will be the connection to this network of a substantial part of South America by the inauguration of telephone service over the New York-Buenos Aires circuit mentioned above.

For the year 1929, the distribution of the transatlantic calls by countries at the European end was about as follows:

England, 52 per cent; France, 32 per cent; Germany, 8 per cent; other countries, 8 per cent.

Although the daily service period was limited at the start by the restriction of the hours for telephone use of the Rugby transmitting station in England, it later became possible to extend the hours so that in the spring of 1928 the service was available about 10½ hours each business day. As the demand for the service increased and additional channels became available to increase the reliability of the service at times when atmospheric conditions were unfavorable, still further extensions were made in the hours of service. The chart in Fig. 2 shows graphically the changes in the hours of service which have been made. Since September 10, 1929 the service has been available on a 24-hour day basis.

The changes that were made in the hours of opening this service in the morning are due in part to changes in London and New York to the daylight saving plan.

The service is in greatest demand during those periods of the day in which the business hours in America and

1. General Manager, American Telephone and Telegraph Co. Long Lines Department, New York, N. Y.

2. K. W. Waterson and O. B. Blackwell. A. I. E. E. JOURNAL, April and May, 1928, respectively.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*



30-40

Europe overlap, although the tendency of this traffic to peak in these hours is not as great as might be expected. It is an interesting fact that even with a time difference of five or more hours, which leaves only a few overlapping business hours, the hour by hour demand for the transatlantic telephone service displays quite the same characteristics as generally comparable long distance telephone traffic in this country. Fig. 3 shows the distribution by hours of the transatlantic traffic and for purposes of comparison the distribution of other person-to-person traffic originating at New York. The remarkably close agreement may be explained in part by the fact that the usual business hours in this country correspond to the afternoon and evening in Europe, at which times there seems to be the greatest demand for transatlantic telephone facilities for conducting business and for social conversations.

The basic rate from New York to London is at present $45 for three minutes with slight additions for extensions in Europe or America. The initial rate of $75 was reduced to the present level on March 4, 1928 and this was, of course, responsible for some growth in business. The messages per day, averaged monthly, increased from 13 in February 1928 to 45 in May, only three months after the rate reduction, although part of this increase was due to additional points reached by the service during this period.

The volume of business offered in the European service has grown rapidly. From a start of only a few messages each day in 1927, it has grown until during 1929 the average was close to fifty messages per business day. Fig. 4 shows this graphically. The largest number of messages handled in any one day to date was 139. Aside from the seasonal variations which usually result in a falling off of business during the summer, and the drop following the opening due to the falling off of calls placed partly out of curiosity, the trend has shown a consistent increase. Some of the factors

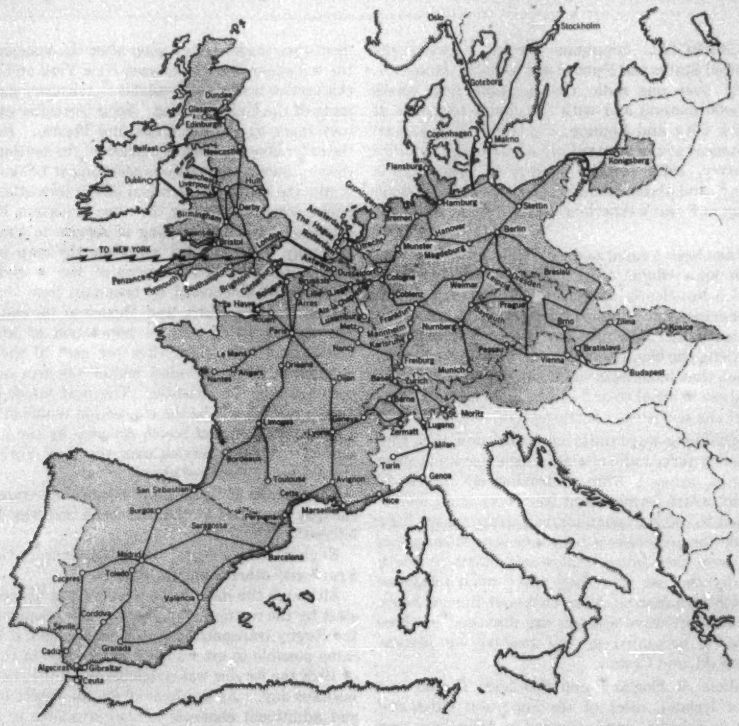



FIG. 1—MAP SHOWING AREAS REACHED BY TRANSATLANTIC TELEPHONES DURING THE YEAR 1929

contributing to this, other than the changes in rates, are the improvements in transmission and speed of completing connections, the increase in points within reach of the service, the extension of service hours, and an increasing appreciation by the public at large of the value of this service.

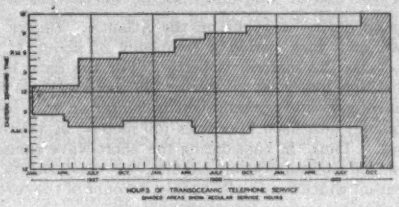



Fig. 2

As to the nature of the business handled, social calls seem to make up a large percentage of the transatlantic telephone traffic. The actual percentages of the business which may be classified as social, business, or otherwise, are as follows:

Social, 48 per cent; Bankers and Brokers, 27 per cent; Merchants, 4 per cent; Miscellaneous 21 per cent. It should be appreciated that there may be some inaccuracy in this classification, since it is largely based on the location of the called and calling telephones.

With connections as long as those involved in transatlantic service, and with circuits subject to the transmission variations inherent in radio, there is a likelihood that some atmospheric or other conditions will cause momentary interference to conversation. The

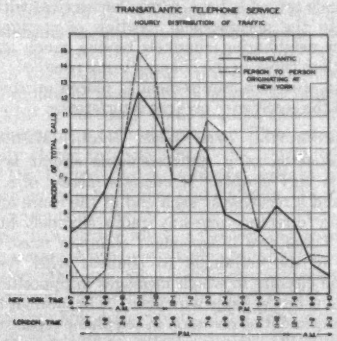



Fig. 3

results of transmission observations on New York-Great Britain traffic for the month of September 1929 are shown on Fig. 5. It will be noted that there were only about 5 per cent of the messages on which there were sufficient adverse reactions to result in less than 75 per cent of the elapsed time from beginning to end of the connection being chargeable.

As mentioned before, the scope of the transatlantic telephone service has been broadened by extensions from time to time to contiguous areas in both Europe

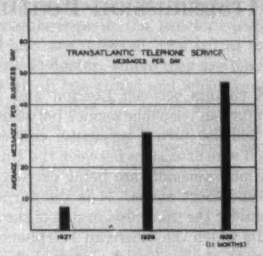



Fig. 4

and America. Further extensions by land lines can be expected to areas not now served, but it appears that in so far as the United States is concerned, because of the wide scope of the present land line system, the major extensions to new areas will, of necessity, be by means of new overseas services. Among these are the proposed telephone connection to South America and the ship-to-shore radio telephone service recently inaugurated. To strengthen further the ties already made, there is a comprehensive program under way which includes a transatlantic telephone cable and a second long-wave transatlantic circuit. Additional short-wave channels to Europe and South America may be added, if required by future developments of the business, and it is to be expected that telephone service to other countries will be established from time to time, as may be justified by the requirements for this form of communication.

The technical means to make this possible are now largely available, but, of course, other factors such as economic considerations must be taken into account.

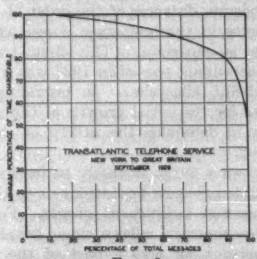



Fig. 5

While continuous and consistent progress is looked for, the ideal of a world-wide telephone service operating on a comprehensive and commercial basis and with a high degree of reliability is something which must be approached gradually and with patience.

## Discussion

For discussion of this paper see page 643.

# Transoceanic Telephone Service—Short-Wave Transmission

## Transmission Features of Short-Wave Radio Circuits

BY RALPH BOWN[1]

Non-Member

TRUNK circuits between London and New York which furnish telephone service between these two cities and also permit successful conversation by means of toll wire extensions between the United States and Europe more generally are being carried over both long waves and short waves. It is the purpose of this paper to consider the transmission side of the new short-wave circuits which the American Telephone and Telegraph Company and the British General Post Office have made available for this service. In doing this we shall proceed from the more general considerations, relating to wavelengths and communication channels, through a discussion of the principles governing the general design of the system, into a brief summary of practical performance results.

The frequency range so far developed for commercial radio use is roughly 20 to 30 million cycles wide, extending from about 10 kilocycles to perhaps 25,000 kilocycles per second. There are two parts of this whole spectrum suitable for transoceanic radiotelephony—the long-wave range which is relatively narrow, extending roughly from 40 kilocycles to 100 kilocycles, and the short-wave range which in its entirety is much broader, extending from about 6000 kilocycles to 25,000 kilocycles.

It is evident that the long-wave region, including perhaps only 50 kilocycles, offers opportunity for development of relatively few telephone channels, particularly in view of the fact that it is in use by a number of telegraph stations. Also it must be borne in mind that for telephony these waves are suitable for only moderate distances of the order of 3000 miles and for routes in the temperate zones where static interference is moderate. The first transatlantic radiotelephone circuit opened in 1927 was a long-wave circuit (58.5-61.5 kilocycles). In providing the next few channels for the initial growth of the service the opportunity to determine the utility of short waves was embraced.

The short-wave range is vastly wider in kilocycles but, nevertheless, has its limitations as to the number of communication facilities it affords. For a given route of a few thousand miles a single frequency gives good transmission for only a part of the day. For example, from the United States to Europe a frequency of about 18,000 to 21,000 kilocycles (17 to 14 meters) is good during daylight on the Atlantic. But in the dawn and dusk period a frequency of about 14,000 kilocycles (22 meters) is better. For the dark hours something like 9000 kilocycles (33 meters) gives best transmission and for midnight in winter an even lower frequency near 6000 kilocycles (50 meters) is advantageous. Thus, in considering the short-wave range in terms of communication circuits, we must shrink its apparent width materially to take account of the several frequencies required for continuous service.

At the present time the frequency spaces between channels are much greater than the bands of frequencies actually occupied by useful transmission. This elbow room is to allow for the tendency of many stations not to stay accurately on their nominal frequencies but to wander about somewhat. But in spite of this allowance, cases of interference are common and one of the activities which must be carried on in connection with a commercial system is the monitoring of interfering stations and the accurate measurement of transmitting frequencies to determine the cause of the conflict. To permit intensive development of the frequency space offered by Nature the greatest possible constancy and accuracy of frequency maintenance in transmitting sets will be required.

The fact that channels have been assigned (within wide bands set aside for a particular service) with little regard to the geographical location of stations may result in neighboring channels having much stronger signals than those in the channel being received. When this is so, a severe requirement is placed on the selectivity of the receiver to prevent interference.

### Interconnecting with Wire Circuit Extensions

The skeleton of a radiotelephone circuit is in its essentials very simple. It consists merely of a transmitter and a receiver at each end of the route and two oppositely directed, one-way radio channels between them. These two independent channels must be arranged at the terminals to connect with two-wire telephone circuits in which messages in opposite directions travel on the same wire path. The familiar hybrid coil arrangement so common in telephone repeaters and four-wire cable circuits might appear to solve this problem, were there not difficulties peculiar to the radio channels. In the short-wave case large variations in attenuation occur in the radio paths within short intervals of time. These would tend to cause re-transmission of received signals at such amplitudes that

1. Department of Development and Research, American Telephone and Telegraph Company, New York, N. Y.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

severe echoes and even singing around the two ends of the circuit would occur unless means were provided to prevent this.

To overcome these fundamental transmission difficulties, an automatic system of switches operated by the voice currents of the speakers has been developed.[2] These devices cut off the radio path in one direction while speech is traveling in the reverse direction and also keep one direction blocked when no speech is being transmitted. The operation is so rapid that it is unnoticed by the telephone users. Since this system prevents the existence of singing and echo paths, it permits the amplification to be varied at several points almost without regard to changes in other parts of the system, and it is possible by manual adjustment to maintain the volumes passing into the radio link at relatively constant values, irrespective of the lengths of the connected wire circuits and the talking habits of the subscribers.

Fig. 1 gives a schematic diagram of the United States end of one of the short-wave circuits showing the

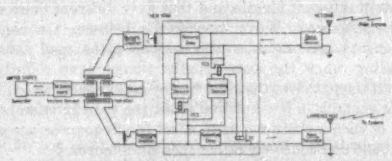


Fig. 1—Circuit Diagram Illustrating Operation of Voice-Operated Switching Device

essential features of a voice-operated device which has been used. This kind of apparatus is capable of taking many forms and is, of course, subject to change as improvements are developed. The diagram illustrates how one of these forms might be set up. This form employs electro-mechanical relays. The functioning of the apparatus illustrated is briefly as follows: the relay TES is normally open so that received signals pass through to the subscriber. The relay SS is normally closed to short circuit the transmitting line. When the United States subscriber speaks his voice currents go into both the Transmitting Detector and the Transmitting Delay circuit. The Transmitting Detector is a device which amplifies and rectifies the voice currents to produce currents suitable for operating the relays TES and SS which thereupon short circuit the receiving line and clear the short circuit from the transmitting line, respectively. The delay circuit is an artificial line through which the voice currents require a few hundredths of a second to pass so that when they emerge the path ahead of them has been cleared by the relay SS. When the subscriber has ceased speaking the relays drop back to normal.

2. For detailed description of this system see "The New York-London Telephone Circuit" by S. B. Wright and H. C. Silent, *Bell System Tech. Jl.*, Vol. VI, October, 1927, pp. 736-749.

The function of the Receiving Delay circuit, the Receiving Detector, and the relay RES is to protect the Transmitting Detector and relays against operation by echoes of received speech currents. Such echoes arise at irregularities in the two-wire portion of the connection and are reflected back to the input of the Transmitting Detector, where they are blocked by the relay RES which has closed and which hangs on for a brief interval to allow for echoes which may be considerably delayed. The gain control potentiometers shown just preceding the transmitting and receiving amplifiers are provided for the purpose of adjusting the amplification applied to outgoing and incoming signals.

The relief from severe requirements on stability of radio transmission and from varying speech load on the radio transmitters which this system provides permits much greater freedom in the design of the two radio channels than would otherwise be possible.

## The Radio Channels

One of the first questions which comes up in considering the design of a radio system is the power which can be sent out by the transmitter. The word "can" is used advisedly, rather than "should," since in the present art the desideratum usually is the greatest amount of power that is technically possible and economically justifiable. There are few radio systems so dependable that increased power would not improve transmission results. At very high frequencies the generation of large powers is attended by many technical difficulties but fortunately the radiation of power can be carried out with much greater efficiency than is feasible at lower frequencies. At 18,000 kilocycles (about 16 meters) a single half-wave radiator or doublet is only about 25 ft. long and it is possible to combine a number of them, driven in phase by a common transmitter, into an antenna array which concentrates the radiated power in one geographical sector. In that direction the effectiveness may be intensified 50 fold or more (17 db.) and waste radiation in other directions reduced materially. Thus, one of the transmitters at Lawrenceville, New Jersey, used in the short-wave transatlantic circuits when supplying 15 kw. radiates in the direction of its corresponding receiving station as effectively as would a non-directive system of about 750 kw.

The transmitting antennas also give some directivity in the vertical plane, increasing the radiation sent toward the horizon and decreasing that sent at higher angles. It is not yet certain that vertical directivity is always advantageous and this effect has not been carried very far.

At the receiving station the radiated power has dwindled to a small remnant which must be separated from the static as far as possible and amplified to a volume suitable for use in the wire telephone plant. Here again directive antenna arrays are of value. A receiving antenna system sensitive only in a narrow

geographical sector, and that lying in the direction from which the signal arrives, excludes radio noise from other directions and thereby scores a gain of perhaps 40 fold (16 db.) in the power to which the signal can be amplified without bringing noise above a given value. It also scores against noise which arises in the tubes and circuits used for amplification, since the combined action of the several antennas of the array delivers more signal to the initial amplifier stage where such noises originate.

Thus, it is evident that transmitter power, transmitting directivity, receiving directivity, and quiet receiving amplifiers are of aid in providing signal transmission held as far as possible above the radio noise. In a well designed system the relative extents to which these aids are invoked will depend upon economic considerations as well as upon the technical possibilities of the art.

There is one other type of noise than that provided by Nature which is of particular importance at short waves,—electrical noise from the devices of man. One of the worst offenders is the ignition system of the automobile. The short-wave transoceanic receiving station at Netcong, New Jersey, is so located that automobile roads are at some distance, particularly in the direction from which reception occurs. Service automobiles which produce interference cannot be allowed near the antenna systems unless their ignition systems have been shielded. Also, electrical switching and control systems incidental to the power, telegraph, and telephone wire systems at the station are shielded or segregated.

At both the transmitting and receiving stations at least three antenna systems are supplied for each circuit, one antenna for each of the three frequencies normally employed. The design and arrangement of these are dictated by the requirements flowing from their uses. The purpose of the transmitting antenna is to concentrate as much power as possible in one direction. The purpose of the receiving antenna is to increase reception from the desired direction and to cut down reception at all other angles. In the former the forward-looking portion of the characteristic is of greatest importance, while in the latter the rearward characteristics need greatest refinement.

## Transmission Performance

In short-wave telephone systems the width of the sidebands is so small a percentage of the frequency of transmission that tuning characteristics of the antennas and high-frequency circuits are relatively broad and impose little constriction on the transmission-frequency characteristic. A flat speech band is easy to obtain over the range of approximately 250 to 3000 cycles employed for these commercial circuits. This relieves the short-wave circuits from many of the problems of obtaining sufficient band width which are troublesome in designing long-wave systems.

Short-wave transmission is subject to one frailty which particularly hampers its use for telephony. This is fading. Where fading is of the ordinary type, consisting of waxing and waning of the entire transmitted band of frequencies, automatic gain control at the receiving station is of value and is employed in the transoceanic circuits under discussion. The amplification in the receiver is controlled by the strength of the incoming carrier and is varied inversely with this strength so as to result in substantially constant signal output. Obviously this control can be effective only to the extent that the signal seldom falls low enough to be overwhelmed by radio noise.

When fading is of the selective type, that is, the different frequencies in the transmitted band do not fade simultaneously, the automatic gain control system is handicapped by the fact that the carrier or control signal is no longer representative of the entire signal band.

Selective fading is believed to result from the existence of more than one radio path or route by which signals travel from transmitter to receiver. These paths are of different lengths and thus have different times of transmission. Wave interference between the components arriving over the various paths may cause fading when the path lengths change even slightly.

If the path lengths differ by any considerable amount, for example, a few hundred miles, the wave interference is of such a character as to affect the frequencies across a band consecutively rather than simultaneously.

With the presence of selective fading there comes into being the necessity of guarding against rapid even though small variations in the transmitted frequency, since if such variations are present a peculiar kind of quality distortion of the telephone signal results.

The varying load which speech modulation places on the transmitter circuits tends to cause slight variations in the instantaneous equivalent frequency which are known as "frequency modulation" or "phase modulation" depending on their character. To prevent this effect the control oscillator must be carefully guarded against reaction by shielding and balancing of circuits and the design must be such as to preclude variable phase shifts due to modulation in subsequent circuits of the transmitter.

It is apparent that if there are two paths of different lengths, two components which arrive simultaneously at the receiver may have left the transmitter several thousandths of a second apart. If the transmitter frequency has changed materially during this brief interval trouble may be expected. The trouble actually takes the form of a distortion of the speech as demodulated by the receiving detector.[3]

Defects in short-wave transmission due to radio noise, minor variations in attenuation, fading, and distortion are nearly always present to some extent and,

3. For a discussion of this phenomenon see "Some Studies in Radio Broadcast Transmission" by Bown, Martin, and Potter, *I. R. E. Proc.*, Vol. 14, No. 1, p. 57.

when any or all are severe, cause a certain amount of lost service time. These interruptions are of relatively short duration and, furthermore, there is enough overlap in the normal times of usefulness of the several frequencies available, so that shifting to another frequency may give relief. There is, in addition, a kind of interruption which from the standpoint of continuity

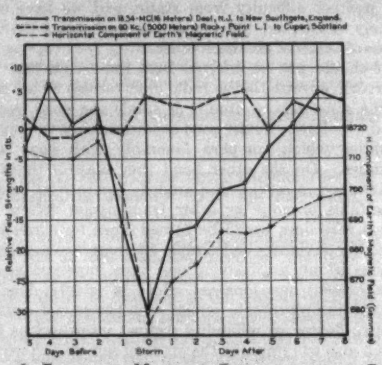



FIG. 2—EFFECT OF MAGNETIC DISTURBANCES ON RADIO TRANSMISSION

of service is more serious. At times of disturbance of the earth's magnetic field, known as "magnetic storms," short-wave radio transmission is generally subject to such high attenuation that signals become too weak to use and sometimes too weak to be distinguishable. These periods affect all the wavelengths in use and may last from a few hours to possibly as much as two or three days in extreme cases. They are followed by a recovery period of one to several days in which transmission may be subnormal.

Severe static may cause interruption to both long- and short-wave services at the same time but the short waves are relatively less affected by it and are usually able to carry on under static conditions which prevent satisfactory long-wave operation. On the other hand severe fading or the poor transmission accompanying a magnetic disturbance may interrupt short-wave service without affecting the long waves adversely,—in fact magnetic disturbances often improve long-wave transmission in the daytime. The service interruptions on the two types of circuits are thus nearly unrelated to each other and have no definite tendency to occur simultaneously. This is the principal reason why both long-wave circuits and short-wave circuits appear essential to reliable radiotelephone service.

On routes which are very long or which cross tropical areas which result in static sources facing the directive receiving antennas, long waves cannot as yet be successfully employed and short waves alone are available. However, experience tends to indicate that on North and South routes such as between North and South America, the interruptions associated with magnetic storms are less severe and of shorter duration.

The cycle of events which accompanied a particularly severe magnetic storm[4] in July, 1928, is shown graphically in Fig. 2. The light dotted curve shows the variation in the horizontal component of the earth's field. The heavy solid line follows the daily averages of the short-wave received signal field. It is apparent that the disturbance took two days to reach its peak and

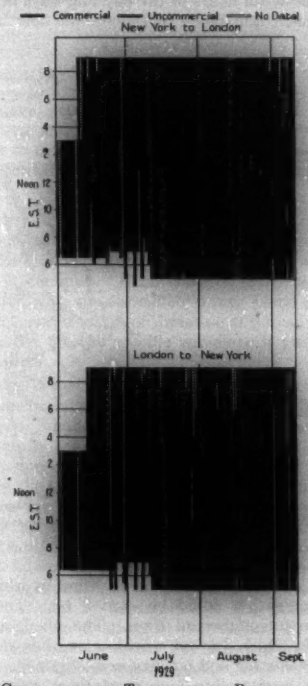



FIG. 3—CHART SHOWING TRANSMISSION PERFORMANCE OF A SHORT-WAVE TRANSATLANTIC TELEPHONE CIRCUIT

the recovery to normal took nearly a week. The heavy dotted line shows received field on long waves (60 kilocycles) and indicates that transmission was improved slightly at the same time the short waves were suffering high attenuation.

The experience with transatlantic telephone service on short waves covers a period of nearly three years,

4. Data regarding other magnetic disturbances are given in a paper by C. N. Anderson, entitled "Notes on the Effect of Solar Disturbances on Transatlantic Radio Transmission," *I. R. E. Proc.*, Vol. 17, No. 9, September, 1929.

there having been available a one-way channel from the United States to England used as an emergency facility for the first year and a half, a two-way circuit for the next year, and two circuits since June, 1929. It is only in this later period, however, that a circuit has been available operating regularly with the amounts of transmitter power and antenna directivity which have been mentioned.

The performance of the two one-way channels forming this circuit is charted in Fig. 3. The charts are plotted between hours of the day and days in the year so that each unit block represents one hour of service

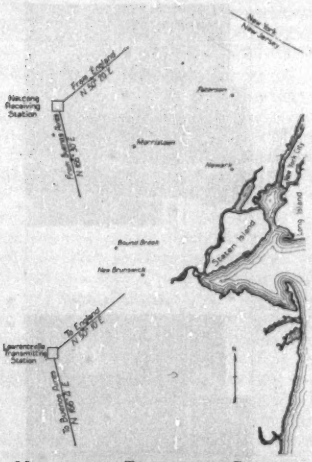



FIG. 4—MAP SHOWING TRANSMISSION CONSIDERATIONS AFFECTING LOCATION OF STATIONS

time. The solid black areas are time in which commercial operation could be carried on. The dotted strips are uncommercial time. The blank areas are for time in which, for one reason or another, the circuit was not operating and no data were obtained. Perhaps the most outstanding feature of these charts is the tendency of the lost time to fall in strips over a period of two or three days. These strips coincide approximately for both directions of transmission. The principal ones are about July 10, 15 and August 2 and 17. These are characteristic of the interruptions accompanying magnetic disturbances of the kind which occur at irregular intervals of a few days to several weeks. They are, of course, not as severe as the disturbance illustrated in Fig. 2.

It is apparent that for these three summer months this new circuit gave a good account of itself and furnished commercial transmission for something like 80 per cent of the time that service was demanded of it. In these same months the long-wave system suffered its greatest difficulty from static, and we have concretely illustrated the mutual support which the two types of facilities give each other.

It should not be inferred from these data that the short-wave transatlantic radio links furnish 80 per cent of the time talking circuits as stable and noise free as good wire lines. Under good conditions they do provide facilities which compare favorably with good wire facilities. On the other hand they may at times be maintained in service and graded "commercial" under conditions of noise or other transmission defects for which wire lines would be turned down for correction, since the obviously undesirable alternative is to give no service at all until conditions have improved again. The present development effort is largely directed toward improvements which will insure not only a greater degree of reliability against interruptions but which also will improve the grade of service as a whole.

In the foregoing little has been said about the stations and plant since a description of these and the operation of them are treated in two companion papers by Messrs. Cowan and Oswald. It may be well, however, to view the physical scene broadly as set forth on the accompanying map, Fig. 4.

The geographical arrangement of the transmitting and receiving stations was governed among other things by transmission considerations. The two stations were placed about 50 miles apart because this is approximately the distance for minimum signal and at a lesser or greater distance the signals from the American transmitter might be strong enough to offer some interference to receiving the English or South American stations on adjacent channels. For the same reason they were placed at considerable distances from the transmitters and receivers of other communication agencies. The Netcong receiving station lies to the north of the Lawrenceville transmitting station so as not to be in paths of strong signals from the directive antennas which face northeast toward England and southeast toward South America. This configuration also places the transmitter outside the sensitive angles of the directive receiving antennas.

## Discussion

For discussion of this paper see page 643.

# Transoceanic Telephone Service—Short-Wave Equipment

## Technical Features of the New Short-Wave Radio Stations of the Bell System

A. A. OSWALD*
Member, A. I. E. E.

*Synopsis.—The application of short-wave radio transmission to transoceanic telephone circuits is developing apparatus and stations designed specifically to meet the needs of these services. This paper describes from the radio point of view the important technical features and developments incorporated in the new transmitting and receiving stations of the American Telephone and Telegraph Company located respectively at Lawrenceville and Netcong, New Jersey, and it outlines some of the radio problems encountered in the station design.*

* * * * *

SHORTLY after transatlantic telephone service was opened in January, 1927 the long-wave radio circuit between New York and London was supplemented, first by an experimental short-wave radio link in the west-east direction and later by a short-wave link in the east-west direction.[1] From this beginning, as an auxiliary to the long-wave circuit, the short-wave system has been improved steadily so that its average performance throughout the year now more nearly approaches that of the long-wave system and it has become an important part of the transoceanic facilities. The relative merits of the two systems, their combined usefulness, and their transmission features are the subject of another paper and will not be discussed here.[2] For the present purpose it will be sufficient to note that there are now in operation between New York and London, one long-wave and three short-wave two-way circuits and that within a few weeks a short-wave circuit will be available between New York and Buenos Aires.

The radio transmitting units for the New York end of these four circuits are located at the new station which the American Telephone and Telegraph Company has recently established at Lawrenceville, New Jersey. The receiving units are concentrated at Netcong, New Jersey. The factors entering into the selection of these station locations are outlined in another paper[3] and therefore need not be mentioned further. This paper is limited in scope to a necessarily brief description of the transmitting and receiving systems and apparatus, a discussion of technical features in the station layouts, and an outline of the major problems encountered in the station design. Comprehensive treatment of individual units is properly left for other entire papers. It will be convenient to deal with the transmitting and receiving stations separately and in each case to consider briefly the system and apparatus of one channel before describing the general station plan.

### Transmitting System

The four channels at Lawrenceville are equipped with independent transmitters using certain auxiliary apparatus in common. Each channel involves a radio transmitter with its associated power plant and wire equipment, and a group of directive antennas designed and adjusted for the specific wavelength assignments of the channel.

The general method of transmission, with the exception of directional sending, is the same as that employed for program broadcasting stations in that the radiated signal contains the carrier and both sidebands. Systems in which one or more of these components are suppressed at the transmitter appear to offer further means of improving short-wave transmission, and the necessary apparatus for the practical application of such systems when operating at frequencies in the order of 20,000 kilocycles is undergoing development. However, throughout the development of the transmitters as now installed at Lawrenceville the possibility of future major modifications in the method of transmission has been kept in mind. For this reason the modulator-amplifier system was adopted. In this system the signal which is to be radiated, is prepared by modulation processes at relatively low power levels and thereafter amplified the requisite amount. The amplifier and its power plant, representing a large proportion of the investment in equipment, can be continued in service with no appreciable alterations, even though the system of transmission and the modulating apparatus undergo radical changes.

The general scheme of transmission is shown in Fig. 1. After passing through the line terminal and control apparatus, which includes standard repeaters, the voice currents are further amplified and employed to modulate

*Bell Telephone Laboratories, New York, N. Y.

1. O. B. Blackwell, A. I. E. E. Journal, Vol. XLVII, pp. 369-373, May 1928.
2. R. Bown, page 624.
3. F. A. Cowan, page 638.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

the plate voltage of an oscillator consisting of two 250-watt tubes connected in a push-pull circuit and oscillating at the frequency of the carrier which is to be transmitted. The frequency of such an oscillator, if not carefully controlled, will wander outside of the assigned frequency band, thus causing interference with other services and it will also suffer variations during the modulation cycle which contribute to fading phenomena encountered at the distant receiving

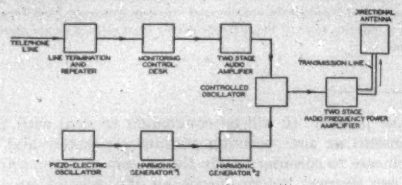



Fig. 1—Block Schematic of Transmitting System

station. In order to reduce these effects the oscillator is held in step at the desired carrier frequency by means of a second oscillator which is electrically removed from the reactions normally influencing and tending to vary the frequency of the controlled oscillator. Every precaution is taken to maintain accurately the frequency of the second oscillator and among other things it is governed by a piezo-electric quartz crystal whose temperature is regulated closely.

Since it is impractical to use crystals cut sufficiently thin to oscillate directly at frequencies in the range 10,000 to 20,000 kilocycles, thicker crystals of lower frequency are used in combination with harmonic generators which multiply the crystal frequency first by two or three and then by one or two as the case requires. By virtue of the wide differences between the input and output frequencies of the harmonic generators these intermediate steps tend to isolate the crystal oscillator from the other radio circuits and thus aid in stabilizing the frequency.

The modulated radio frequency output of the controlled oscillator is applied to the grids of a two-stage power amplifier employing water-cooled tubes designed for operation at these frequencies. The first stage contains two tubes and the second stage contains six. The tubes are arranged in push-pull circuits, the entire system being carefully balanced to ground. The carrier output power from the last stage is 15 kw. With 100 per cent modulation this corresponds to 60 kw. at the peaks of the modulation cycle. In other words, a radio telephone amplifier of this type, rated at 15 kw. when provided with a sufficiently large d-c. power source, could be used as a 10,000-kilocycle continuous wave generator of 60 kw. capacity.

The radio signal delivered by the amplifier is conveyed to the antenna by means of a 600-ohm open wire transmission line. The antenna itself is both a very efficient radiator and a highly directive one.

### Transmitting Equipment

At the transmitting station the apparatus for each channel comprises, (1) wire terminal equipment and repeaters, (2) a voice frequency control desk, (3) the radio transmitting set containing the oscillators, modulators, and power amplifier, (4) a power control board, (5) rectifying apparatus and filters for supplying direct current at 10,000 volts, (6) motor-generators for providing various circuits with direct current, (7) water circulating pumps, tanks, and cooling units.

The wire terminal equipment and repeaters at the transmitting station are standard units mounted on relay racks beside the voice frequency testing apparatus common for all channels.

The voice frequency control desk provides facilities by which the attendant can monitor the incoming voice currents and the outgoing radio signal. Means are provided for observing the volume of these signals. Oscillators are provided for the purpose of quickly checking the performance of the system during line-up periods and for sending Morse signals over the radio link when required. The control desk is also equipped with apparatus for direct telegraph communication with the technical operator at New York.

The radio transmitter consists of seven independently shielded units mounted on a common sub-base to form a single assembly, 4 ft. by 20 ft. by 7 ft. high. Some of the units are subdivided into several small shielded compartments. Very effective electrical screening or shielding between the various parts of a short-wave transmitter is essential. Otherwise stray fields introduce unwanted feedback couplings which produce

Fig. 2—Front View of Short-wave Radio Transmitter of Type used at Lawrenceville

distortion effects and spurious oscillations. Fig. 2 is a front view of the transmitter. Beginning at the left there are two units for speech amplification, one for radio frequency generation and modulation, one unit each for the first stage, the interstage circuit, and the last stage of radio-amplification, and a double-sized unit for the output circuit. It is interesting to note that the over-all length of this assembly is as much as five-eighths of a wavelength at the highest frequency in its operating range, which is 9000 to 21,000 kilocycles. Each transmitter is required to operate at

several assigned frequencies within this range and to change in a few minutes from one to another. This is done by changing coils and varying condensers in the oscillator and amplifier circuits and switching to different quartz crystals. Except in cases where two assigned frequencies are in harmonic relationship, it is necessary to provide a crystal for each of the frequencies. The crystals are mounted in an oven and continuously maintained at 50 deg. ± 0.05 deg. cent. by recording regulators. In order to avoid long interruptions to service in the event of a crystal failure or other circumstance requiring the opening of the oven and the subsequent re-establishment of temperature equilibrium, the ovens and crystals are provided in duplicate.

The electrical problems which are encountered by the engineer designing a power amplifier for these high frequencies arise largely from the inherent stray or distributed capacities and inductances which are far less important at lower radio frequencies. For example, between the anodes of the amplifier circuit there exist capacities, which are composed of capacities within the tube itself, the direct capacities between the tube water jackets and mounting plates and the like. The total value of this composite capacity in the last stage is approximately 100 m. m. f. This value cannot be appreciably reduced by any change in design which now seems desirable. The reactance of 100 m. m. f. at 20,000 kilocycles is about 80 ohms. Thus the engineer is confronted at the outset with a generator (the tubes) which has an internal impedance in the order of 2000 ohms but across whose terminal is shunted inherently an 80-ohm reactance. Fortunately, this obstacle can be surmounted by introducing resonance effects but nevertheless it places very important limitations on the design of the associated circuits. These problems become more difficult with increase of either power or frequency. Increase in power requires higher voltages and currents and thus larger elements, spaced farther apart. The augmented bulk increases both stray capacities and unwanted inductance of leads. Higher frequencies increase the magnitude and therefore the relative importance of these effects.

The power control board has nine panels equipped with the necessary instruments and apparatus for controlling and distributing all power to the transmitter. The motor-generators, pumps, fans, oil circuit breakers, and other apparatus are remotely controlled from this point. A system of relays and signal lamps provides protection and indicates the location and general nature of any trouble. With the exception of the application of high-voltage direct current, the entire system starts up and shuts down in the proper sequence in response to the manipulation of a master control switch.

Direct current at 10,000 volts is supplied to the anodes of the power amplifier tubes by a transformer and rectifier using six standard two-electrode thermionic tubes. The rectified current is filtered separately for each stage of the amplifier. This is necessary to prevent distortion by interstage modulation caused by the common impedance of the rectifier. Effects of this nature become important as the requirements placed on unwanted modulation products become more stringent.

## Transmitting Antennas

The antennas at Lawrenceville all have comparatively sharp directional properties. Such antennas are readily realized when dealing with radio waves of very short wavelengths. Although the fundamental principles involved in producing these directional effects have been known for many years, economic limitations effectively prevented their application to transmitting antennas for long wavelengths. These limitations are altered immensely in the case of antennas for short wavelengths and, when the useful propagation properties of short waves became known, great stimulus was given to the development of antennas for directional sending and receiving. The same type of antenna can be used, of course, for both purposes but, since the objectives when sending and receiving are somewhat different, the tendency has been to develop arrangements adapted to each case.

Directional transmission is a very large subject and will only be touched upon sufficiently to describe in a very general way the antennas at Lawrenceville. There are many possible arrangements and combinations and the engineers must choose from these the ones most suitable for their purpose. In general all of the schemes depend upon producing interference patterns which increase the signal intensity in the chosen direction and reduce it to comparatively small values in other directions.

One of the methods of obtaining a sharply directive characteristic is to arrange a large number of radiating elements in a vertical plane array, spacing them at suitable distances and interconnecting them in such a manner that the currents in all the radiating members are in phase. A simple way of accomplishing this result and the one which is now being employed at Lawrenceville depends upon the manner in which standing waves are formed on conductors. It is generally known that current nodes and current maxima will recur along a straight conductor whose length is an exact multiple of one half the wavelength of the exciting e. m. f. and that the phase difference between successive current maxima is 180 deg.[4] Such a conductor when folded in a vertical plane as shown in Fig. 3 and with its length adjusted slightly to compensate for the effects of folding, satisfies the aforementioned requirements for producing directional radiation. The arrows in Fig. 3 indicate the relative directions of current flow and the dotted line indicates the current amplitudes along the conductor. It will be noted that the instantaneous currents in all

4. This assumes of course that the conductor is in space free from objects affecting its electrical properties and that the ends are free or properly terminated to produce reflections.

the vertical members are in the same direction and that in the cross members their directions are opposed. Due to these current relations and the physical positions of the elements, the cross members radiate a negligible amount of energy whereas the vertical members combine their effects for the directions perpendicular to the plane of the conductor. In other directions destructive interference reduces the radiation from the vertical members. The system is equivalent to four Hertz

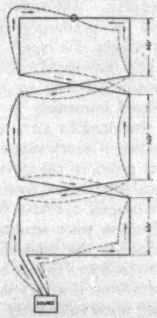


Fig. 3—Conductor Bent to Form One Section of Simple Directive Antenna

The type used for transmitting at Lawrenceville

oscillators driven in phase, and arranged in two groups one half wavelength apart, the two oscillators of each group being placed one above the other. Both computation and experiment have shown that with this system of radiation there is an improvement of approximately 6 db. In other words the same signal intensity in the chosen direction is obtained with one-fourth of the power required by a one-element radiator. A second similar conductor system placed directly behind the first in a parallel plane one-quarter wavelength away, will be excited parasitically from the first conductor and will act as a reflector, thereby creating a unidirectional system. It has been found that the reflector further reduces by 3 db. the power required to maintain a given signal intensity in the desired direction, thus bringing the total gain for the system up to 9 db. This is also in agreement with the theoretical computations.

It is obvious that the system in Fig. 3 can be extended vertically to include more radiating elements by increasing the length of the conductor and it can be enlarged horizontally by placing several units alongside each other, care being taken to obtain the desired phase relations by transmission lines of the proper length. In this way large power savings may be effected. At Lawrenceville the maximum gain is about 17 db. (a power ratio of 50) over a vertical halfwave oscillator. The enlarged system lends itself readily to mechanical support and forms so-called exciter and reflector "curtains" which are suspended between steel towers appropriately spaced. Aside from other considerations, which will be mentioned in connection with station layout, the size of the antenna is influenced by the complex and variable nature of the wave propagation through space. At present this determines the degree of directivity which is most useful for the average conditions.[5]

The closed loops of each unit corresponding to Fig. 3 greatly facilitate the removal of sleet. In addition to loading the antenna mechanically, ice, having a dielectric constant of 2.2 at these high frequencies, adversely affects the tuning. At Lawrenceville sleet is removed by heating the wires with current at 60 cycles. This is accomplished without interfering with the service by employing one of the less familiar properties of a transmission line. The same property also is used to effect impedance matches wherever the transmission lines are branched. If a line, exactly one-quarter wavelength long, of surge impedance $Z_o$ is terminated with a load $Z_R$, the sending-end impedance $Z_s$ is equal to $Z_o^2/Z_R$. If $Z_R$ is a pure resistance the sending-end impedance is a pure resistance. Hence a quarter-wavelength line may be used to connect two circuits of different impedances and these impedances may be matched by controlling the value of $Z_o$ either by varying the diameter of the conductors or their spacing. Likewise, if $Z_o$ is fixed and $Z_R$ is made very small, then $Z_s$ will be extremely large.

In Fig. 4 two units of the type shown in Fig. 3 are excited through transmission lines 1 and 2 of equal length in order to give the correct phase relations in the

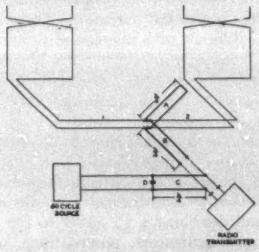



Fig. 4—Antenna Sleet-Melting Circuit

radiating elements $R$. The lines are joined in parallel by condensers of low impedance at radio frequencies and they are connected in series for 60-cycle currents by the quarter-wavelength line $A$ which, being short-circuited at the one end, presents a very high impedance to radio frequency currents at the other end and therefore behaves like an anti-resonant circuit. The quarter

5. J. C. Schelleng, "Some Problems in Short Wave Telephone Transmission," I. R. E. *Proceedings*, June 1930.

wavelength line $B$ serves as a transformer and is adjusted to match the impedance at the junction of lines 1 and 2 with that of the radio transmitter. The quarter wavelength line $C$ is effectively short-circuited for radio frequencies by the condenser $D$ and acts the same as $A$. These quarter wave lines consist of short lengths of pipe mounted on frames under the antenna curtains as shown in Fig. 5.

### Transmitting Station

Among the first radio problems encountered in the design of a transmitting station for several channels are those concerning the size, shape, and number of antennas, their directions of transmission, their relative positions from the point of view of mutual interference, and their grouping around the transmitters.

Fig. 5—Section of Antenna System at Lawrenceville

Showing lower portion of curtains and quarter wave transmission line used as transformers and anti-resonant circuits

The number of antennas required for each channel is determined by the hours of operation and the average grade of service which the system is expected to render. For service covering a large portion of each day several wavelengths are necessary. Transmitters Nos. 1, 3, and 4 at Lawrenceville each are assigned three frequencies. No. 2 has five assignments in order to improve the likelihood of at least one channel being available throughout the entire day at all seasons.

The size and shape of the antennas are, of course, determined by the directivity wanted, by the type employed, the frequency assignments, and by considerations of cost. They are governed also by the necessity of connecting several antennas to the same transmitting set. This involves both the spacing and arrangement of antennas to avoid adverse mutual reactions and it requires that attention be given to the losses in the connecting transmission lines, which are by no means negligible. Operating economies suggest concentrating all the transmitters at one point but the cost per kilowatt hour of modulated high-frequency power must be taken into account when considering the use of long transmission lines. It should be recognized, of course, that in the early applications of a comparatively new art, it is impossible to approach anything like accurate evaluation of all the factors entering into economic balances and furthermore very considerable weight needs to be given to the probable future trend of developments.

At Lawrenceville all of the antennas for the three channels to England are arranged in a straight line about one mile long. The direction of this line is perpendicular to the great circle path to Baldock, England, where the signals are received, (Fig. 6). The antennas for the fourth channel are similarly arranged in a line 1500 ft. long and they are directed for transmission to Buenos Aires, Argentine.

Placing several antennas in a single line reduces the cost of the supporting structure, and all the antennas have a clear sweep in the direction of transmission. By locating them in proper sequence with respect to wavelengths it is possible without objectionable interference, to place the antennas end-to-end and thus use supporting towers in common. Due to the wide difference in wavelength between adjacent antennas and their right-angle position with respect to the line of transmission, their proximity has no appreciable effect different from that of the towers. The proper selection of tower spacing in respect to wavelengths makes it possible to erect a uniform supporting structure. This has the advantage of flexibility and will permit future alterations of either the location or size of a given antenna. At present, each antenna occupies the space between three towers.

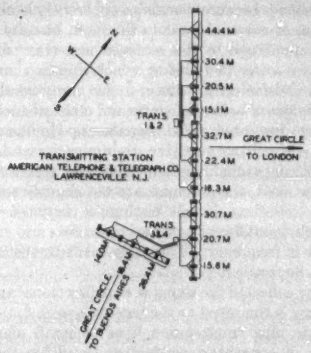



Fig. 6—Arrangement of Antennas at Lawrenceville Transmitting Station

In order to avoid undue loss in the transmission lines the radio transmitters are grouped in two buildings. The buildings each contain two transmitters and are identical in layout, in so far as the radio equipment is concerned. Building No. 1 has additional space for the

central wire terminating and testing equipment. This apparatus is contained in an electrically screened room which effectively prevents high-frequency fields from interfering with the proper functioning of the apparatus.

### Receiving System

Short-wave reception is characterized by less difficulty with static than that encountered with long waves. On the other hand it suffers interference from sources such as the ignition systems of passing airplanes and automobiles, which ordinarily do not disturb long-wave systems. Frequently the incoming radio waves suffer wide and rapid swings in intensity and there are variations in the apparent direction of arrival. On account of the extremely high frequencies the apparatus and antenna structures are very different from those for the long waves; otherwise the general schemes of reception are similar, directional effects and double detection methods being employed for both.

The radio wave is collected by means of a directional antenna array whose prime function is to improve the ratio between the desired signal and unwanted noise or other interference. This it does in two ways: *viz.*, (1) by increasing the total signal energy delivered to the receiver and (2) by discriminating against waves whose directions of arrival differ from the chosen one. Increasing the total energy collected from the incoming message wave permits the detection of correspondingly weaker signals because there is an apparently irreducible minimum of noise inherent to the input circuits of the first vacuum tube in the receiver[6] and this noise establishes a lower limit below which signals cannot be received satisfactorily. Since, under many conditions, the directions of arrival of static and other disturbances including unwanted radio signals are random, it is obvious that sharp directive discrimination aids very materially in excluding them from the receiver. On the other hand, the antennas are not sharply resonant systems and they do not distinguish between waves from substantially the same direction and closely adjacent in frequency. This duty is left to the circuits of the radio receiver.

Having collected the signal with a directional antenna the energy is conveyed to the receiving set by means of concentric pipe transmission lines of small diameter. The use of concentric conductors simplifies the prevention of direct signal pick-up by the lines, it reduces losses and prevents external objects from influencing the transmission properties, thus allowing the line to be buried in the ground or placed a few inches above the surface where it will have no appreciable adverse effect on the antenna performance.

Referring now to Fig. 7, the radio currents arriving over the transmission line are first amplified by two stages of radio amplification involving tuned circuits which discriminate further in favor of the wanted signal. The signal delivered by the radio amplifier is at a suitable level for efficient demodulation and is applied to the grid of the first detector. By means of a beating oscillator whose frequency is suitably adjusted, the first detector steps the signal carrier frequency down to a fixed value of 400 kilocycles from one in the range 9000 to 21,000 kilocycles which depends, of course, on the distant transmitting station assignment. The intermediate frequency signal at 400 kilocycles then passes through a combination of amplifiers and filters which further exclude the unwanted interference. The wanted signal reaches the second detector where it is demodulated and the voice currents reproduced. The latter are then amplified and applied to the telephone lines.

A portion of the output from the intermediate amplifier which would normally go to the second detector grid, is diverted and further amplified. It is then supplied to a device which automatically tends to maintain the receiver output volume constant by controlling the bias potential of the first detector grid circuit. The

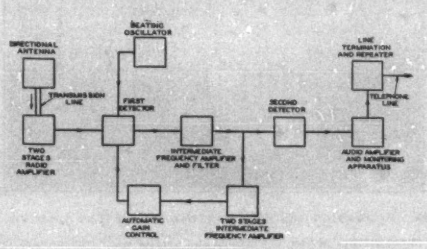



Fig. 7—Block Schematic of Receiving System

time constants are adjusted so that this gain control does not respond to the normal variation in signal power corresponding to speech modulation. Otherwise, of course, there would be serious distortion effects. This device partially offsets the ill effects of wide fluctuations in signal intensity but it does not overcome the deterioration in signal quality which usually accompanies the low field strengths during such fluctuations.

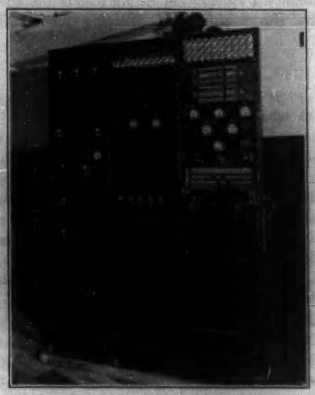
### Receiving Equipment

At the receiving station the apparatus for each channel comprises (1) the radio receiving set, (2) a power plant for the receiver, (3) wire terminating equipment and repeaters. The latter are located at a central point in the station along with certain voice frequency testing apparatus used in common by all channels and supplied with power from a common source.

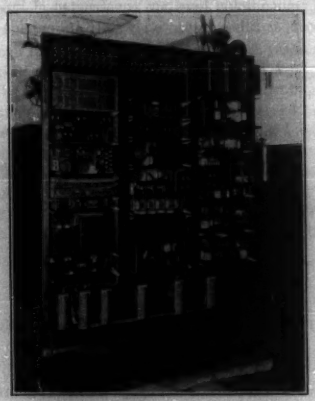
A radio receiving set which embodies the above described system and of the type installed at Netcong is shown in Fig. 8. It consists of a large number of individually shielded units mounted on panels and assembled on three self supporting racks of the type commonly employed in the telephone plant. This permits the use

6. J. B. Johnson, *Physical Rev.*, July 1928.

without modification of certain standard pieces of equipment, such as jack strips, fuse panels, meter panels, audio frequency filters, and the like. It also permits the removal and repair or substitution of units with a minimum of delay. The set is required to receive signals at three fixed frequencies in the range 9000 to 21,000 kilocycles. This involves connections with



A



B

Fig. 8—Short-wave Radio Receiver (A) Front View (B) Rear View

three antennas through three separate transmission lines. The tuning of the antenna and transmission line terminations are rather lengthy processes requiring precise adjustments. In order to facilitate quick changes from one operating frequency to another without intricate tuning operations, the first stage of radio amplification is provided in triplicate and the switching is done between the first and second stage. Thus the antennas are permanently connected to the set and their adjustments remain undisturbed. The circuits of the second stage require tuning when the frequency is changed. Hence to tune the receiver on any one of the assigned frequencies the attendant merely moves the dials of the second stage to predetermined settings, switches the grid circuit to a first stage which is already tuned and connected with the proper antenna and he adjusts the beating oscillator to obtain an intermediate frequency of 400 kilocycles. Screened grid tubes are used for the first two stages of amplification. A key shelf is provided with telephone and telegraph facilities. The power plant consists of standard 24-volt and 130 batteries, rectifier charging units and automatic regulators.

## Receiving Antennas

In discussing antennas for directional sending it was mentioned that an identical antenna could be used for receiving purposes, but since the requirements in the two cases are not the same, quite different structures have been developed, although the methods of obtaining directivity are alike. In the sending case the reduction of random radiation ceases to be profitable when the increment thus added to the energy, which is radiated in the direction of the distant receiving station, is a relatively small part of the total. In the receiving case, although the response to the wanted signal may not be increased appreciably by further improvement in the directive pattern, the reduction in noise and interference from random directions justifies additional improvement. Expressed another way, the objective in the transmitting case is a high gain compared to a nondirectional antenna, whereas in the receiving case the objectives are, first, a high average signal-to-noise ratio and, second, a gain sufficient to override the noise inherent in the receiving set. Satisfying the first accomplishes the second.

Improvement of the average directional discrimination means a nearer approach to ideal conditions. Whereas steel towers, sectionalized cables, guys and the like, when properly located relative to the conductors of a sending antenna, do not cause any appreciable power loss, their presence near the receiving antenna may prevent the realization of the extreme directive properties which are wanted. Moreover, there is need for much greater rigidity in the positions of the conductors. For this reason the antennas at Netcong are supported on wooden frames constructed like large crates.

Due to the variable conditions surrounding the propagation of short waves in space, the vertical angle of arrival of the signal wave at the receiving station frequently changes considerably throughout a twenty-four hour period and is not always the same from day to day. In order to combat this variable condition, it

appears desirable to select an antenna arrangement which does not have sharp directional properties in a vertical plane passed through the horizontal direction of arrival. The type of antenna selected for Netcong meets this requirement by having only a single horizontal row of quarter-wave vertical elements in one plane. Another solution, of course, would be to provide several antennas of different characteristics and to shift about from one antenna to another as the conditions warranted.

Fig. 9 is a general view of one of the Netcong receiving antennas. Like the transmitting antennas, the conductors are arranged in two parallel planes one-quarter wavelength apart in order to obtain a unidirectional system. The conductor in each plane is bent and terminated as indicated in Fig. 10 but is much longer than that shown. The vertical members are marked *A*. As in the transmitting case the directional

Fig. 9—One of Receiving Antennas at Netcong. (24.7 Meter Wavelength)

effect depends upon the manner in which standing waves occur along the conductor. A signal wave arriving broadside to the array, induces voltages in the vertical members which are identical in phase and amplitude.

Because the vertical members are interconnected alternately at the top and bottom by members of one-quarter wavelength and the last horizontal members are one-eighth wavelength, the net effect of the induced voltages is the establishment of standing current and voltage waves along the conductor. The receiver is connected at a voltage anti-node and the current which flows through it is proportional to the sum of the voltages induced in the vertical members. In the case of a signal wave arriving from the horizontal directions parallel to the plane of the array, the voltages in the vertical members are in successive quarter-phase relationships, no standing waves are produced, and no current flows through the receiver. Because current nodes occur at the center of each horizontal member, the loss by reradiation from these members is negligible. This is an important feature which contributed to the selection of this type of antenna for Netcong.

The size of the antenna is determined largely by the manner in which the signal waves arrive although costs cannot be wholly neglected. The useful length is limited by the fact that random fading occurs at distances as short as ten wavelengths and it is doubtful if an antenna this long would realize the computed improvement. The cost per decibel gained is small for the initial steps, but it mounts very rapidly as the length of antenna increases. The height also is limited by cost and by the necessity of allowing for considerable

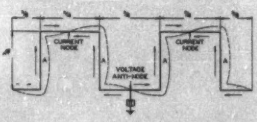



Fig. 10—Diagram of Simple Directive Receiving Antenna

variation in the vertical angle of arrival as discussed in a previous paragraph.

The antennas at Netcong are six wavelengths long and the lowest conductors are about 10 ft. off of the ground. The gains over that of a half wave vertical antenna are in the order of 16 db. (power ratio of 40). The average improvement in signal-to-noise ratio is of the same order. There are certain null points toward the sides and rear for which the ratio of directional discrimination is very large.

The transmission lines are constructed of inner and outer copper tubes respectively 3/16 in. outside diam-

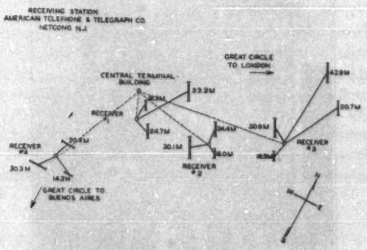



Fig. 11—Arrangement of Receiving Antennas at Netcong Receiving Station

eter and 5/8 in. inside diameter. The tubes are held concentric by torroidal shaped insulators made of Isolantite, a ceramic product similar to porcelain and well adapted for high-frequency voltages. This same material is used for insulating purposes throughout the transmitting and receiving antennas. Transmission lines are supported a few inches above the ground and are connected to earth at short intervals. The lines vary in length from 200 to 1500 ft. One of the interesting problems in connection with their design is the

provision of means for allowing variation in length with temperature. Ordinary expansion joints introduce difficulties with electrical contacts and impedance irregularities. To avoid these the lines are made 10 per cent longer than otherwise necessary and they follow a sinuous course which permits the necessary bending. Sharp turns are not permissible because experiments have shown that they cause reflection disturbances. The measured loss in 1000 ft. of line at 20,000 kilocycles is 2 db.

### Receiving Station

The radio problems encountered in the layout of the receiving station, in general, include most of those already mentioned in connection with the transmitting station, but their solution in some instances is quite different. In addition there are requirements imposed by sources of radio noise both within the station itself, and in the surrounding area which is beyond the control of the station.

The number of antennas is determined, of course, by the frequency assignments of the distant transmitting station. Where two assignments are within 100 kilocycles it is possible to use the same antenna for both, but thus far, this has not been done at Netcong.

The size of the antennas is not limited appreciably by the length of transmission lines because other factors make it necessary to separate them rather widely. On this account and also because the receiving apparatus and its power plant are small, comparatively inexpensive units, it is economical to place the receivers in small buildings centrally located with respect to the group of antennas for one channel. In this case the lengths of transmission lines are not controlling factors and the dimensions of antennas are governed primarily by the considerations previously outlined when describing the individual antenna. The small height of the antenna permits them to be placed in the line of reception of other antennas spaced ten wavelengths or more away and of widely different frequencies such as those of one channel. Antennas adjusted for the same order of frequency are separated more than this. On the other hand, to avoid adverse reactions no two are placed adjacent and end-to-end as at the transmitting station. The end-to-end separation at Netcong is in the order of four wavelengths. The areas surrounding antennas are cleared of trees and kept free of all overhead wires or conducting structures to avoid reflection effects which disturb the directional characteristics of the antenna systems.

The locations of antennas are also influenced materially by the necessity of avoiding interference from the ignition systems of internal combustion engines. This imposes a requirement that the station site be isolated from air routes and roads carrying heavy traffic. The antennas are placed as far as possible from secondary roads which cross their line of reception.

The layout at Netcong is shown in Fig. 11. There are thirteen antennas arranged in four groups with a receiver building for each group. A headquarters building located at the road entrance contains the wire terminating equipment, line repeaters, and voice frequency testing apparatus. The power plant at each receiver and the entire central terminal apparatus at the headquarters building are placed in electrically shielded rooms to prevent radio noise disturbances emanating from them and reaching the receivers directly or via the antennas.

The radio stations described herein are pioneer commercial applications in the development of short wave telephone transmission. Although progress has been rapid and far-reaching our knowledge of the behavior of short waves is by no means complete. It is reasonable, therefore, to expect that the future holds many improvements and that the information obtained by further fundamental investigations may materially alter both our views of the transmission phenomena and our ideas of what the apparatus and stations should be.

## Discussion

For discussion of this paper see page 643.

# Transoceanic Telephone Service—Short-Wave Stations

## Planning and Construction of a Short-Wave Radio System

BY F. A. COWAN[1]

Member, A. I. E. E.

IN the Spring of 1928 the use of the transatlantic telephone service which was inaugurated a year previously with one long wavelength radio circuit was increasing rapidly and gave promise of growing to such proportions as to require a number of additional telephone circuits by the end of 1929. In addition it was considered desirable to broaden the scope of the overseas service to include a telephone connection with South America. It was decided after careful consideration of the whole situation to provide these new circuits by means of short wavelength radio. At that time there was in operation a one way New York to London short wavelength channel which had been used during the summer of 1927, and at times during the winter, to supplement the existing long wavelength circuit. In the opposite direction some transmission tests at short wavelengths had been made but no use had been made of the channel for service. For the New York to London channel, an experimental transmitter at Deal Beach, N. J., was used and during the transmission tests from England to this country, the signals were received with experimental equipment located at Cliffwood, New Jersey. A survey of the situation indicated that to care properly for the extensive development being planned, it would be desirable to establish new transmitting and receiving centers to serve as the United States terminals for short wave circuits in the Atlantic area.

| Step | Scheduled completion date for service |
|---|---|
| Receiving center with first receiving unit for second New York-London circuit | June 1, 1928 |
| Transmitting center with first transmitting unit and second receiving unit for third New York-London circuit | June 1, 1929 |
| Second transmitting unit to release experimental transmitter at Deal Beach | Sept. 1, 1929 |
| Third transmitting unit and third receiving unit for fourth New York-London circuit | Dec. 1, 1929 |
| Fourth transmitting unit and fourth receiving unit for first New York-Buenos Aires circuit | Feb. 1, 1930 |

As a first step, it was decided to establish the first unit of a receiving center to be used for receiving in this country from England on a one way channel which would be associated with the then existing one way New York-London channel in setting up a second complete transatlantic circuit. Plans for the initial and succeeding steps, together with the desired completion dates, are given in tabular form.

### Coordination of Work

In carrying out a large program of work, particularly when the work is of a pioneering character or when the interval between the starting date and the desired completion date is small, it is essential that all phases of the work be carefully scheduled and coordinated. In the early stages of the work on the short wave radio project a schedule of work covering each item in some detail was worked out and distributed to all involved in the development. To insure smooth progress of the planning and construction work covered by this schedule, joint meetings between the engineers and the representatives of the construction forces were held at frequent intervals and those phases of the job needing special consideration were handled promptly.

### Selection of the Sites for the Transmitting and Receiving Centers

Since a large percentage of the overseas business originates in New York, this city has been selected as the United States terminal of all the existing or proposed overseas services in the Atlantic area. Another advantage in terminating the circuits at New York is that there is radiating from this point a veritable web of main long distance trunk circuits which furnish ideal outlets for that portion of the traffic to points other than New York.

With New York fixed as the terminal point the selection of sites for the transmitting and receiving centers was governed primarily by transmission considerations. Other factors, such as proximity of land lines for connecting the centers with New York, cost of land, availability of a reliable and adequate power supply, and accessibility, also entered into the final selection of the sites. The availability of a reliable power source of comparatively large capacity is a more important factor at the transmitting center. At the receiving points, since smaller amounts of power are required, the plant can be operated for several hours from storage batteries and the use of a reserve gas engine driven power plant

1. American Telephone & Telegraph Company, New York, N. Y.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*



30-30

is feasible. This is a fortunate condition since the comparative isolation required to reduce the likelihood of noise interference from ignition systems of internal combustion engines or from electrical machinery usually results in suitable receiving sites being somewhat remote from the sources of power supply. Except for the need of guarding against the possibility of electrical noises at the receiving center, the transmission considerations governing the selection of sites are concerned principally with the locations of the transmitting and receiving stations relative to each other and in turn with their location relative to the circuit terminal at New York and to radio stations of other communication agencies.

With respect to the desirable distance from New York

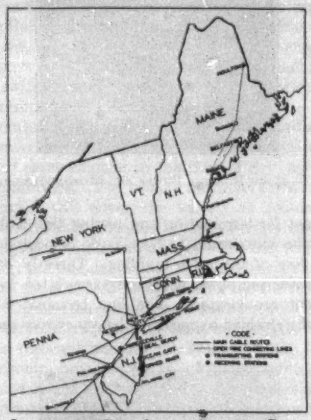



Fig. 1—Location of Bell System Overseas Radio Transmitting and Receiving Stations

there appears to be no outstanding advantage in favor of locating short wavelength radio stations at a distance from the circuit terminal even when the radio transmission path could be appreciably shortened thereby. In the case of long wave radio transmission, however, there are greater advantages to be gained by shortening the transmission path, and for the receiving station there is also the added argument for securing a site sufficiently northerly located to effect a material reduction in static noises. For this reason the receiving point of the long wave radio circuit used between New York and London, is located at Houlton, Maine, some 600 miles from New York.

Even when it is desirable to locate the radio stations near the circuit terminal, as in the short wave system, it is not practicable to locate them very near a city the size of New York. There is also the necessity of keeping the distance between the transmitting and receiving stations near the value which will minimize interference between the two. These centers should in addition be so located with respect to each other that for the important directions of transmission the normal directive characteristics of the antennas assist in reducing the possibility of interference between transmission in the two directions.

The sites actually selected by applying the principles discussed in the foregoing and their locations relative to each other are shown by Fig. 1, which indicates the locations of the various transmitting and receiving stations in the United States used in overseas radio telephone service. The transmitting and receiving centers for short wave use are all located within sixty miles of New York. All of these stations are on, or very near main cable routes and are connected with New York city by cable circuits. They are readily accessible by automobile. Special roads have either been constructed, or are now being constructed in those cases where the plots are off the main highways.

The transmitting center designated as Lawrenceville having an area of about 900 acres, and the receiving center designated as Netcong having an area of about 450 acres, are the recently established ones used in the short wave system with which this paper is principally concerned. There are provided at present at these points, the United States terminals of the four overseas telephone circuits, three to Europe, and one to South America, the plans for which were discussed in the foregoing. The centers have been planned to care for additional circuits in the future.

## General Layout at Lawrenceville

The buildings at Lawrenceville and Netcong are specially designed. At Lawrenceville there are at present two main buildings, each containing two radio transmitters. Both buildings are of fireproof construction employing reinforced concrete and hollow tile with a brick exterior. The two buildings are identical with regard to that part devoted to the radio transmitters. One of the buildings, however, contains more office space, a line terminal room, a machine shop, and a garage which are intended to serve the entire center when fully developed. The floor plans for the first and second floors of the main building which are about 75 by 95 ft. are shown in Figs. 2 and 3.

On the ground floor of each building, occupying the entire width at the rear, are transformer vaults and rooms containing forced draft radiator units for cooling the water from the high power, water cooled vacuum tubes. Directly in front of these and also extending the full width of the building, is a room containing the water-pumps, the regular and emergency motor-generators and starters, and their transfer switches. Fig. 4 is a view of this equipment. Directly above the power room, and of equal floor area, is the transmitter room. The two transmitters are located in line on one side of the room with their switchboards in line directly opposite. They may be clearly seen in Fig. 5, which is a

general view from one end of the transmitter room. The turrets containing voice frequency control and monitoring equipment may be observed in the center of the room. The overhead structure supports the radio transmission lines connecting the antennas to the transmitter, as well as the system of filtering lines used in connecting the sleet melting power to the transmis-

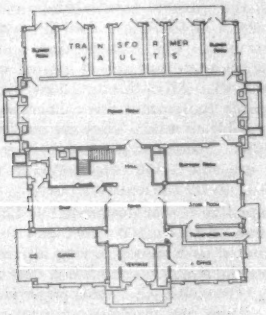



Fig. 2—First Floor Plan, Main Building at Lawrenceville, New Jersey

sion lines. Control of all equipment is centralized in the transmitter room and the attendants on duty remain there except for routine inspections. The 10,000-volt plate supply rectifiers are located in an extension of the

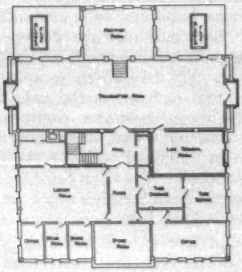


Fig. 3—Second Floor Plan, Main Building at Lawrenceville, New Jersey

transmitter room at a slightly higher floor level over the middle transformer vaults. Beneath the rectifier room and on each side of the center vault there are high-voltage switch chambers each containing switch gear by means of which the complete substitution of transformer vault equipment from regular to spare may be effected by the operation of a single switch handle in the transmitter room. All switches and apparatus compartments are interlocked to prevent incorrect manipulation and to protect men doing maintenance work.

In general the layout of the equipment in the various rooms and vaults is such that one set is on the left of the building, a second on the right, and the common spare equipment in the middle. This simplifies the cabling to the transfer switches which permit cutting the spare equipment into service. The major elements of each transmitter which are likely to develop trouble and require an appreciable length of time to repair, are included in this spare equipment.

The central line terminal room, which contains the

Fig. 4—Room Holding Pumps and Motor Generators

equipment for terminating and testing the cables furnishing the wire circuits to New York, is located on the second floor of the main building. Directly below it the batteries and power equipment associated with this equipment are located. The line terminal room is electrically shielded by means of heavy copper sheeting,

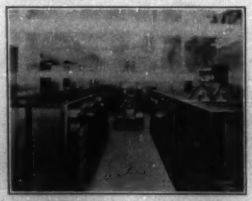


Fig. 5—Transmitter Room at Lawrenceville

covering the floor, ceiling, and walls. The windows have fine mesh gauze screen substituted for the copper sheeting, and the door is provided with a metal covering which is bonded to the copper sheeting of the walls. This shielding is provided to prevent the high-power radio frequency waves from feeding back into the line terminal equipment and causing distortion or preventing the proper functioning of the testing equipment.

In addition to the radio transmitting power equipment associated with each transmitter individually or available for connection with either transmitter, each of the buildings is provided with transformers to supply

power for lights, machine shop operation, vacuum tube testing, and other uses. The power for all purposes is provided from two outdoor substations, one for each building, having a total capacity of 1200 kv-a. Each of these substations is located in the rear of the building it serves. Separate power cables leading to the various power units within the buildings are equipped with oil circuit breakers and disconnecting switches which permit the isolation of a unit in trouble for repair without shutting down the unaffected units. Both the power connections and the telephone circuits to New York are brought into the property in underground cables to prevent pick-up of the radio signals causing insulation breakdowns or other troubles. The entire power and telephone layout is provided with spare equipment, cables, and switching mechanisms, so as to minimize the possibility of a service interruption of serious magnitude, due to trouble in power or telephone connections. As in the case of the switches within the building all power switches and compartments are interlocked to prevent improper operation.

As pointed out in a paper by Mr. Bown, satisfactory short wave transmission requires wide changes in wave length to meet changes in the time of day, season, or other conditions. For usual conditions three selected wavelengths will cover the variety of requirements encountered fairly adequately, but at times additional wavelengths prove advantageous. For this reason one of the circuits to England has five wavelengths assigned although the South American circuit and the remaining two to England have only three assignments. A separate antenna is required for each wavelength. Therefore the transmitting antenna system for the four existing circuits provides for 14 distinct antennas, 11 for transmission to England, and 3 for transmission to South America. Each of the regular antennas comprises an exciting and reflecting array supported in the space between three towers located in a line. For all but one antenna the spacing of towers for the antennas is 250 ft. A greater separation is required for the antenna used in operation at a wavelength of about 45 meters, and the towers are therefore spaced 365 ft. apart. The antennas for transmitting in the same direction are located end to end in the same line. This permits supporting antennas from both sides of all towers in a line except the two end ones. This close spacing of antennas is made possible by arranging the order of the antennas with respect to wavelength so that adjacent ones are very different in wavelenghts. The antennas for transmitting to England are supported by 21 towers located in a line about a mile long, running approximately northwest and southeast, and those for transmitting to South America are supported by seven towers in a line about a third of a mile long, running almost east and west. These two lines form a huge *V* when viewed from the air. Fig. 6 is an aerial picture of the Lawrenceville center showing the antenna towers and the two transmitter buildings.

To secure the proper characteristics it is necessary in some cases that the antenna arrays have a height of about 150 ft., so to secure flexibility and allow for sag in the supporting cable, the supporting towers have been made a uniform height of 185 ft. The towers were specially designed to meet the unusually severe conditions likely to be imposed at times by high winds and ice acting upon the antenna arrays. It may be of interest to note that antennas of the type used, act very much like huge curtains suspended from the towers and in consequence the overturning moment at times of cross winds is very large. In consideration of this, the cross section of the towers has been made rectangular rather than square, with the long axis of the rectangle perpendicular to the line of the towers. Head guys have been placed on the end towers and the entire line tied together by guys between the tops of towers. To minimize any possible reaction upon the antennas these guys have been sectionalized with high-voltage strain insulators. The regular interval used between insulators is varied with the wavelength of the antenna and ranges from around 25 ft. for the lowest wavelength to about 120 ft. for the highest wavelength.

Fig. 6—Aerial View of the Lawrenceville Center
Showing the antenna towers and the two transmitter buildings

The towers are equipped with unusually large concrete foundations, the dead weight of which alone is calculated to be sufficient to prevent overturning at the highest cross wind velocities anticipated. Another interesting feature of the tower system is the provision which must be made for lowering and raising the antenna curtains to permit repairs or adjustments. For this purpose four winches are located at the base of each of the towers in a line, except the end towers which have only two winches. The winches are provided with two gear ratios to meet the varying load conditions likely to be encountered.

The Lawrenceville station is located in the line of flight of a regularly flown air route, and to guard against accidents the towers have been lighted in accordance with the latest recommendations of the Department of Commerce. All told over 150 lights are used for this purpose. At the ends of each row of towers larger lights having 1000 candlepower are used.

The antenna curtain is supported by cables running from tower to tower and attached at each end to the winches. These cables, which are called main supporting cables, are sectionalized in the same manner as the guy cables. The antenna curtains hanging from the main supporting cables are kept taut by vertical and horizontal stay wires equipped with counter weights. Below the curtains the transformers used in combining

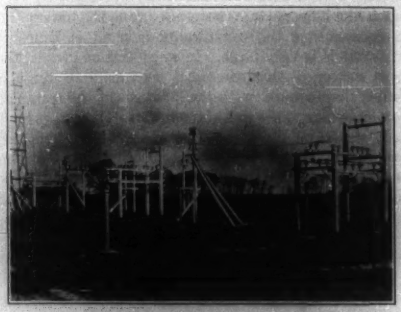


Fig. 7—Lines Feeding Lawrenceville Station

the various parts of antenna are located. These transformers are actually parallel brass tubes one-quarter wavelength long, spaced the proper distance apart and supported by power type insulators on wooden frame-

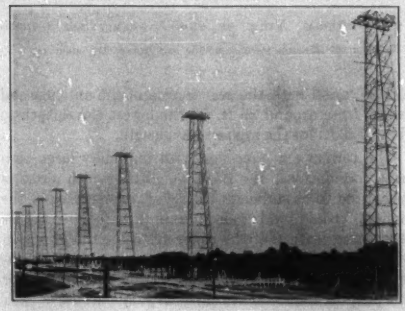


Fig. 8—Transmitting Antenna at Lawrenceville

works. A view of the antenna transformers and associated transmission lines is shown in Figs. 7 and 8.

## General Layout at Netcong

At the Netcong receiving center the development has been along the line of setting up separate receiving units for the different channels at various points and bringing the received signals into a central line terminal station. The central station, because of the importance of the service concentrated therein, is a substantially fireproof building of brick construction. This building provides office space, a line terminal room, a central power transformer station, and an emergency gasoline engine driven power plant. The line terminal room is electrically shielded in the same manner as described for the transmitting center, but in this instance to prevent the radiation of radio frequency noise to the antennas rather than to protect the apparatus from interference.

The central terminal and administration building is so located on the property as to be the first point reached when entering by the main entrance road. To guard

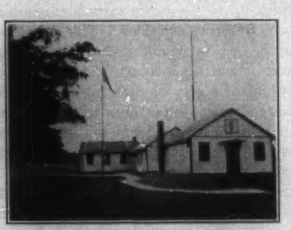


Fig. 9—Receiver Building at Netcong

This building also houses temporarily the line terminal equipment

against automobile interference, all but selected cars are stopped at this building and the journey from that point continued on foot or by special transportation.

The individual channel receiving stations are small wooden frame buildings. This type of structure was adopted because the receiving art is developing rapidly and receiving equipment is not thought to have the same permanency as transmitting equipment. Also in case of fire the service affected would be limited and equipment of this type could be replaced rapidly with

Fig. 10—Part of Terminal and Testing Equipment at New York Terminal of Overseas Circuits

a minimum of lost time. A photograph of one of the receiving buildings is shown in Fig. 9. The equipment in these buildings is located in two rooms, one for the radio receiving set proper and the other for the power supply consisting of storage batteries with charging and

voltage regulating equipment. This latter room is shielded in the same manner as the line terminal room in the central terminal and administration building to prevent radio frequency noise from this equipment being radiated and picked up by the antennas. Power and telephone connections for these buildings come from the central terminal building in cable.

Each receiving building has three or more antennas grouped around it, one for each wavelength received. These antennas are supported by huge wooden frame structures. The size of these frameworks varies with the wavelength to be received. Expressed in terms of wavelengths the dimensions are about as follows, ¼ wavelength wide, from ⅓ to ½ wavelength high, and 4 to 6 wavelengths long. The long axis of the structure is perpendicular to the direction of desired reception. The upright and horizontal members of the structure are bolted together with fish plates and strengthened by cross bracing. The entire framework is carried on concrete foundations which have been made especially large to prevent the antenna overturning in high winds or getting out of alinement due to settling. The active elements made up of copper tubes are supported on the sides of the structure with "stand off" insulators. The transmission lines from the antennas to the receiving stations are concentric copper pipes supported about one foot above the ground by driven iron stakes. To care for expansion and contraction with temperature, these pipe lines are made to follow curving paths.

In addition to the regular receiving units there is another receiving station at the Netcong center which is provided with a receiving set arranged for accurate field strength measurements and other radio testing equipment. This unit is called the Channel Observing Station. This station maintains a continuous check on the radio transmission conditions and advises the New York Control office as to the opportune time for the changes in wavelength which are necessary from time to time each day. Very accurate measurements of the frequency of received signals can also be made by the channel observing station. In case of interference to the telephone circuits from radio stations assigned to neighboring wavelengths such measurements facilitate the correction of the difficulty.

### Terminal Arrangements

The New York terminal of the overseas circuits is located in the Telephone Building at 24 Walker Street, which building is also the long distance office serving the greater part of the New York metropolitan area. The special terminating and testing equipment is located on the twenty-fourth floor of this building. There are at present eight units which are used for the various overseas services, four being used for the short wave systems we have been considering. Fig. 10 shows a portion of the equipment in this room. From the terminal room the circuits go to the long distance switchboard where the operators are located.

### Results

The construction work on this project occupied a period of about two years from start to finish. Some of the work was carried out under particularly trying conditions. At times very unfavorable weather conditions were encountered. A considerable portion of the construction involved new types of plant for which there was neither precedent to be followed as to procedure nor experience with which to establish the necessary time intervals accurately. By careful coordination of the work, however, the desired completion dates for the various parts of the project were realized. The three additional European circuits have been placed in service and tests are now in progress looking towards establishing a New York-Buenos Aires circuit.

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## Discussion

### TRANSOCEANIC TELEPHONE SERVICE

(Miller, Bown, Oswald, and Cowan)

New York, N. Y., January 30, 1930

**Bancroft Gherardi:** The engineer from the very nature of his work is necessarily chiefly concerned with the technical aspects of such a question as is before us this morning, the improvement and extension of communication service. But as engineers we don't want to have altogether out of mind the social and economic results that may be expected to follow from what we are doing.

Going back only about fifteen years ago to 1915, universal telephone service did not exist even throughout the United States. The eastern part of the United States could not telephone to the western part of the United States, or vice versa. By developments that had been made in the preceding few years, however, in 1915 the two coasts of the United States were tied together telephonically. So that we can really say from 1915 on we had within the United States and with our sister country Canada, service which extended practically wherever there were settlements of any size.

This, however, by no means gave universal service, although as many of you know, it has been for many years the policy and the aim of the Bell System to give universal telephone service so that anyone at any time, could talk to anyone else quickly, clearly, and conveniently.

An enormous advance has been made since 1915. Most of Europe has been brought into the picture. The possibility of communicating with ships at sea has been demonstrated, and one of our large transatlantic liners, the *Leviathan*, is now equipped for the giving of commercial telephone service and has given such service on her most recent transatlantic trip.

In addition, the development in a sister art has created still another problem for the telephone engineers. As airships have developed the problem comes up of communicating with airships, and the technical features of that problem have been solved.

Mr. Miller has told you some of the proposed extensions of intercontinental service which are under way. I do not think he mentioned the fact that a station is planned and under way on the Pacific Coast looking toward the West and doing our part in making it possible to communicate with the Islands of the Pacific and with the Continent of Asia. So it is not going too far to say that the scientists, the research experts, and the engineers have done their part to render universal telephone service practicable, and that the applications have gone a long way to make such service a reality. Mr. Miller mentioned the fact that today from New York City or any other place in the United States or Canada, it is possible to communicate with about 85 per cent of all the telephones in the world.

After these connections are made other problems will remain to be solved, but they will not be the problems of the engineer. They will be problems of a social nature. I will mention but two of them. One arises from the fact that the world is approximately spherical in shape and that therefore when in some parts of the world it is daytime in others it is night. We already encounter differences of time between San Francisco and London of eight hours. Another hour is added to that difference in time when San Francisco communicates with Germany.

I recently had a very interesting test conversation. I was located in New York and on a Thursday afternoon, at four p. m. I spoke by telephone to a man located in Sydney, Australia, only with him it was Friday morning at six a. m. Not only was there a difference in hours but there was actually a difference in days. Incidentally, also, there was a difference in seasons. He was in midsummer while I was in midwinter.

There is no doubt whatever that the difference in time will furnish a certain limitation on the use of telephone service under certain conditions, but I have no doubt that in many cases the service will be so valuable to meet the desired needs of the users that the difference in time will be overcome. It is interesting to note that on the transatlantic telephone service we have service practically all hours of the day and night, showing that if people want to talk badly enough they will be willing to talk even in the early hours of the morning.

The other difficulty is the language difficulty. Obviously people cannot speak to each other unless they can use the same language. Here, however, I feel we are going to have some help from another sister development of recent years, in which the Bell Telephone Laboratories have had an important part. I refer to the talking movies. What the ultimate outcome of this language question is I don't know, but I feel quite confident that world-wide telephony adds an additional incentive to those that already exist with the increase in travel that goes on year by year, with the closer social connections that exist year by year through the different parts of the world, to the establishment of some universal language, and if we get such a universal language the people who I think will have created the major demand for it will be the scientists, the research people, and the engineers in their development of transportation, communication, and the talking movies.

**F. B. Jewett:** There are two things I should like to say a word about. The first is a brief word concerning one of the technical problems which confront us, and the second has to do with some of the fundamental factors which confront those of us who would give a universal telephone service with the means that are now at our command.

Mr. Bown in his remarks referred to difficulties in the radio transmitting medium which were presumably connected with disturbances in the sun. If that is a fact, and there is every reason to believe it is, I surmise that in the years just ahead of us a great deal of useful information will be obtained by a closer cooperation between those of us who are interested in this sort of thing and, we will say, our astronomical friends. On my return from Japan recently, I stopped in Pasadena for a few days, and on one occasion when I was visiting Dr. Hale I was given a most vivid ocular demonstration of the magnitude of the magnetic forces which are related to the sun spots. I had occasion to look at some of the spectral lines in and near one of the sun spots which was then on the face of the sun, a sun spot many times the size of the earth, which indicated magnetic forces in this vast electromagnet comparable to and possibly many times greater than any magnetic forces which we can produce even artificially on earth. The lines of the solar spectrum in and at the edges of the sun spot were split apart in the so-called Zeeman-effect manner, to a degree which I had never seen in a laboratory here on the earth, indicating a magnetic disturbance of a magnitude which was beyond our conception.

If, as I presume, these disturbances are definitely connected with the disturbing forces we observe, it seems to me that a need of closer cooperation between our scientific people interested in the transmission of electrical energy and the astronomers is indicated.

The other thing I wanted to call to your attention, because it seems to me that it is extremely fundamental to all of our considerations in the development of telephone service, is certain underlying differences which exist between telegraph transmission and telephone transmission for commercial purposes, and certain requirements which are involved in the building up and giving of what we conceive to be adequate telephone service.

For the most part, telegraph service is a delayed service. There may be exceptions to it, but in general it is a service which involves a greater or lesser degree of delay between the filing of a message and its delivery to its recipient. That being so, additional and possibly erratic delays may not be of great moment. This tends to minimize the deleterious effects of the delays due to fading or static.

On the other hand, telephone service in its ideal form is for the most part, a no-delay service, and the ideal telephone service would be one in which anyone desiring to speak to anyone else, could do it, as Mr. Gherardi indicated, easily, satisfactorily, and economically at any time he so desired.

If that is the ideal, and I think it is, then any factors which have to do with erratic delays are highly objectionable.

To go back, if you examine any of the applications of modern science, you will find that to a large extent the degree to which they are used and the degree to which they have become an integral part of our social and business structure, is closely related to their dependability, and so it is with regard to telephone service. It doesn't suffice in the giving of a telephone service to be able to do it well sometimes. If telephone service is to be used by people for their social and business purposes as an integral part of their scheme of living, it requires that it should be done well substantially all of the time. That is, you cannot expect anyone to make use of telephone or telegraph service, or any other form of applied science as an integral factor in the organization of his business unless he can depend on it.

Unfortunately, up to the present time, so far as the kind of telephone service we are now talking about is concerned, namely, transoceanic service, which at the moment has to be done by radio, there is not either with long waves or short waves, that degree of reliability which would permit of the maximum development of its use and the maximum incorporation of that type of service into the social and business structure of the world. It is true that by the use of a combination of long-wave transmission and short-wave multiple channel transmission, such as we have had here described to us, we are approximating to that degree of reliability, but we are still somewhat in the position that at times people cannot use the service just as they would like to use it. It is for that reason that we have, as was indicated in one of the papers, contemplated and are in the process of putting in as a supplement to radio a telephone cable across the Atlantic, not with the idea that it will supersede in any large measure the traffic handled over the radio channels but that it will provide an additional degree of security looking towards the giving of continuous service, and so tend to make the thing more nearly the type of plant, the type of structure which enables people to contemplate the use of telephone service with equanimity and surety.

In the radio side itself, and contemplating its future development as it pertains particularly to telephony, we are of course confronted with all of the difficulties that have been mentioned, and also with the fact that the increasing demand for radio channels for all kinds of purposes is eating into what now appears to be a limited supply of the available channels. What the future has in store for us with further research and development work, particularly in the very short wavelengths, of course

nobody can say, but it is quite clear that whatever extension there may be to the number of available channels, that number is still pretty small, and if reliable telephone service across great stretches of water can be established in one place, the demand for a large number of channels may increase to an embarrassing extent, so that it is incumbent upon the scientists and engineers to do everything they can, not only to conserve what we now have, but also to extend the range of availability of channels.

It seems to me from what little I know of the work as to both radio telephony and radio telegraphy, that every step we are making at the present time to the better utilization of what we have is tending to an enlarged use of what is available. The improvements which have here been indicated, and many others which have not been indicated, are all tending to make for a more efficient use of these channels, but there is still a very large amount of work to be done.

I merely mention these points because they tend to amplify what Mr. Gherardi said, that over and beyond the purely technical problems there are some controlling problems inherent in the social and business life of the world which determine to a very large extent not only the course which our development work should take but place definite limits on the things we can or cannot do.

**A. E. Kennelly:** There is one point in the remarks made by Dr. Jewett that I should like to emphasize, namely, the relatively close dependence between radio communication and solar activity. It seems that we are dependent upon the sun not only for our beneficent conditions of warmth, food, and life, but also for maintaining in satisfactory performance our long-distance radio communication.

During the last year, the Eiffel Tower has, I believe, issued every day at eleven-twenty Greenwich mean time, a meteorological bulletin which is followed by a series of brief remarks concerning cosmical disturbances that have an influence upon radio communication, namely, sunspot activity, magnetic activity, the earth's atmospheric electrostatic activity, and also seismometric disturbances. That service is part of the regular meteorological bulletin. Unfortunately, we don't often hear the Eiffel Tower across the Atlantic, but we are informed that the French Government is about to repeat this daily radio-cosmic broadcast from two of its radio stations simultaneously, commencing at 20.00 Greenwich mean time, namely Lafayette, on a wavelength of 16,900 meters, and Issy-les-Moulineaux, on a wavelength of 32.5 meters.

The Scientific Union of Radio Telegraphy, or the U. R. S. I., is much interested in this and similar subjects relating to the propagation of electromagnetic waves over the surface of the earth, and it seeks by a special liaison committee to develop a system through meteorological bulletins, of rapid intercommunication concerning disturbances, whereby radio observers may not only be able to forewarn as to possible suspensions of communication but also through collection of statistics, indicate their influence upon transmission.

It is quite possible that in the years to come, such communications may be of great scientific value in addition to their communication importance, but I merely wish to point out that information concerning magnetic disturbances and sun-spot disturbances have, at the present time, a certain commercial importance, and a certain engineering importance, so that what is going on in the sun has a certain dollar-and-cent value for us to know, in relation to long-distance radio communication.

I am making a plea, therefore, for the sympathetic consideration of any plans which may be fostered in this country by the meteorological authorities at Washington, for the rapid dissemination of cosmic information that may affect radio. I am hoping that it may be possible to do here what the Eiffel Tower has already done during the last twelve months, and I think that we may hope for such extension of service from the Arlington Station and other radio stations in the near future.

One thing more. Mr. Gherardi and Dr. Jewett referred in a very interesting way to the language question which, of course, is important sociologically. I should like to ask a question as to what the percentage of telephone communications, roughly speaking, has been in regard to distribution among the languages of the world, and what the indications are in regard to the difficulties of telephonic communication upon a language basis.

**G. W. Kenrick:** Dr. Bown and Dr. Jewett have both emphasized the complexities and importance of radio transmission phenomena in transoceanic telephony; students of radio communication are hence confronted with the problem of determining what type of experiments are best adapted to gaining information which will enhance its reliability. There are several methods of investigation which may be utilized. The most obvious and perhaps most widely employed method has been to observe the actual communication efficiency of the circuit, (*i. e.*, articulation, intelligibility, frequency characteristics, etc.). This gives us a very good index as to the value of the channel under observation at the particular time of the tests. Unfortunately, however, this method may not be best adapted to indicating what will happen to the channel tomorrow, and it is only by a long series of consistent observations that some indication as to its actual reliability may be obtained.

Such observations always run the risk of neglecting long-time variations such as those associated with the eleven-year sun spot cycle which has been shown to have an important correlation with magnetic disturbances. It therefore becomes of interest to evolve experimental methods which will serve to separate the various causes of the transmission phenomena in order that they may be separately studied and appropriate means adopted for their successful elimination where they are undesirable.

In addition to the regular measurements of field strength already indicated, there are other methods of investigation which are very interesting and which I think will play an increasingly important part in future investigations of radio transmission.

Notable among these is a method evolved by Breit and Tuve, of the Department of Terrestrial Magnetism, and also used by Heising of the telephone group and numerous other investigators. In this method a signal in the form of pulse of very short duration (in the order of $10^{-4}$ seconds) is transmitted. This pulse in general travels from the transmitter to the receiving point by a number of distinct paths through the upper atmosphere (supposedly corresponding to a series of rays multiply reflected from the earth's surface en route). At the receiving point the responses to this single pulse due to signals arriving over these several paths may be separated by the variable time delays they have encountered and the transmission along individual paths, hence studied separately.

The importance of this method of investigation lies in the fact that the effects produced by components of the received signal arriving over the various paths are separated and hence susceptible of individual investigation, whereas measurements of field strength alone (or of transmission characteristics) give only the results of the syntheses of the transmission arriving over these several paths. Thus, signals arriving by various paths may combine in such a manner as to produce selective phase interference at the receiving point, and important distortion doubtless results from this cause. By means of multiple receiving antenna rays, however, signals suffering from this type of distortion may perhaps be successfully combined. Signals suffering selective distortion and attenuation along a single path are, however, much more difficult of utilization. The method described is helpful in furnishing further information as to what factors are mainly responsible for the particular type of fading experienced. It is also admirably adapted to studies of Heaviside-Kennelly layer heights and other factors which may be correlated with magnetic and solar elements.

It therefore seems that the methods outlined may be of considerable help in the study of the problem. It remains, however,

for the radio engineer interested in transmission to be always on the lookout for new methods which will serve to further separate and clarify the various agencies entering into this extremely interesting but extremely complex problem of long distance communication.

**J. J. Pilliod:** When one contemplates the purchase of about a thousand acres of land in one site to be used as a transmitting station, and five hundred acres or so for a receiving station, a line of towers a mile or more long, 185 feet high, and other things of the kind referred to in these papers, problems are encountered which are not to be treated lightly, and which are entirely out of the range of the ordinary amateur type of radio station operation as contrasted with what we are trying to do here of giving a consistent, commercial telephone service.

**A. Nyman:** The discussion this morning did not consider the theoretical features of transmission of short waves, but it would be interesting to know about the recent theories of polarization of radio waves and the turning of the plane of polarization. I understand that experiments have been made to determine the amount of turning of the plane of polarization and, for long distances, considerable degree of turning from vertical to horizontal plane or vice versa takes place.

There is a type of wave known as circularly polarized and of a type generally attributed to light waves. It may be thought of as a spiral wave with the plane during ¼ cycle as vertical and the next ¼ cycle as horizontal, the plane thus turning all the time from one plane to the other. It would be interesting to know whether any experiments have been made to utilize this circularly polarized radio wave, as it would seem that such a wave would possess certain advantages with regard to transmission and reception, which are not possessed by the ordinary polarized waves.

**T. G. Miller:** I should just like to do what I can to answer Professor Kennelly. The nature of the business where we turn facilities over to people to talk makes it rather difficult to get the statistics we should like to have. In my paper I pointed out that the statistics we had and the classifications, business and social, were obtained entirely from the location of the telephones which were used. For that reason it is not very accurate. We have no reliable information, as to the percentage using different languages, but unless I am very much mistaken the predominant use is English. Possibly about 85 per cent of the calls are in English. Many of the calls from Paris and Berlin are filed by Americans who are over there.

**Ralph Bown:** In answer to Mr. Nyman's question, I do not know of any experiments which have been made with circularly polarized transmission. Vertically polarized transmission as represented by the transmission from antennas having vertical elements, and horizontally polarized transmission from antenna systems having horizontal elements, are both in commercial use. Vertical polarization is used largely by American stations, whereas, I believe, the German stations at the present time go in more for horizontal transmission.

Whether the use of the kind of polarization he refers to, circular polarization, would improve transmission results, of course must be left to experiment. Such experiments as I am familiar with, in which attempts have been made to analyze the distortions and the variations which occur at the receiving station, are not conclusive as to the effect of polarization changes.

# The Conductivity of Insulating Oils

BY J. B. WHITEHEAD* and R. H. MARVIN*

Fellow, A. I. E. E. Member, A. I. E. E.

*Synopsis.—The paper describes experiments on the charging current and other associated phenomena in high grade transformer oil. The charging currents remaining after the elimination of the initial transient were studied to within a few hundredths second of application of continuous voltage. Two samples of the same oil obtained at different times differed radically. In one case the charging current fell off from the start, while in the other it remained constant for an appreciable time or even temporarily increased. On reversal of polarity after a long charge the initial current with both specimens was the same as before reversal, but with one a large momentary increase occurred a few seconds later. Evidence is given on the time of recovery of the initial condition. The existence of space charges in the charged oil is shown, and the time of formation of these charges together with the resulting non-uniform distribution of voltage is measured. The importance of the charging current in its early stages is emphasized, since it is the initial conductivity which determines the a-c. loss.*

*In an appendix a theoretical discussion is given on the influence of the space charges. It is shown that at least qualitatively these account for the observed phenomena.*

## Introduction

In this paper we present the results of a series of studies on the initial, or short-interval conductivity of high grade insulating oil. New evidence is presented as to the properties of the ions involved, the peculiarities of the resulting electric conduction, the wide variations of the latter with slight change of conditions, and other matters having apparent bearing on the behavior and life of the oil as an insulator.

The conductivity of these highly refined oils may be measured but is so low that they must be regarded as among the most excellent insulators. Their conductivity is anomalous in character, *i. e.*, it does not fall in with the well established laws of electrolytic conduction, as observed in liquids of higher conductivity. As we pass from the electrolytes into the poorer conducting liquids, the conductivities of the latter are found to vary widely with the degree of purity and care in preparation. This class of liquids, examples of which are chloroform and benzol, in the "pure" state have conductivities from $10^{-6}$ to $10^{-8}$ mho to the cu. cm. In many hydrocarbons values as high as $10^{-13}$ are found. Further Jaffé, Schröeder, and others[1] by electric cleaning, inert electrodes, and high voltage, have reduced the conductivity of certain liquids as low as $10^{-18}$ mho to the cu. cm.

The conductivity of these extremely poor conductors is evidently of different character from that of the electrolytes. Ohm's law is not obeyed, the departures being greater the purer the liquid. In some cases a saturation current, analogous to that in gases, is observed. The nature of the ions which are active is not known. Under close purification and control the conductivity is subject to radio active influence, to the nature of the electrodes, and to impurities which cannot be completely removed by the electric field.[1] As we shall see below, the best insulating oils fall into the class of extremely carefully refined liquids, and so their conductivities and other electrical properties are not completely understood.

Experimental studies of these questions are difficult by reason of the excellent insulating properties of these oils. A-c. measurements are difficult by reason of the small values of dielectric loss, and large values of capacity current. Continuous current observations usually involve the long time application of voltage, and give little information as to the behavior under alternating frequency.

## Experimental Methods

In the present work the principal observations were those of the charge and discharge currents under continuous voltage. The photographic records begin within a small fraction of a second after the application of voltage or short circuit. An Einthoven string galvanometer was used, in conjunction with a rapid, charging, short circuiting, discharging, and reversing switch. Further description of this apparatus is given in an earlier paper.[2] With this combination it was possible to insert the string galvanometer after 0.002 sec. following the first application of voltage, and after 0.002 sec. of short circuit in taking a record of discharge. Under best conditions the photographic record gives a reliable reading beginning 0.02 to 0.04 sec. following the application of voltage on charge, or of short circuit on discharge. Current values for intervals beyond one minute after charge or discharge connection were obtained on a sensitive D'Arsonval galvanometer. A special application of a gold leaf electroscope for the measuring of potential gradient is described below. A few measurements of dielectric loss under alternating stress have been made, using a Wien bridge, with amplified sensitivity. The experiments are continuing in this direction.

The oil was placed in an open glass vessel, into which were immersed a pair of parallel plates, constituting the measuring condenser. The plates were of brass, each of 311 sq. cm. area, and each completely surrounded by a guard ring 3.7 cm. wide in its own plane. The plates were both supported from the same superstructure, which provided means for varying the distance between plates, at the same time maintaining

*Both of The Johns Hopkins University, Baltimore, Md.

1. For numbered references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

accurate parallelism between the two plates and their respective guard rings. The maximum separation was 2 cm. The back of each plate was completely screened, as were also the measuring leads from the central plates. Owing to the extremely small currents to be measured, careful attention to the screening and the avoidance of leakage over insulating supports was necessary at all points. It was also found advisable to have the plates extend to very nearly the full width of the containing vessel. Otherwise at the wider spacings of the electrodes observations were disturbed by external fields, and by

Fig. 1—Oil "A"—Charge at 1500 Volts

Spacing of plates, 0.15 cm

diffusion and slow currents in the oil. Continuous voltage up to 1500 volts was used for various plate spacings between 0.15 and 2 cm. All observations were made at atmospheric pressure and temperatures in the neighborhood of 25 deg. cent.

## The Oils

*Oil (A).* This oil was of the highest grade of insulating oil, furnished by a well known refinery. Amongst other data furnished by the manufacturer is the following: "Resistivity $1.8 \times 10^{14}$ ohms per cu. cm.; moisture content about 0.002 per cent; air content unknown, but approximately saturated."

As measured by us the conductivity of the oil, after 30 min. under continuous potential, varied somewhat with the electric stress, and between the values $1.74 \times 10^{-16}$ and $3.6 \times 10^{-16}$ mho per cu. cm. These figures indicate an improvement over the maker's figures, and also the extremely high insulating character of the oil.

The oil was ordered furnished in a 3-gal. container, which was sealed at the refinery. It was placed in the measuring cell without further treatment. We will speak of this oil as Oil (*A*).

*Oil (B).* As a deteriorated oil, a sample of the same oil as Oil (*A*) was taken from a 50-gal. metal drum, which had been shipped under the same conditions, but from which oil had been drawn from time to time over a period of several months. Deterioration, if present, was due solely to such air as had been admitted to the drum during the withdrawals of oil, and to any possible influence of the walls of the drum itself. The residual conductivity of this oil showed very much wider variations with electric stress than did Oil (*A*). Under approximately similar conditions Oil (*B*) showed a residual conductivity of from 7 to 8 times that of Oil (*A*). The average figure of $2.4 \times 10^{-15}$ mhos per cu. cm. shows however that the oil still had very high insulating value.

## Observations on Oil (*A*)

*Charging Current Curves.* Fig. 1 shows the photographic record of the charging current-time curve when 1500 volts are applied to Oil (*A*), with plate spacing of 0.15 cm. This curve resembles the typical dielectric absorption curve noticed in solids. It is, however, of brief duration, the current reaching an approximately constant value after 3 sec. This curve is reproduced in Fig. 2, together with those on the same specimen taken at 1000 and at 500 volts. The curves are not of exactly the same shape, and the initial ordinates increase more rapidly than in proportion to the voltage. The final long time conductivity is independent of voltage in the range studied. We call attention to the probable value of the short interval method for further study of this relationship in its bearing on the approach to breakdown voltage.

*Discharge Curves.* It is usually assumed that good dielectric liquids show no residual charge. Both the oils studied here are in general accord with this assumption.

In taking the discharge curves the condenser is short-circuited for 0.002 sec., which is more than sufficient for the complete disappearance of the circuit transient. The galvanometer is then cut into the discharge circuit.

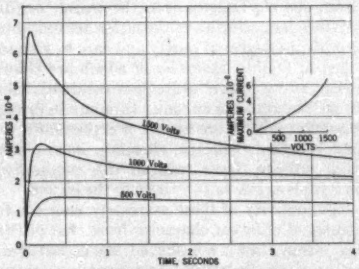


Fig. 2—Oil "A"—Current on Charge

Spacing of plates, 0.15 cm.
Area of plates, 311 sq. cm.

On the records we find no evidence of an initial peak value, corresponding to a normal residual charge. There is, however, a suggestion of a sustained low valued current decaying relatively slowly. Thus on discharge there is no initial high-value of current and indeed evidence of any residual charge whatever is limited to a long slow discharge of such low value as to be difficult to detect.

*Charge at Reversed Polarity.* The pronounced differences between the charge and discharge conditions above raise several questions as to the type, permanence, or rate of recovery, and other features of the

anomalous conductivity indicated by the charging current. Consequently a series of records was taken in which a period of charge was followed by a reversal of voltage. The sequence of operations was as follows: Following a long period of charge the circuit is opened for 0.005 sec., after which the circuit is closed in the reverse direction. After 0.0025 sec., during which the reversal of geometric charge and circuit transient have disappeared, the string galvanometer is put in circuit.

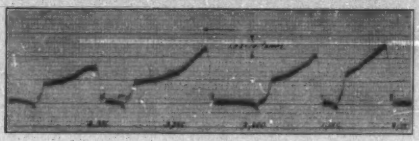

FIG. 3—OIL "A"—CHARGE WITH INTERVALS OF SHORT CIRCUIT

No foregoing charge
1500 volts. Spacing of plates, 0.15 cm.

After the short photographic record the d'Arsonval galvanometer gives the long time current values.

On reversal the initial peak is absent, at 0.2 sec. the current is somewhat though not much greater than that immediately before reversal and decays slowly to that value. We interpret this result as indicating an appreciable though not great recovery of initial conductivity during the 0.005 sec. interval of open circuit; and that on quick reversal of field the conductivity remains substantially unchanged.

FIG. 4—OIL "B"—CHARGE WITH INTERVALS OF SHORT CIRCUIT

Long time foregoing charge
1500 volts. Spacing of plates, 0

*Successive Short Interval Charges.* Further evidence of the time necessary for the recovery, after interruption and short circuit, is given by the record of Fig. 3, which shows a succession of charging intervals all at the same voltage and polarity, but with short circuits of varying duration in between, and in Fig. 4, in which we have the same succession of charging intervals, but which are taken after a very long foregoing period of charge. These records show that the shorter the period of interruption and short circuit, the greater the difference between the foregoing current pulse and that which follows, and conversely, the longer the period of interruption the more nearly the approach to the original condition. Fig. 4 also indicates that following a long period of charge the succession of charging curves are all somewhat lower in value and steeper, suggesting either that the long period of charge has caused some clean-up of original conductivity, or expressed in another way, that the recovery of the initial condition is retarded by a prolonged period of charge. The falling value of the current with time, however, remains in all cases very pronounced.

To further study the rate of recovery, beginning after a long period of idleness, a series of charging curves was taken, each of 15 min. duration with increasingly long intervals of idleness in between. In this way it was found that about 3 hr. was necessary to restore the oil to its initial condition.

## OBSERVATIONS ON OIL (*B*)

*Charging Current.* The charging current time curves of this oil differ markedly from those of Oil (*A*). They

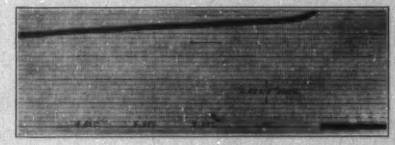

FIG. 5—OIL "B"—CHARGE AT 1500 VOLTS

Spacing of plates, ¼ cm.

are characterized by an initial value, which remains approximately constant over a period of two sec. or more. This is indicated by the record of Fig. 5, which should be compared with that of Fig. 1, both being taken under approximately the same conditions. The difference between the two is further emphasized by the long time curve of Oil (*B*) in Fig. 6.

At times the initial portion of the charging curve for Oil (*B*) contains a slight hump shortly after the application of voltage. (See Fig. 7.) The appearance of this hump is limited to records taken at the higher values of gradient, and is sometimes entirely absent. Evidence is presented below to indicate that this is the result of an unequal distribution of space charge, following some foregoing period of charge or discharge.

The essential differences between the two oils are: (1) that the initial values of charging current in Oil (*B*) are well in excess of those in Oil (*A*); (2) these initial values in Oil (*B*) are substantially constant over an interval of a second or more, while those in Oil (*A*) are falling rapidly from the start; and (3) the initial values in Oil (*B*) are closely proportional to the applied voltage, while those in Oil (*A*) increase more rapidly than the voltage.

Whatever be the causes of these differences in two samples of the same oil, it is evident that these causes must be of quite common occurrence. Moreover Oil (*B*),

somewhat poorer though it appears as compared with Oil (*A*), must still be regarded as in a highly satisfactory condition as regards ordinary insulating purposes. It seems to us therefore that in view of the differences shown, we have in the short interval current curves an important method for the study of the properties and especially the deterioration of high-grade insulating oils. Our own studies are continuing.

*Discharge Curves.* The records of discharge current in this case, as in the case of Oil (*A*), show little evidence

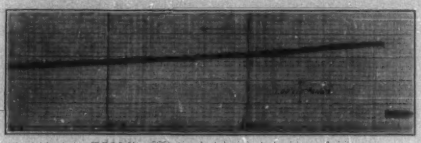

Fig. 6—Oil "B"—Charge at 1500 Volts

Spacing of plates, 1 cm.

of a definite residual charge. There is, however, some evidence here also, as in Oil (*A*), of a slow but long sustained value of discharge current.

*Charge at Reversed Polarity.* The conditions for this test were prolonged application of voltage followed by a brief period of open-circuit, and then the application of an equal value of reverse voltage, the string galvanometer then being cut in for reading the reverse current, all as described for Oil (*A*).

The outstanding features of all records of this char-

Fig. 7—Oil "B"—Charge at 1500 Volts

Spacing of plates, ½ cm.

acter on Oil (*B*) are as follows: At first the reverse current is approximately constant over a period of perhaps 1 sec., and at about the same value as that at the end of the preceding period of charge in the opposite direction. The current then rises rapidly to a maximum, this maximum occurring anywhere from 2.5 to 7 sec. after the reversal. The magnitude of this maximum may be as great as 40 times the initial constant value of current on reversal, and from two to three times the initial value of charging current when voltage is applied to the neutral oil, the ratio increasing with increasing field strength. These peaks in the reverse current are not evident in the lower range of values of field strength. For higher values the principal peak may be followed by a tendency to a second peak of very low value before the current reaches a final constant value, see Fig. 8.

This reversed polarity curve clearly suggests that the oil possesses two types of conductivity. One of these is quick in response, and is seen in the initial and final charging current, in the initial current on reversal, and may therefore be any one of the several types of conductivity which have been suggested for liquids, namely electrolytic, or perhaps a type analogous to that in gases, as suggested by observations of Mie,[3] Schröeder,[4] and others, in ultra-refined liquid dielectrics. Evidence in favor of the latter is presented in the saturation experiments to be described below. The second type of conductivity is that involved in the high peak in the reverse current. This evidently suggests either the presence of some large and slow moving ions, or some slow process of recovery of the initial conductivity pertaining to the neutral oil. It is difficult to see how the latter can be the explanation, since the peak in reference has a definite time lag after the idle period of open and short circuit, and since there is no way in which a mere reversal of voltage would have an influence on an orig-

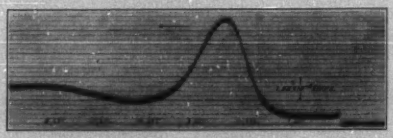

Fig. 8—Oil "B"—Reversal of Polarity at 810 Volts

Spacing of plates, ½ cm.

inal rate at which ions of a particular type are produced.

We were led, therefore, to consider the possibility of the presence in the oil, when voltage is applied, of space charges which are not drawn out at the electrodes by the electric field, and which exist in the form of heavy slow-moving ions. Such a charge or cloud of ions would not only account for the maximum of the reverse current curve, but would also set up a polarization e. m. f. and so possibly contribute to the original slowly decaying character of the charging current of the neutral oil. The following experiments seem to prove beyond question the presence of such space charges.

*Non-uniform Potential Distribution.* If after the application of voltage the oil contains separated space charges of opposite signs, and these are distributed through the mass of the oil, they upset the normal uniform potential gradient generally ascribed either to a perfect dielectric or to a uniformly conducting material, and cause a non-uniform potential gradient. Such non-uniform gradients have been observed by Mie,[3] in carefully refined ethyl ether, and his results have been used by Schröeder[4] to show that the last traces of conductivity in liquids obey the laws of gaseous conduction. Our

results indicate that such non-uniform gradients are present in the oil ($B$), thus indicating further its good insulating character. We have not studied Oil ($A$) in this particular, but judging from the character of the curves for reversed polarity, we suppose that the departure from a uniform potential gradient would be much less than in Oil ($B$).

The experimental method is simple in principle, being merely that of measuring the potential acquired by a test electrode or probe placed at different positions between the two charged plate electrodes. The experimental application of this principle, however, involves many difficulties, chief among which are the low values of current in the oil, and the consequent up-setting of the normal existing condition, if any considerable charge is taken by the test electrode and the detecting instrument. A zero method is necessary and was obtained as follows: An inclined gold leaf electrometer was used as having very low electrostatic capacity, high sensitivity, and rapid deflection. The case of the electrometer was insulated and connected to one terminal of a variable voltage, d-c. generator. The leaf of the electrometer is first connected to the case. The potential of the case is then raised to the estimated potential of the test electrode, as indicated by a succession of approximate observations. The leaf is then disconnected from the case and connected to the test electrode. If the latter is at the same potential as the case, no change in deflection results. Otherwise a deflection is obtained and another adjustment of voltage made. Evidently at zero reading the potential of the test electrode is the same as that of the d-c. generator, which may be read independently. Greater sensitivity may be obtained by charging the gold leaf. This may be done by incorporating in the insulated electrometer system a 200-volt radio battery. This method was used in our experiments. The test electrode consisted of a very light and thin rectangular copper frame about 6.3 cm. square, over which was wound a 0.005 in. diameter "Therlo" wire, forming a sort of grating. This was rigidly fitted to a carriage moving in a slot on the super-structure of the electrode system, and along which it could be moved to different positions in the oil by screw motion. The principal result of these studies is as follows:

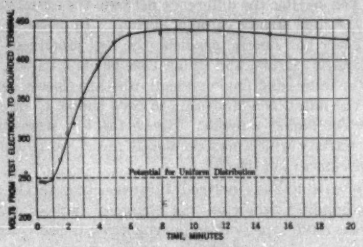


FIG. 9—OIL "B"—VARIATION OF TIME OF POTENTIAL DISTRIBUTION IN TRANSFORMER OIL

Area of plates, 311 sq. cm.
Spacing of plates, 2 cm.
1500 volts between plates
Test electrode ¼ cm. from grounded terminal

On first application of voltage the potential distribution remains uniform throughout for from 15 to 30 sec. The potential at any point off the central plane then changes with time at first rapidly and then arrives more or less abruptly at a final steady value, after from 5 to 10 min. This is indicated by the curve of Fig. 9, which thus shows the time rate of change of the potential of plane occupied by the test electrode from its initial value pertaining to a uniform field between the plates.

The distribution of potential in the final steady condition is shown in Fig. 10. Our final check on the accuracies of these final observations was the agreement of values as measured from either electrode at ground potential, and with reversed polarity in each case. The observations under the several conditions are indicated by the groups of points for each position of the test electrode.

It is evident from the curve of Fig. 10 that there is a marked variation of potential gradient between plates, that it is symmetrical with reference to the two plates, and that the gradient is greatest towards the two electrodes. The shape of the curve suggests that the potential gradient is steepest near the electrodes. There is an indication, however, of a distributed space charge, rather than a thin layer of high potential difference at the surface of the electrodes, as suggested by Hartshorn,[5] Black,[6] and others. Fig. 11 shows the relation between the time variation of the potential of the test electrode and the resulting total current through the oil. It is seen that the interval during which the potential gradient at any one point is changing most rapidly is also the interval during which the charging current is dropping most rapidly. This is the relation which would

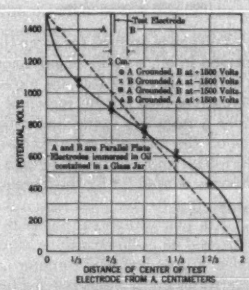


FIG. 10—OIL "B"—DISTRIBUTION OF POTENTIAL IN TRANSFORMER OIL IN STUDY CONDITION

(After passage of current for 30 min.)

obtain if the fall in current were due to the accumulation of a counter or polarization e. m. f., due to an accumulation of space charge near the electrode. It is obvious, however, that some other phenomenon is involved in the decay of the current, since it continues to decrease after the potential of the test electrode has become constant.

*Detection of Space Charge.* The presence of a space charge may be directly observed by the following simple

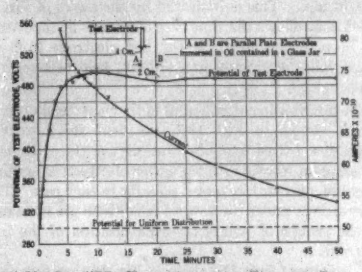


FIG. 11—OIL "B"—VARIATION WITH TIME OF POTENTIAL DISTRIBUTION AND CURRENT IN TRANSFORMER OIL

Area of plates, 311 sq. cm.
1500 volts between plates

experiments: Voltage is applied for some time to a pair of plates immersed in oil, a ballistic galvanometer being connected in series. If the plates are moved suddenly parallel to themselves into a fresh region of oil, the galvanometer gives a negative swing, indicating that the original charge on the plates is greater than that which pertains to the initial application of voltage to fresh oil. This can only be accounted for by the increased capacity in the original oil, due to the polarizing influence of the space charge. If a pair of neutral plates is moved into the region of stressed oil, following the withdrawal of the active electrodes, a gold leaf electrometer connected to the neutral electrodes gives a sharp deflection, followed by a slow decrease, due to the space charge or polarization of the oil from which the polarizing field has been withdrawn.

*The Saturation Currents.* In Fig. 12 is found a number of complete charging current time curves on Oil (*B*), the initial values being taken from the string galvanometer records and the later values being read by the galvanometer. The spacings are from 0.25 to 2 cm. and the voltages 750 and 1500 volts. We note two important characteristics of these curves. First the initial value of current, which we have already noted remains constant for 1 sec. or more, (not evident in these curves owing to the extended scale), is shown to be almost exactly proportional to the potential gradient indicating a constant initial conductivity. The value of this conductivity, from the average of 30 records taken over the whole range of spacings and voltages, is $5.1 \times 10^{-14}$ mho per cu. cm. Of interest also is the fact that a saturation condition is indicated in the values of the final steady current. The readings at 1500 volts show that the final steady current decreases with decreasing spacing below 1 cm. spacing. The comparison of the curves at 750 volts and 1500 volts indicates that with double spacing at the same gradient the current increases. These facts are in general agreement with the saturation phenomenon in gases, although the numerical relationships are not exact.

Considering further these current time curves, it is noted that the greater the spacing and the less the voltage, the smaller the difference between the initial value and the final steady value of current. In other words, the lower the electric gradient the less prominent the absorption feature, and in our case below 0.25 volt per mil the initial and final conductivities are closely equal. But the initial conductivity has been shown to be constant for higher stresses: Hence the low stress final conductivity which may be readily measured is seen as a true constant of the oil.

We have already noticed, however, that in Oil (*A*) corresponding values on the charging current curves increase more rapidly than in proportion to the voltage. Consequently an early hope that the above mentioned

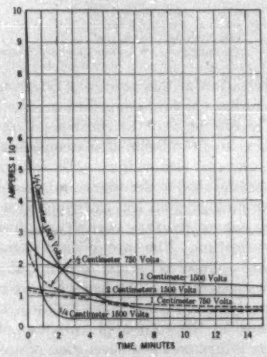


FIG. 12—OIL "B"—CURRENT ON CHARGE AT VARIOUS SPACINGS AND VOLTAGES

Area of plates, 311 sq. cm.

simple relation for Oil (*B*) might hold for all oils had to be abandoned.

*Energy Loss Under Alternating Stress.* The exceptionally high insulating properties of these oils result in very low values of energy loss. Measuring equipment of unusual sensitivity is necessary for the measurement of these losses in such small samples as represented by our test cell. However, in using a high sensitivity Wien bridge with three stages of amplification, we have succeeded in measuring the loss at 1500 and 1000 volts, 60 cycles, the resulting values being $1.13 \times 10^{-4}$ and

$0.43 \times 10^{-4}$ watts. These figures represent power factors in the neighborhood of 0.0003. The figures, as checked by repeated observations, and in terms of the accuracy of the bridge setting, are estimated to be correct within from 5 to 10 per cent.

The charging current curves under continuous voltage may be expressed in terms of apparent resistance, and the values corresponding to the initial peaks of charging current curves for the conditions under which the above alternating measurements were made are $3.33 \times 10^{10}$, $3.13 \times 10^{10}$, and $2.24 \times 10^{10}$ ohms for 500, 1000, and 1500 volts respectively. If the alternating loss be expressed in terms of parallel connected resistance, the figures given in the foregoing paragraph are $2.4 \times 10^{10}$ and $2.73 \times 10^{10}$ ohms for 1500 and 1000 effective alternating voltages respectively.

These figures indicate that the apparent resistances computed from the charging current curves are of the correct order of magnitude to account for the a-c. loss. In other words, the anomalous conductivity of the liquid is sufficient to account for the loss and it is not necessary to invoke any more obscure causes. One[7] of us has recently shown that this is accurately true for high grade impregnated paper insulation. It is our hope to extend our studies to a more exact correlation between continuous and alternating characteristics of these oils.

## Conclusions and Discussions

The principal results of the work are:

1. Charging current curves of a high grade insulating oil have been studied to within a few hundredths second of the first application of continuous voltage, over the range 0.25 to 100 volts per mil.

2. Typical dielectric absorption curves are found in some cases. In others striking differences and peculiarities are found. Two orders of the same oil differed radically. The method gives great promise for the detection of fundamental differences among various samples and materials.

3. Short time discharge studies gave no evidence of residual charge.

4. Under continuous potential the oils show a non-uniform potential gradient. This is found to be due to space charges in the volume of the oil.

5. Long time application of continuous potential improves the oil substantially, but only for a limited time, the oil slowly reverting to its original state.

6. Loss measurements under alternating stress indicate that the anomalous conductivity under continuous stress is sufficient to account for all the loss.

One of the outstanding results of the work is the wide difference found in the properties of two oils, supposedly the same, and typical of the best grade of the insulating oils of practise. There is little or no difference in the history of the oils. Moreover, no appreciable change in the properties of either oil was observed over a period of months, during which the oils were being studied and each exposed to the air. Each oil was apparently originally saturated with air, and any influence of the air is probably to be found in its relation to the original make-up of the oil, since there was no appreciable change during the experiments.

Considering the bearing of these variations in properties on the performance of the oil as an insulator, it is reasonable to assume that the most important are the short time characteristics. Here the two oils differ radically and we may expect corresponding differences in the behavior under alternating stress. The high flat curves of Oil (*B*) suggest many more and larger ions than in Oil (*A*). It is not certain that this indicates a more advanced deterioration, although this seems probable, in view of the indirect evidence of the greater number and size of ions present in Oil (*B*).

The pronounced space charge found in Oil (*B*) is evidently a very slow phenomenon and there is no evidence that it has a direct bearing on the behavior under alternating stress at commercial frequencies. The time interval for the reversal of the position of space charge permits computation of the specific velocity ($1 \times 10^{-4}$ cm. sec. volt cm.) of the ions involved. This figure indicates a slow and probably large and heavy ion. It is also probable that the long period required for the recovery of the original properties of the oil, and also the hump sometimes noticed in a charging curve (see Fig. 7), are to be attributed to the slow motion of clouds of space charge, particularly in the absence of an electric field. There is little or no direct evidence of the presence of space charge in Oil (*A*), although indirect evidence indicates it is present in some degree. In an appendix we have attempted to give a picture of the character of the space charge, which seems to explain the principal experimental results.

It appears probable that the peculiarities and variations that we have been studying are due to oxidation in presence of the absorbed air. So interpreted the results throw interesting light on the limits of oxidation, influence on conductivity and loss, rate of elimination, recovery, progressive deterioration, etc. It is our hope to continue the studies in these directions.

The work has been carried out under the provisions of a grant by the Engineering Foundation to the Johns Hopkins University, the problem being sponsored by the American Institute of Electrical Engineers. Contributions to the fund have been made by a number of industrial corporations. The authors wish to express their appreciation of the constant interest and encouragement of the Engineering Foundation and of the support of the contributing companies.

## Appendix

### Space Charge in Liquid Dielectrics

Remembering that the liquid in the original neutral condition contains an equal number of positive and negative ions, uniformly distributed through the body of the liquid, space charges, when the liquid is subjected

to electric stress, may arise in two obvious ways. The first is by the withdrawal or loss of ions of one sign from any particular region. The second is by a similar excess or gain of ions of one sign. In each case reference is had to the original neutral state of the liquid as regards the number of ions of each sign per unit of volume.

## Space Charge Due to Withdrawal of Ions of One Sign

Consider the application of a continuous potential difference to a pair of parallel plates immersed in the liquid. The resulting motions of the ions of opposite signs in opposite directions tend to withdraw the ions of one sign from the neighborhood of the electrode of the same sign. This in effect constitutes a space charge in the neighborhood of each electrode. The magnitude and the distribution of this space charge evidently depends upon the velocity with which the original ions are withdrawn, the rate of regeneration of new ions, the rate of diffusion and recombination, and probably other factors as well. We may say, however, that during a brief period of time following the application of voltage there is a central section in which the original density of both positive and negative ions remains the same, this region, however, becoming thinner with increase of time. On the two sides of this central region there are regions in each of which there is an excess of ions of one sign, thus constituting a space charge. This simple picture is sufficient to explain a number of the experimental results reported above.

The conception of the motion and separation of the ions, and the resulting conductivity, is much the same as that in the more highly developed theory of electrical conduction in gases. In fact the application of this theory to liquids has been examined by Mie[3] both analytically and experimentally in connection with his observations on the final steady current in highly purified ethyl ether. He finds and accounts for a steeper potential gradient near the electrodes, this gradient becoming less as saturation is approached. The work of Mie has led to a general acceptance of the fact that in highly refined simple dielectrics the laws of current conduction in the steady state are in fair accord with the theory of gaseous conduction.

Apparently the variation of the current with time, following the first application of voltage, which as we have seen is present in the very best insulating liquids, has never been explained in terms of ionic theory. This is accounted for by the complex character of the phenomenon, into which enter several components not completely understood, for example the origin and rate of generation of new ions, rates of recombination and diffusion, variations in the size and mobilities of the ions, etc. As a consequence it has so far not been possible to combine these several components in a simple differential equation admitting a general solution. Yet, it is obvious that a slow withdrawal of ions and an accumulation of space charges near the electrode, resulting in a polarizing e. m. f., must cause some such decreasing current time relation as is observed in experiment. If we make several assumptions which are not too violent, even although there is little experimental evidence in support, it is easy to deduce an expression for the current, which is in approximate agreement with experiments.

Let $n_o$ be the number of ions of each sign per cu. cm. in the neutral oil before potential difference is applied, $v$ the specific velocity of the ions of either sign, $n$ the number of new ions formed per cu. cm. per sec., $\epsilon$ the charge on each ion, $K$ the dielectric constant, and $n_t$ the number of ions per cu. cm. in the region of the space charge at any instant $t$. The value of $n_t$ will obviously depend on $n$ in its relation to the total velocity with which the ions are withdrawn under the influence of the external field, as well as on the rates of recombination and diffusion of the ions. For the sake of simplicity we may assume simply that $n_t$ is a decreasing function of $(E\,v)$, in which $E$ is the applied potential gradient, thus $n_t = f\,(E.\,v.)$; also, $n_o > n_t > n$.

After time $t$ the boundary between the central group of both types of ions, and the region of space charge, has advanced to a distance $v\,t$ from each electrode. At this time the ions $n_o$ of each sign in the central region will move under an electric gradient due to the external applied potential difference, less the counter potential difference due to the space charges. The ions $n_t$ in the space charge region will also move in a field made up of the external gradient less an average value of the counter field due to the space charges. The total current in the external circuit will be that due to the joint motion of these two groups of ions. The relative numbers of each group is determined by the relation of $v\,t$ to $l$, $2\,l$ being the distance between plates.

The current at time $t$ will thus be:

$$i_t = n_o\,\epsilon\,v\left(E - \frac{4\,\pi\,n_t\,v\,t\,\epsilon}{K}\right)\left(\frac{l - v\,t}{l}\right)$$

$$+\, n_t\,\epsilon\,v\left(E - \frac{4\,\pi\,n_t\,v\,t\,\epsilon}{2\,K}\right)\left(\frac{v\,t}{l}\right).$$

$$= E\,v\,\epsilon\left(n_o - n_o\,\frac{v\,t}{l} + n_t\,\frac{v\,t}{l}\right)$$

$$-\,2\,\pi\,v\,\epsilon^2\left[\,2\,n_o\,n_t\left(1 - \frac{v\,t}{l}\right) + 2\,n_t^2\,\frac{v\,t}{l}\,\right]t.$$

It is readily seen that this current decreases continuously with the time and has the following values for the several values of the time as indicated:

When $t = 0$, $v\,t = 0$, $i_t = E\,v\,e\,n_o$

$t = \dfrac{l}{v}$ $\quad i_t = E\,v\,e\,n_t - 4\,\pi\,n_t^2\,\epsilon^2\,v\,t$

$t > \dfrac{l}{v}$ $\quad n_t$ decreases further in accordance with $n_t = f\,(E\,v)$, with $n$ as a limiting value

Thus this picture of the accumulation of space charges due to the withdrawal of ions of either sign from the neighborhood of the electrodes, explains an initial conductivity obeying Ohm's law, saturation current, and a charging current decreasing with time. The absence of a discharge current may also be explained as follows: On short circuit as the space charges recombine in the liquid, a part also passes into the electrodes in the absence of an external e. m. f. and recombine through the external circuit, thus forming a current in the opposite direction. On the other hand, there are two conspicuous phenomena in the experimental studies which are not accounted for by this theory, namely, the maximum of current which is observed on the reversal of polarity as shown in Fig. (8), and the unequal potential gradient. There is apparently no way in which the maximum on reversal can be explained in terms of space charge originating in a withdrawal of ions of one sign. It is therefore necessary to add something to the picture already presented. We find this in the second type of space charge mentioned above.

### Space Charge Due to Excess of Ions of One Sign

In an earlier paper we have called attention to the following picture of another type of space charge. We may assume a number of free ions always present, even in the more refined insulating liquids. The intense electric field near each of these ionic charges attracts to it a cloud of neutral dielectric molecules, thus increasing the mass and size of the ions and surrounding the central charge with a non-conducting envelope of greater or less thickness. On application of continuous difference of potential these enlarged and heavy ions of opposite sign move slowly and in opposite directions. When these ions reach the electrodes, owing to the non-conducting envelopes of neutral molecules the charges of many of the ions will be unable to escape and ions will accumulate in a layer or layers close to the electrode. Thus on first application of a potential difference, the ions will tend to move to the electrodes with velocities proportional to the external field, thus resulting in a current obeying Ohm's law. As the layer of space charge accumulates near the electrode, the polarizing or counter e. m. f. rises, the velocity of the ions back of the space charges falls off, and the current decreases with time. At very low values of voltage the number of ions arriving at the electrodes may not exceed the number which normally give up their charges and no space charge will accumulate. For very high voltages the ions reach the electrodes more rapidly, pack more tightly, discharge less rapidly, and the tendency will be for a thinner layer of space charge, a sharper potential gradient near the surface and a total charging current starting with a high initial value, but falling rapidly to a final constant value. At sufficiently high values of voltage this final current might have a saturation characteristic. Unper this last condition the high field intensity between the space charge and electrode will pull the charges from the centers of the molecular groups as rapidly as new ions arrive at the outer face of the space charge.

An exact analysis covering the processes of regeneration, recombination, diffusion, and other factors, is as difficult here as in the foregoing case, but it is not difficult to show, with simple assumptions, as in the foregoing case, that the current decreases with time.

A review of the experiments on Oil ($B$) will show that they are in general qualitative accord with the foregoing. The initial charging currents obey Ohm's law. Their rates of decay and their final values show the variation with field intensity and the saturation characteristics as described. The actual presence of space charge is shown and its resulting influence in producing a non-uniform potential gradient. The experiments with reversal of polarity are especially significant in revealing the slow reversal of position of the opposite space charges with resulting maximum of current. The time required for this reversal shows at once the velocities of motion of these ions as $1 \times 10^{-4}$ cm. per sec., per volt, per cm., which is low for this type of liquid and indicates the large and heavy character of these ions. Other phenomena of interest are the relation between the rates of decay of charging current, and the accumulation of space charge, as related to potential gradient and the records showing repeated charging intervals, in the evidence they afford as to the rates of accumulation and recovery in the successive active and idle periods.

It is to be noted that the phenomenon of the accumulation of space charge in Oil ($B$) is a relatively slow matter. The decrease in charging current, the rate of reversal of charge, and the accumulation of space charge, all extend over considerable intervals of time. It is not evident that the steep short time curves of Oil ($A$) are due to the same cause, although it appears not improbable. It is more likely that both types of space charge occur in all oils of this type and that their differences are to be accounted for by the varying magnitudes of the two types.

One feature of this work which stands out as yet unexplained is the departure of the initial charging current values in oil ($A$) from Ohm's law. Work is being carried further in a study of this question and of the relation between the continuous current and a-c. characteristics.

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## Discussion

**W. B. Kouwenhoven:** The discovery of the presence of a space charge in a liquid dielectric, reported by Drs. Whitehead and Marvin, is a very important one. I have also found evidence of this phenomenon in a specimen of high grade cable compound. In this particular specimen to which I refer, all of the dielectric loss is accounted for by conduction. In our early studies of this material we took oscillograms of the charge and discharge currents under continuous potentials at approximately three-hour intervals. The charge period used extended over forty minutes, and was followed by a discharge or short circuit period of a couple of hours. A high sensitivity galvanometer measured the currents following the oscillograms and after about ten minutes no measurable discharge current could be detected. It was assumed that the compound had fully recovered its initial characteristics in the intervals between charges. The results, however, did not check; the conduction current was a maximum for the initial charge run of the day, the subsequent tests giving lower values.

Fig. 1

A study of the phenomena was therefore made. Fig. 1 herewith shows oscillogram 151, giving the charge and discharge currents of the initial 500-volt continuous potential applications. The charging current is a straight line having a value $10 \times 10^{-4}$ amperes and remains constant during the entire length of the oscillogram. The d-c. calculated conduction loss is 50 microwatts which checks with an a-c. dielectric loss of 51 microwatts measured at an alternating potential of 500 volts, (effective) 60 cycles, immediately preceding the oscillogram 151.

In Fig. 2, oscillogram 154, is a record of the charging current at 1500 volts, obtained with this same specimen after allowing a short circuit or recovery period of forty minutes following the initial application of continuous voltage.

Oscillogram 154 does not show a constant value of charging current. Instead the charging current rises to twice its initial value about 1¼ sec. after the application of voltage, and then decreases gradually. This rise in charging current we believe is due to a space charge set up in the oil during the preceding charge period. As the length of the short-circuit period was increased the rise in charging current became less pronounced and its maximum occurred at a later time. In this particular compound it required a short circuit period of seven hours for the space charge to vanish and the material to return to its initial condition.

We also found that the previous direct-current history of the oil had a considerable effect upon its dielectric loss, as measured under alternating potentials. The application of direct current apparently improved the compound and lowered its dielectric loss.

Fig. 2

**C. L. Dawes:** (communicated after adjournment) May I ask if the authors noted any effects of occluded air. Apparently the electrodes were immersed in an open vessel containing the oil. It has been our experience that under such conditions a very appreciable amount of air becomes entrapped, probably in the form of very small globules which adhere to the surface of the electrodes. We find it necessary to prepare such samples under very high vacuum in order to eliminate entrapped air.

On page 653 it is stated that "Each oil was apparently saturated with air and any influence of the air is probably to be found in its relation to the original make-up of the oil." This occluded and absorbed air may in part explain the space-charge ionization effects which are discussed later in the paper.

# High-Voltage Corona in Air

BY SIGMUND K. WALDORF*

Associate, A. I. E. E.

*Synopsis.—In the last few years contributions to corona literature by Holm, Ryan, Willis, and others have shown that the space charge liberated by alternating corona reacts on the corona to a high degree in determining its characteristics. This investigation studies the nature of these effects as influenced by variation in the limits of travel of the space charge.*

*The three properties of corona readily lending themselves to experimental observation, the wave form and the value of the corona current, and the corona loss, have been observed when high alternating voltages are applied to a small smooth cylindrical conductor placed successively along the axes of four sizes of metal cylinders. In addition four frequencies of the alternating voltages were used. All the work has been done under atmospheric conditions.*

*The theory of the influence of space charge as developed by Holm has been tested by experiment and a marked discrepancy is indicated. Values of power loss due to corona, as measured, differ appreciably from those predicted by Holm, but in general follow the quadratic relation suggested by Peek.*

*Unusually large and clear oscillograms afford much interesting qualitative information as to the influence of space charge travel on corona.*

* * * * *

ALTHOUGH corona has been studied for many years and under many conditions, only in recent years have investigators realized that the space charge accompanying alternating corona plays an important role in determining the coronal characteristics. Since 1924, the papers published on corona have dealt principally with this space charge, attempting to fix the limits of its travel from the discharging conductor, and with the effects of the variation of these limits upon the magnitude of the corona loss and of the corona current. The work up to that time has been treated in the well-known books by Thomson,[1] Townsend,[2,3] Peek,[4] and Schumann.[5] Recently S. Whitehead[6] has given a brief outline of the subject with an extensive bibliography. Other recent contributions dealing with high-voltage phenomena and including good bibliographies of the corona literature are those of A. Roth[7] and U. Retzow.[8]

An important recent contribution to the theory of corona formation and behavior is that of Holm.[9] He has developed a formula for the calculation of the corona loss, and Willis[10] has developed a corresponding one for the corona current, both of which have been based on the theory that the space charge moves outward from the corona discharge at a definite rate fixed by the mobilities of the ions involved. As has been pointed out by these two authors, the accurate determination of these mobilities is extremely difficult. Both have chosen average values of mobilities for their respective formulas and each gives experimental observations in general accord with his theoretical development.

Carroll and Ryan[11] attempted to determine the manner in which the space charge moves by the insertion of an exploring wire in the electrostatic field. Willis[10] obtained the farthest travel of the charge. In this latter determination a minimum of charge is prevented from returning to the wire and thereby a minimum of distortion of the field results. In the free and unrestricted state the whole amount of charge liberated by the corona is thought to return to the corona wire or to combine with the charge of the succeeding half wave. When the opposite electrode is sufficiently close to the wire, varying amounts of the space charge reach it and are prevented from returning to the wire or recombining. The exact amounts depend upon the supply frequency and the electrode spacing, other controlling factors remaining fixed.

The present investigation studies the effects of the restriction of travel of the space charge upon the corona loss and upon the wave form and value of the corona current. The alternating corona discharge was formed on a hard drawn solid copper wire, 0.204 cm. in diameter, in air at atmospheric pressure. The wire was placed in succession along the axes of four guarded hollow sheet metal cylinders of 155, 61, 30½, and 15 cm. diameter, respectively. In accordance with the theory just discussed, varying amounts of the space charge reach the walls of the cylinders each cycle, under a given set of conditions, depending upon the respective cylinder diameters. The greater the cylinder diameter, the farther the charge must travel to the cylinder walls and hence the less the amount that will reach them in a half cycle of voltage at a given frequency.

The frequency of the supply voltage must also enter as a factor determining this amount. The lower the frequency, the more time allowed after the formation of corona for the outward motion of the charge, and hence the more going to the walls of a given size of cylinder in each half cycle. Thus in addition to using four sizes of cylinders, sinusoidal voltages of four commercial frequencies of 30, 40, 50, and 60 cycles per second were used.

Changes in the values of corona loss and current, and variations in current wave form under these various conditions give new evidence as to the influence of space charge travel.

*Research Assistant in Electrical Engineering, The Johns Hopkins University, Baltimore, Md.

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## I. The Measurement of Corona Loss and Current

Holm has been an outstanding contributor to our knowledge of corona formation with his work on the development of a quantitative theory of space charge behavior. As his formulas include a form for the calculation of conditions about a wire in a cylinder, it has been possible in this investigation to compare directly theoretical and experimental values of space charge travel and of corona power loss. The corona loss observations have also been compared qualitatively with the quadratic relation suggested by Peek.

### Apparatus and Experimental Method

The corona loss was measured with a quadrant electrometer wattmeter connected in the usual manner for power measurements. The needle voltage up to a maximum of 1800 volts was supplied by a 2 per cent and a 5 per cent tap on the transformer high-voltage winding. By insertion of resistance to ground in the guard electrodes of the corona cylinders, they were always raised to the same potentials as the central or measuring electrodes. This guard resistance was regulated until a vacuum tube voltmeter connected between the two circuits gave a minimum deflection, indicating both at practically the same potential.

This voltmeter was arranged so that it could be converted by a simple switching operation into an amplifier having a sharply peaked response at the higher audio frequencies. In this latter capacity it served as an excellent corona detector when a radio headset was connected to its output. Below the critical value of voltage, the charging current of the corona wire is of perfectly smooth wave form, but at the instant of corona formation higher harmonics are introduced. When this current acts on the corona detector, a low hum is heard at the supply frequency below corona voltage. At the critical voltage a loud and high frequency buzz begins, which serves to give exceedingly sharp and definite indications of the formation of the discharge.

The vacuum tube rectifier and d-c. microammeter used for measuring the corona currents were of the usual type and need no detailed description. The high voltage was measured by reading the charging current of an air condenser in parallel with the corona cylinders.

### Wattmeter Calibration

The electrometer wattmeter was calibrated with 60-cycle alternating current and a pure resistance load, the load voltage being applied directly to the electrometer needle. The transformer taps used to supply needle voltage for the corona measurements were checked as being correct with potential transformers. As a further check a power measurement was made using a length of high-voltage cable with various amounts of known resistance in series as a load. This checked the electrometer constant as well as the 5 per cent transformer tap within 1.2 per cent for values of loss greater than a watt. For losses less than a half watt, the measurements checked within a twentieth of a watt, which is satisfactory at the very low values of power factor. The 2 per cent and 5 per cent taps were checked against one another during each set of corona loss observations by taking a loss reading first with the 5 per cent tap and then with the 2 per cent tap with the wire voltage at about 36 kv. These comparisons agreed within about 1.8 per cent. These checks, together with other data taken and the manner in which readings could be checked indicated an over-all accuracy approximating 2 per cent for all but the lowest values of loss (less than a few tenths of a watt).

### Corona Loss Observations

The power loss measurements were made in each of the four sizes of cylinders at 50 and 60 cycles.

The critical voltage as indicated by the corona detector was always from two to four hundred volts higher than that at which a measurable loss began, except in the 15-cm. cylinder where the detector and wattmeter gave similar indications of corona formation. This discrepancy is to be expected as the electrometer had a very high sensitivity, readily indicating losses of the order of two to four hundredths of a watt. Due to minute surface irregularities there is a slight amount of ionization loss before the principal discharge occurs. This very small loss affects the electrometer, but the corona detector is dependent for its indications upon the principal discharge starting at a slightly higher voltage. However, in the smallest cylinder, the presence of ionization causes an appreciable break in the current wave due to the space charge traveling immediately to the cylinder wall, resulting in an indication by the corona detector. The presence of the loss and the appreciable break in the current wave form appearing at the same time causes both the wattmeter and the detector to show the beginning of corona formation.

For these measurements, the critical voltage was taken as that at which the ionization loss first appeared. All observations in this work were made on a simple common basis of comparison: namely, equal voltage increments above the respective critical values. It is recognized that a given voltage increment will produce more severe electrostatic conditions in a small cylinder than in one of greater diameter, but the existing gradient relations cannot be determined at present due to an inexact knowledge of the influence of the coronal space charge.

As the air density varied slightly for the several sets of loss observations, they have all been corrected to standard conditions of air temperature and pressure by the relation given by Peek,[4] that the loss varies inversely as $\delta$, where

$$\delta = \frac{3.92\, b}{273 + t}$$

$\delta$ = air density
$b$ = barometric pressure in centimeters
$t$ = air temperature in deg. cent.

The relative humidity varied from about 50 per cent to 70 per cent for the various sets compared.

The results of the power measurements are given in Fig. 1, in which the curves have not been drawn to the origin to avoid confusion. The actual observations, however, were carried through that region. The effect of the restriction of the space charge by the walls of the smaller cylinders, although not very pronounced, can

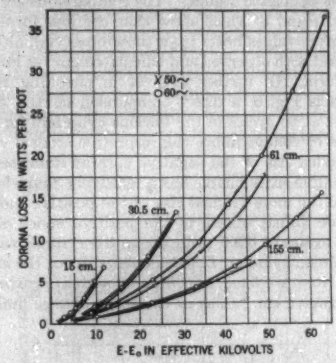


FIG. 1—VARIATION OF CORONA LOSS WITH CYLINDER SIZE

Corrected to $\delta = 1$

be traced in the form of these loss curves. As the cylinder diameter is reduced, for a given excess of voltage above the critical value the loss increases slightly more rapidly than in inverse proportion to the square root of the spacing, as the work of Peek[4] would indicate. Especially is this true in the 15-cm. cylinder, where the loss curve rises much more sharply in proportion than do those corresponding to the larger cylinders. Here a great deal of charge reaches the cylinder walls and has the effect of a high conduction current in phase with the voltage. This may be seen on the oscillograms obtained when using this cylinder, as illustrated in Fig. 10.

## CORONA CURRENT OBSERVATIONS

The average values of the positive and negative half waves of the corona current were measured in each of the four cylinders using voltages of 30, 40, 50, and 60 cycles. The curves of Figs. 2 and 3 illustrate the general characteristics of the corona current as affected by the space charge.

It is interesting to note that the positive and negative currents are always equal in the 155-cm. cylinder at all frequencies, as is shown in Fig. 3. As the cylinder size is reduced this condition no longer exists, the positive current being the larger at first as the voltage is raised, then the negative gaining predominance. This effect is shown in Fig. 2.

Willis'[10] work on the boundary of the space charge explains this behavior of the corona current. He found that the positive space charge had no well defined boundary, but tapered off in intensity due to diffusion. In addition to this the positive corona starts at a lower voltage than the negative, and the positive ions have the greater mobilities in the weak fields. Thus, in the largest cylinder the walls are so remote from the wire as to be out of the range of any appreciable space charge. However, at the lower voltages the walls of the 61-cm. cylinder receive a small amount of the positive charge, resulting in the positive current slightly overbalancing the negative in this voltage region. With a higher voltage, the negative charge begins to arrive at the cylinder in quantity, causing the negative current ultimately to overshadow the positive in magnitude. The large preponderance of the negative current at the higher voltages indicates that the carriers participating in the negative discharge are of greater average mobility in the higher voltage gradients than those of the positive discharge under like conditions.

A further effect of the space charge upon the corona current is illustrated in Fig. 3 in a comparison of the

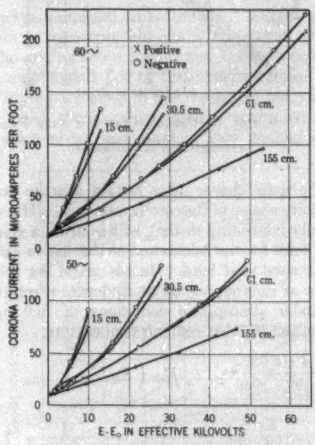


FIG. 2—VARIATION OF CORONA CURRENT WITH CYLINDER SIZE

Average values of half waves

effects of frequency upon the currents in the 155-cm. and in the 30.5-cm. cylinders. In the larger of these there is a relatively wide separation of the current curves, whereas in the smaller they are relatively close together. In the larger cylinder no ions travel to the cylinder walls, so the current is largely capacitative and greatly affected by frequency. In the smaller one the ionic conduction current forms a considerable portion of the whole, and as has been pointed out, is little

affected by frequency. This reduces the capacitative effect and tends to make the corona currents have the same magnitude at all frequencies for fixed voltage conditions.

## II. Check of Corona Loss Formulas

*The Holm Formula.* Holm's[9] formula for the calculation of corona power loss has been based on the theory

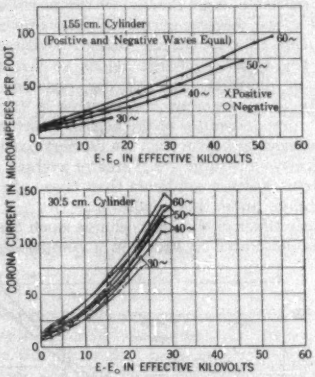


Fig. 3—Variation of Corona Current with Frequency

Average values of half waves

that the space charge takes certain average positions for definite phases of the corona discharge. His work is especially interesting in that he has given a relatively simple form for the calculation of the loss in cylinders such as were used here. He has given the following formula as suitable for use at moderate effective voltages under atmospheric conditions of 76.0 cm. air pressure and 20.0 deg. cent. air temperature.

$$W = \frac{4 \cos 0.6\,\alpha}{9 \times 1000} \cdot f \cdot E_{eff} \left( E_{eff} - \frac{E_1}{2} \right) \left[ \frac{1}{\log_e \frac{D}{L_0}} - \frac{1}{\log_e \frac{D}{a}} \right] \frac{\text{kw.}}{\text{km.}}$$

where

$$E_1 = a \log_e D/a \times 42.3 \left( 1 + \frac{0.3}{\sqrt{a}} \right) \text{kv.}$$

$$L_0^2 = \frac{3 \times E_{eff} \times 10^3}{\sqrt{2} \log_e D/a} \times \frac{\alpha}{2\,\pi\,f} \text{ cm.}^2$$

$$\cos \alpha = \frac{E_1}{2\,E_{eff}}$$

$L_0$ = average distance of space charge from middle of wire
$f$ = frequency
$a$ = radius of wire
$D$ = radius of cylinder

The loss observations have been corrected to the conditions of Holm's formula where $\delta = 1.018$, following the method of Peek's loss formula, for their comparison with the calculated values. The comparisons are given in Figs. 4 and 5, which show that the loss formula of Holm gives values lower than those observed, although in general both observed and calculated curves have the same form. Of further interest in checking Holm's formula is Fig. 6, a direct comparison of the corona currents at 60 cycles in the various cylinders for equal excesses of voltage above the respective critical values. The sudden rise of the negative current indicates that the negative space charge has a relatively sharp boundary and the more gradual rise of the positive indicates the more diffuse nature of the positive space charge. For an excess of 6000 volts above the critical value in the 30.5-cm. cylinder, $L_0$ as calculated from the expression of Holm is 4.5 cm. as compared with approximately ten or twelve cm. radius of the space charge indicated

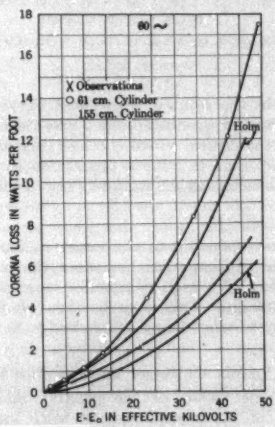


Fig. 4—Agreement of Observed Corona Loss with Loss Curves Calculated from Holm's Formula

by the upward trend of the currents in Fig. 6. The experimental conditions of this comparison are quite different from those upon which the formula has been based, unrestricted motion of the space charge. This, no doubt, accounts at least in part for the large discrepancy between the observed and calculated average position of the space charge. However, the observed loss in the 155-cm. cylinder where the space charge has unrestricted motion, also indicates that the Holm

formulas underestimate the length of the excursion of the space charge.

*The Peek Formula.* F. W. Peek, Jr.,[4] has derived an empirical formula for the corona loss which states that the loss increases as the square of the excess of voltage above the critical value $E_0$. To investigate the accuracy of this formula, the square root of the observed corona power loss is usually plotted against the wire voltage directly, or for convenience of comparison, against the excess voltage as was done in Fig. 7. The curves of Fig. 7 approximate straight lines very closely except in the early stages of the corona formation, indicating that the loss in the cylinders follows the quadratic relation within the upper range and conditions of these observations. The departure from the quadratic law in the initial stages of corona formation has been attrib-

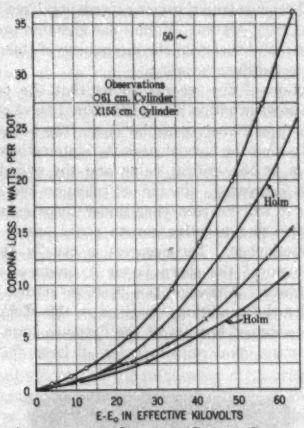


Fig. 5—Agreement of Observed Corona Loss with Loss Curves Calculated from Holm's Formula

uted by Peek to surface irregularities on the conductor, an explanation not completely satisfactory here, as this work has been done with a clean conductor.

## III. The Study of the Wave Form of the Corona Current

As early as 1904, Ryan[12] published the results of an investigation of corona by means of a cathode ray oscillograph. In 1913 Bennett[13] made an oscillographic study of corona using a reversed current transformer to amplify the small corona currents sufficiently for the operation of an oscillograph vibrator; Whitehead and Inouye[14] used a contactor method for determining the corona current wave form; a number of later investigators[15,16,17,18] have employed the cathode ray oscillograph in making such studies. For the present work the Duddell electromagnetic oscillograph has been used, adapted by means of a special vacuum tube amplifier to the small corona currents obtained with laboratory apparatus of moderate size. This combination has proved itself to be most satisfactory and has been the subject of an earlier paper by the author.[19]

The combined amplifier and oscillograph as used is essentially a voltmeter recording the voltage variations between the terminals of a resistance through which flows the current to be studied. The input of the device

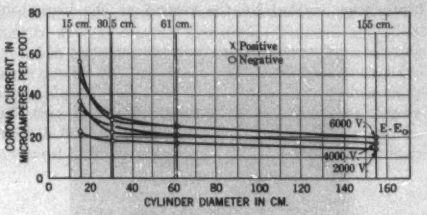


Fig. 6—Variation of Corona Current with Cylinder Diameter at Constant Excess of Voltage above the Critical Value at 60 Cycles

was always connected across the input resistance in the low-voltage measuring circuits of the corona cylinders with the grid return grounded and the grid connected to the ungrounded side of the input resistance. (The term "input resistance" is used to denote the resistance across which the amplifier input is connected for the observation of a wave form.) This method of con-

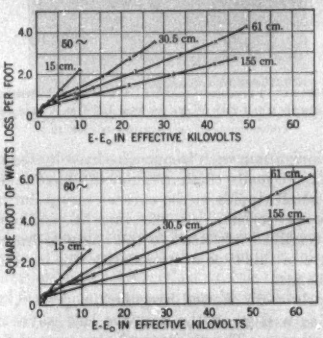


Fig. 7—Check of Peek's Law of Corona Loss

nection makes the half waves above the zero axes on the oscillograms correspond to those when the corona wire is negative, and those below, to when it is positive.

### Extraneous Factors Affecting the Wave Form of the Corona Current

To isolate those effects due to the space charge alone, other factors affecting the corona current were first determined and then their influence eliminated. It was

found that a sinusoidal voltage could only be obtained on the corona wire when the two primary windings of the high-voltage transformer were connected in series. With the parallel connection, the magnetizing current of the transformer was large enough to introduce harmonics into the alternator wave form.

The "oscillations" or irregularities in corona current waves have been the subject of discussion for some time. Bennett[13] found true damped oscillations of definite frequencies started by the corona at the instant of

Fig. 8—Some Typical Corona Current Oscillograms Obtained with the Wire in the 155-Cm. Cylinder

Transformer ratio is approximately 400 to 1

copious ionization, with frequencies fixed by the circuit constants. Usually these irregularities have taken the form of small ripples in the current waves during the existence of corona. As the present oscillographic method readily lends itself to the study of transients, the nature of this type of irregularity was investigated at some length.

The early work showed irregularities present on the positive as well as on the negative half waves of the corona current. The positive ripples were definitely traced as arising from extraneous discharges in the high-voltage circuit. After this circuit had been completely reconstructed to eliminate all discharges except that surrounding the corona wire, all traces of the high-frequency ripples disappeared from the positive corona current, those in the negative remaining.

## Effects of the Space Charge on the Corona Current

Observations made with the corona wire suspended in the largest cylinder, 155 cm. in diameter, were taken as those representative of conditions where the space charge has absolute freedom of motion. Willis,[10] using this same cylinder, found that no space charge would reach its walls at 60 cycles with voltages up to 100 kv. applied to wires comparable to the No. 12 (Brown and Sharp gage) wire used here. Some typical oscillograms taken under such conditions are shown in Fig. 8. For voltages below the critical value, the charging current of the wire is of purely capacitative nature. As the voltage is raised, a critical value is reached (70.0 tertiary volts for the oscillograms shown) at which a break appears in the current wave, caused by the formation of corona and resulting increased current due to ionization. The positive break is always found to be of a relatively gradual nature, whereas the negative is very sharp. As the voltage is raised farther the ionization current becomes larger, causing increasing large breaks in the current waves. Holm,[9] has given an excellent description and theory of the mechanism of these characteristics and their variation.

Inspection of the records shows that the positive corona always produces a smooth current wave and the negative an extremely irregular one. The behavior of the positive corona current peak is of interest when the voltage is at the critical value and the cylinder diameter is decreased. In Fig. 8, taken in the largest cylinder, it will be seen that under these conditions the positive and negative corona peaks are of about equal prominence. The negative is usually detected first because of the sharp break it produces in the current wave. Although the positive corona forms first under the conditions obtained in this work, it is difficult to detect because of the flattened form of its initial current break with cylinders of large diameter.

Fig. 9—This Record Shows the Existence of Appreciable Positive Corona Current before the Appearance of Negative Corona

This is due to the passage of positive space charge from the wire to the walls of the 15.0-cm. cylinder

However, as the cylinder size is reduced, the positive peak becomes gradually more and more pronounced. In Fig. 9 there is an appreciable positive corona current before the appearance of the negative. In light of recent discussion this is to be expected. Where the electrode distances are great, as in the largest cylinder, no charge reaches the cylinder walls and hence the current change indicated at the initial corona formation is only the very small increase in the displacement current. As the walls of the cylinder are approached nearer the corona wire they arrive within the range of travel of the

space charge. As this approach is continued, increasing quantities of charge arrive at the cylinder, which is manifested by increased current flow, or in other words, by an apparent increased conductivity of the air. In this way a very appreciable positive current flows in the smaller cylinders before the negative corona makes its appearance.

The nature of the irregularities appearing in the negative corona current is indicated by the oscillograms. At the lower voltages the ripples are very pronounced, becoming less so with increasing wire voltage. The results of Lee and Kurrelmeyer,[20] working with d-c. corona, are helpful in explaining this behavior. They found negative corona to be of irregular character, occurring as minute localized discharges on the wire which became more numerous as the voltage was increased. Such a condition tends to make the negative corona current more regular in form at the higher voltages. With a large number of localized discharge points, the characteristic variations in intensity of ionization at the individual points will not occur in unison, consequently the variation over a length of conductor taken as a whole will not be as great as when there are fewer points of discharge. Thus, when the conductor voltage is several times the corona voltage, the oscillograms show the negative corona current wave approaching the positive wave in apparent smoothness. Fig. 8 illustrates this tendency.

It has been found that these ripples are much more prominent at 30 cycles than at 60. This is because the ionization current is in larger proportion to the capacity current at the lower frequency and appears with greater prominence in comparison to this reduced charging current component. By taking this into consideration, it is found that the amplitude of the ripples is of about constant value at all the frequencies used, other factors remaining the same. However, with reduction of cylinder diameter the ripples become more prominent. Here there is the same effect appearing as causes the prominence of corona formation in the smaller cylinders. (See Fig. 9.) When copious ionization occurs at one of the localized negative discharge points, the conduction current arising from the space charge traveling almost immediately to the cylinder walls supplements the displacement current, the only component acting in the larger cylinders. In this manner the restriction of the space charge by the cylinder magnifies the intermittent character of the negative discharge.

As to frequency, the ripples behave consistently in the same manner, having apparently no predominant frequency within the range of the oscillograph. The frequencies are so high that they cannot be measured on the oscillograms with any degree of accuracy, so all that can be said about them is that they are more rapid than about 3500 cycles per second. As the corona discharge is known to cause radio interference, investigation in the higher frequency ranges may yield more definite results. However, our present information seems to indicate that the corona has no definite frequency characteristics and that when such conditions are indicated, the resonant frequencies are probably a property of the experimental circuit and usually can be traced to the circuit constants rather than to the discharge itself. It must be remembered that these high-frequency ripples are a property of the negative corona current alone.

As the cylinder size is reduced and the other conditions left unchanged, the ratio of maximum corona current to average current increases. This effect is illustrated in Fig. 10. The ionization current flows for only a portion of the cycle and in the smaller cylinders has increasing values, increasing the maximum values while affecting the average values to a much less degree. With a fixed cylinder diameter and frequency and increasing voltage, the ratio of maximum to average

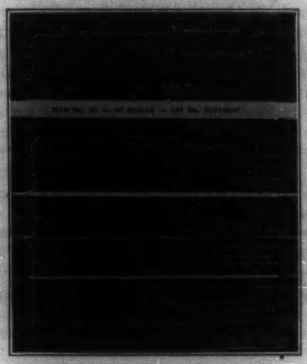

Fig. 10—The Above Oscillograms show the Effect of Cylinder Size

On the wave form of the corona current for the same excess of voltage above the respective corona forming values

values at first increases rapidly, then gradually decreases as the corona discharges for greater percentages of the cycle. The frequency of the applied voltage does not have any appreciable effect on this ratio within the limited frequency range used for these studies.

### Transient Corona Oscillograms

As an interesting supplementary study, a number of observations was made of the formation of corona as the voltage was raised above the critical value. Fig. 11 shows the transient as the voltage was raised slowly, and Fig. 12 shows two transients when the voltage changes occurred quickly. The crosses on the records mark the beginning of steady conditions as found by measurement of the oscillograms.

The observations of transient conditions indicate that 60-cycle corona, when the travel of the space charge is

unrestricted, requires at least one or two cycles to reach a steady condition after the voltage has become stable, —a greater lag than this cannot with certainty be said to occur. The transient records also show that the positive or the negative corona may arrive at the steady state first and that the next succeeding opposite corona current wave after this initial arrival is also in a stable condition.

## IV. Summary

1. The influence of the space charge due to the high-voltage corona on the value and on the wave form of the corona current, and on the corona power loss, have been studied for the case of a smooth wire in a concentric cylinder, over a range of diameters of the latter and of frequencies of the alternating high voltage.

2. The corona loss has been measured over a wide range of conditions by an accurate quadrant electrometer method. The observed corona power losses vary noticeably from the theoretical corona power law for concentric cylinders as proposed by Holm, which aims to include the influence of the space charge travel.

3. The power loss measurements are in general accord with the quadratic law of the excess voltage as proposed by Peek only in the voltage region considerably above the critical value. As these measurements were made with a clean central conductor, the departure from the quadratic law in the initial stages of corona formation cannot be attributed to surface irregularities as Peek has suggested.

4. These results in general indicate that the expressions of power loss heretofore proposed are not completely general, in that the influence of the travel of the space charge in its relation to the separation of conductors is not yet completely understood.

5. The accurate vacuum tube voltmeter which has

Fig. 11—Transient Record of 60-Cycle Corona with the Wire in the 155-Cm. Cylinder

There was no corona present around the wire before the relatively slow voltage rise began

been used for the study of wave form yields larger, clearer, and hence more accurate corona oscillograms than any heretofore recorded.

6. The increased accuracy so obtained has shown that many of the apparent irregularities in corona current waves may be due to irregular high-voltage wave forms and to local discharges in auxiliary high-voltage circuits. In this work, errors of this type have been eliminated.

7. Comparative studies of the oscillograms taken over a range of values of diameter (15 to 155 cm.) of the outer cylinders give much interesting information as to the influence of the space charges of opposite sign on the shape of the corona current waves. Particularly striking is the prominence of the conduction component of the corona current as large quantities of space charge reach the walls of the smaller cylinders.

8. These effects of space charge are a'so readily

Fig. 12—Transient Records of 60-Cycle Corona with the Wire in the 155-Cm. Cylinder

The voltage applied to the wire was changed suddenly

traceable in the variations of the value of the corona current with frequency of the high voltage and with the cylinder diameter.

## Acknowledgment

The author wishes to acknowledge his indebtedness to the Department of Electrical Engineering of the Johns Hopkins University for the use of its apparatus and of its laboratory where these corona studies have been made. Particularly does he wish to express his great appreciation to Dean J. B. Whitehead for his most valuable criticism and many suggestions, to Dr. W. B. Kouwenhoven for his friendly interest and much useful advice, and to Mr. Ferdinand Hamburger, Jr., for his continued cooperation in the laboratory and active assistance at various times.

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## Discussion

**J. B. Whitehead:** Dr. Waldorf has rendered a notable service in the care with which he has conducted his experiments, in the freedom from disturbing influences present in a number of the preceding cases, and particularly in the analysis he has made of the various phenomena that appear in his curves and his oscillograms in the matter of the travel of the space charge. He was unable to bring all of these things out in his short presentation, but all students of corona will find his paper of very great interest and assistance.

I am reminded in the discussion of space charge of some of my own early work on the electric strength of air, in which the actual motion of space charge was brought forcibly to attention, although at that time the importance of its influence on the potential distribution and the behavior of current and loss were not understood. If you use a small glass inside a metal cylinder, and put a small window in the cylinder, under proper relations of voltage and diameter, it is astonishing the force with which a draught apparently of air—obviously it isn't a draught of air—comes out of the window. I made some measurements of the force with which the stream was driven against a little hinged vane; it could be made to stand out towards the horizontal position under the impulse of the ion stream.

I ask Dr. Waldorf what he thinks is the best method of measuring the critical corona voltage in those cases in which the space charge does not reach the outer cylinder. In all of my work I relied entirely upon the space charge reaching the outside electrode for the determination of the critical voltage, and reached the conclusion that it was an extremely accurate method.

**Ragnar Holm:** (Communicated after adjournment) In this paper Mr. Waldorf refers to my treatise on the same subject published in the *Archiv für Elektrotechnik* (Vol. 18, 1927, p. 567), which is entitled "Die Theorie der Wechselstromkorona an Hochspannungsleitungen." He compares the results of his observation with the results of calculations based on my formula and states that they do not agree. This disagreement is rather surprising, and I have therefore taken occasion to check the calculated results. Evidently the error is due to a misinterpretation of the conditions under which the formula must be used, which Mr. Waldorf has made.

Referring to page 578 of the previously mentioned publication, the following condition was stated:

"In the case of a wire along the axis of a cylinder, one must use $E_1/2$, $\sqrt{2}.L$, and $2\,W$ instead of $E_1$, $L$, and $W$ respectively."

However, Mr. Waldorf has not used the factor $\sqrt{2}$ for the second quantity. If he had done so, using the approximate formulas (8a) and (8b), the result would have been:

$$L = 13.4 \text{ cm.}, \quad W = 13.7 \text{ watts per foot}$$

assuming $2\,D = 61$ cm., $f = 50$ cycles, $E_{Eff} = 63.9$ kv., and $E_1/2 = 23.9$ kv.

The value $W = 13.7$ watts per foot agrees exactly with the observed results for $E_{Eff} - E_1/2 = 40$ kv. taken from Fig. 5 of Mr. Waldorf's paper. His calculated result was $W = 9$ watts per foot because the relation $L = 13.4 : \sqrt{2}$ was used.

Furthermore, in Part II Mr. Waldorf calculates for an excess of 6000 volts above the critical value in the 30.5-cm. cylinder

$$L = 4.5 \text{ cm.}$$

and compares this value with a 12-cm. radius of an observed space charge. In this case he should have used my more exact formulas of § 7. The quantity $L_1$ defined in § 6 and calculated from the formula 7 d for $2\,D = 30.5$ cm., $f = 60$ cycles, $E_{Eff} = 27$ kv., and $E_1/2 = 21$ kv.

$$\text{is } L_1 = 12.7 \text{ cm.}$$

I believe these two examples show clearly the source of the discrepancy between the observed results and the results as they were calculated from my formula. It is also clear that the formula yields a result which is in close agreement with the observed values.

**S. K. Waldorf:** Answering Dr. Whitehead's question, the solution to finding the corona starting voltage where the space charge does not extend to the opposite electrode was pointed out by the oscillograms early in the studies of corona. When the corona forms initially, there is a change in the wave form of the charging current of the wire, higher harmonics appearing. The appearance of these higher harmonics affords a means of corona detection, and I employed a rather simple apparatus for their detection and the consequent detection of corona formation. The essentials of this corona detector are given briefly in the description of apparatus and experimental method of the first section of my paper. I believe that this form of corona detector can be improved upon so that we can detect corona formation very readily with any spacing where it is possible to obtain a wave form of the corona current involved.

The communication of Herr Holm is most valuable in pointing out the cause of the apparent discrepancy between the measured corona losses and those given in the curves calculated from the Holm formulas. The revised sample calculated values which he has given are truly remarkable in their agreement with the experimental values, and establish the fundamental soundness of his quantitative analysis of the corona phenomenon.

# Generalized Theory of Electrical Machinery

BY GABRIEL KRON[1]
Non-member

***Synopsis:***—*In the following pages electrical machinery is analyzed from a new point of view. Analytical quantities like magnetizing current, armature reaction, leakage flux, transient reactance are not introduced; only such quantities are used as actually exist in the machine at one particular load. Thereby the theory of electrical machinery is expressed in terms of the minimum possible number of quantities. No hypothetical currents or fluxes are used and no actual physical quantity is left out.*

*The concept of "free energy," used in thermo dynamics, is introduced and generalized.*

*The criterion of good design of all electrical machines is expressed by a constant, the "thermodynamic efficiency" which gives a measure of the effective utilization of iron and space for the transformation of energy. This constant plays a most fundamental role in the steady and transient behavior of the machine.*

*A method is given by which the direction of flow of energy between different parts of any complicated machine can be easily read off the diagrams.*

*The theory of constant-potential and constant-current electromagnets is used as a stepping stone to show that the theory of the polyphase alternator is identical with the theory of the constant-potential polyphase transformer if flux linkages and magnetomotive forces are interchanged. The circle diagrams of the transformer and the alternator are developed as well as the elliptical locus diagram of the alternator with salient poles. Problems in the sudden short circuit and the sudden load variation of the polyphase alternator are also solved.*

*Blondel's diagram for the circular locus of the synchronous motor is derived in a more extended form together with its elliptical locus with salient poles. The elliptical loci of the reaction machine and the synchronous converter are also developed.*

*The circular locus for the polyphase induction motor, the single-phase induction motor, and the repulsion motor are derived.*

*The method of attack used in the paper is applicable not only to circular and elliptical loci, but also to loci of higher curves. The method is used to develop the complete theory and locus diagram of the double squirrel-cage induction motor and the split-phase induction motor with or without condenser (or the so-called condenser motor).*

*Besides those mentioned above the writer has also developed with this method the loci of commutator machines, such as the polyphase induction motor with commutator rotor, the series-polyphase and the shunt-polyphase commutator motors, the compensated series motor, including the effect of the short-circuited brush currents, also the locus of induction motors in cascade and transmission lines. Due to the length of the article, however, their discussion does not appear here.*

*All locus diagrams show the speed and the torque at all loads. They also show the magnitude and phase relation of all actual currents, fluxes, and e. m. fs.*

*A relation of the form r/x is found for the ratio of the work done to the free energy and this one simple formula is sufficient to find the locus diagram and the complete performance of all electrical machinery and transmission lines. It is the only formula used in the paper.*

*In the appendix the relation of the design constants used to the constants of other methods is shown.*

* * * * *

## Part I. The Flow of Energy

### I. The Concept of Free Energy

An investigation concerning the energy stored in a body may be conducted along two different lines. The investigation may determine either (1) how the energy varies from point to point inside the body or (2) how the total energy possessed by the body varies from instant to instant. In the following pages the second type of changes will be studied.

When the energy content of a body changes, the body is said to undergo a change of state. If after a change of state the body comes back to its original state it is said to have passed through a cycle.

During a change of state a certain amount of energy comes from one part of the surroundings which will be called "source" and a certain amount passes out into another part of the surroundings which will be called "load." The departing energy will be called "work."

It will be assumed that no heat energy enters or departs and that the temperature remains constant during a change of state.

In each state the body possesses a certain quantity of energy, which shows the ability of that particular state to do work. This quantity is called by Planck the "free energy" of that state; Gibbs calls it "thermodynamic potential." The "free energy" of a state is analogous to the "potential" of a point in a field, which shows the ability of a unit electric charge residing at that point to do work.

During a change of state (or during the motion of a charge between two points) the work done between the two states (or points) is equal to the decrease of the free energy (or potential).

Careful distinction should be made between the total energy stored in the body and its free energy, its ability to do work. The free energy may reside in the body or partly in the surroundings or even entirely in the surroundings. The amount of work a body can do depends not only on the amount of energy stored in it, but also upon the amount which flows into the body from the surroundings while work is being done.

### II. Energy in Condensers

To show the application of the idea of free energy, a charged condenser will be considered with a dielectric of small permittivity (specific inductive capacity). The change of state will consist of letting the lines of flux follow paths with different permittances. If the lines of flux start from a path with the *minimum* possible permittance and passing through the path with the *maximum* possible permittance return again to the starting position, the state of the condenser passes

1. The Lincoln Electric Company, Cleveland, Ohio.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

through a cycle. This state of change is possible if the dielectric can move freely in space.

Two cases will be assumed: first, the condenser is not connected to a battery, and second, the condenser is connected to a battery.

When the condenser is not connected to a battery, the charge and hence the number of dielectric flux lines has to remain constant during any possible change. When the dielectric is in the condenser, the flux $Q$ follows a path whose permittance $c$ is a minimum, hence the stored energy is $Q^2/2\,c_{min}$. This value is a maximum. Let this value be plotted as $\overline{AC}$ in Fig. 1A. A force is exerted on the dielectric which moves out until the flux follows the path whose permittance is a maximum. Let the ratio $c_{max}/c_{min} = k$. In this state the stored energy is $Q^2/2\,c_{max}$, which is a minimum. Let it be represented by a line $\overline{AB}$, where $\overline{AC}/\overline{AB} = k$. The total work done between the starting state and this state is $\overline{BC}$. Since no more work can be done by the condenser, the free energy possessed by the condenser at the beginning of the cycle is also $\overline{BC}$. In any state $D$ the energy stored in the condenser is $\overline{AD}$, the work done is $\overline{DC}$, the free energy is $\overline{DB}$. $\overline{AB}$ cannot be utilized to do work.

It can be seen that during the change of state the work done is equal to the decrease of free energy. The stored energy decreases while work is done and the free energy resides entirely in the condenser.

The cycle is completed by carrying the dielectric back into the condenser. To accomplish this, work has to be done on the dielectric, hence the free energy and the stored energy again increase. When the dielectric is in its original position, the work done on it was exactly equal to the work done by it.

Hence, during the cycle point $D$ describes a straight line, starting from $C$ to $B$ and back again.

When the condenser is connected to a battery with constant electromotive force, during the change of state the number of flux lines does not remain constant, but increases in proportion to the increase of the permittance, since electromotive force = dielectric flux / permittance = constant. When the dielectric is in the condenser, the lines of flux follow again the path whose permittance is a minimum, their number is the minimum possible and the stored energy is $(Q_{min})^2/2\,c_{min}$. Let this energy be plotted in Fig. 1B as $\overline{AB}$. When the dielectric moves out until the lines of flux follow the path whose permittance is maximum, the number of flux lines increases in the same ratio as the permittance. The stored energy is now $(Q_{max})^2/2\,c_{max}$ and this is $k$ times as large as the energy at the beginning of the cycle. Let this value of energy be plotted as $\overline{AC}$. The ratio $\overline{AC}/\overline{AB} = k = c_{max}/c_{min}$.

While work is done, the stored energy of the condenser increases. The energy necessary to do work and to increase the stored energy comes from the battery. It is shown in text-books that the energy which comes from the battery divides into two equal parts. One part becomes stored energy, the other and equal part becomes work. Hence, when the stored energy in Fig. 1B is $\overline{AD}$, the increase of stored energy is $\overline{BD}$, which is also equal to the work done. The remaining part $\overline{DC}$ represents the energy which will appear later as stored energy, hence it is also equal to the work which the system is able to do in the future, that is to the free energy. $\overline{AB}$ cannot be utilized to do work.

It can be seen that the free energy, the ability of the condenser to do work, does not reside now in the condenser, but it resides entirely outside the condenser in the surroundings, that is, in the battery.

Point $D$ starts at point $B$ and during a cycle moves along a straight line to $C$ and back.

At any point $D$ the stored energy $\overline{AD} = Q^2/2\,c$. Since the number of lines of flux, $Q$, is proportional to the permittance, $c$, therefore $\overline{AD}$ is also proportional to the total number of lines of flux linking the battery at that particular state.

In both cases, with or without battery the maximum possible stored energy is $\overline{AC}$, but the maximum possible work done is $\overline{BC}$. Hence the efficiency, $\eta$ of the condenser to do work in both cases $\eta = \overline{BC}/\overline{AC} = (\overline{AC} - \overline{AB})/\overline{AC} = (c_{max} - c_{min})/c_{max}$.

Summarized, when no work is done, the free energy

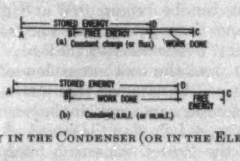


FIG. 1—ENERGY IN THE CONDENSER (OR IN THE ELECTROMAGNET)

in both cases is $\overline{BC}$. As work is done the free energy decreases and in both cases the work done is equal to the decrease of free energy.

## III. ENERGY IN ELECTROMAGNETS

The conception of free energy can be applied to the constant-potential a-c. electromagnet and to the constant-current a-c. and d-c. electromagnets if the dielectric flux, Q, is replaced by magnetic flux, $\Phi$, the dielectric by a magnetic material, permittance, $c$, by permeance $\mathcal{P}$, and electromotive force $E$, by magnetomotive force, $I$. (In the case of a-c. illustrations effective values should be understood.)

The case where the condenser is not connected to a battery and has constant fluxes is analogous to the constant potential a-c. electromagnet where also the number of lines of flux linking the terminals remains constant (neglecting resistance). Referring to Fig. 1A at any particular point $D$ the stored energy $\overline{AD} = \Phi^2/2\,\mathcal{P}$. Since $\Phi$ = constant $\overline{AD}$ is proportional to $1/\mathcal{P}$. But m. m. f. $= \Phi/\mathcal{P}$, that is the current is also proportional to $1/\mathcal{P}$, hence $\overline{AD}$, the stored energy, represents also the current taken by the magnet.

The case where the condenser is connected to a battery and has constant electromotive force impressed

upon it is analogous to the constant-current a-c. or d-c. electromagnet where the m. m. f. is constant. Hence during a change of state (during a stroke) the number of lines of flux is proportional to the permeance and also proportional to the stored energy ($\overline{A\,D}$ in Fig. 1B).

Since the reactance of the winding is proportional to the permeance of the flux-path, the reactance of the magnet varies between two extreme values, $X_{max}$ and $X_{min}$. The efficiency of the electromagnet in both cases $\eta = (\mathcal{P}_{max} - \mathcal{P}_{min})/\mathcal{P}_{max} = (X_{max} - X_{min})/X_{max}$.

It can be seen that in the constant-potential electromagnet the current *decreases* as work is done, while in constant-current electromagnets the flux *increases* as work is done. In both cases the work done is equal to the decrease of free-energy.

## The Flow of Generalized Energy

### IV. The Two Types of Energy

In order to treat the *oscillating* character of energy during one a-c. cycle as a *continuous flow* of energy two hypothetical powers are introduced. It is assumed that at each instant during a cycle two types of power enter the load, the "active" power, $E\,I \cos\theta$ and the "reactive" power, $E\,I \sin\theta$. The active and the reactive powers can be represented at right angles to each other and their geometrical sum represents the total "apparent" power entering the load.

In order to treat the continuous flow of energy as a *steady state*, it will be assumed that with a given $I$ and $\Phi$ two types of energy are stored in the load. One is the "active" energy, $\Phi\,I \sin\theta$ and is stored in a resistance, the other is the "reactive" energy, $\Phi\,I \cos\theta$ and is stored in a reactance. These two energies can be represented at right angles to each other and their geometrical sum gives the total "apparent" energy, $\Phi\,I$ stored in the load. It will be assumed that a given value of $I$ and $\Phi$ define a definite state and a change of state will consist either in a change of $I$ or in a change of $\Phi$.

### V. The General Transformer

An ideal slip-ring induction motor will be assumed which can be used either as a stationary polyphase transformer or a uniformly rotating polyphase alternator when one winding is excited from a d-c. source. The stator winding will serve as a place where energy enters from the source and will be called primary, the rotor winding will serve as a place where energy enters the load and will be called secondary. The space surrounding the two windings will represent the medium in which energy is stored and which will be subjected to a cycle. The resistances of the windings will be neglected.

In case of the condenser and the electromagnets a change of state was represented by compelling the lines of flux to follow paths with different permeances. The change was effected by moving a piece of magnetic or dielectric material in the path of the flux lines. In this machine it will be assumed also that a change of state will occur if the flux lines linking the primary follow paths with different permeances. But this change of state will be regulated not by a moving piece of magnetic material but by varying the current in the secondary, that is by varying the load.

### VI. Energy in the Transformer

First let it be assumed that the machine is working as a transformer. Let constant flux link with one of the phases of the primary. This constant flux, sinusoidally distributed in space, may assume any position between two extreme values. One extreme occurs when the impedance of the load is infinite, that is when the secondary is open. In that case the flux follows the path of maximum possible permeance, $\mathcal{P}_{max}$. (Fig. 2A) and the stored energy is $\Phi^2/\mathcal{P}_{max}$. The other extreme occurs when the impedance of the load is zero, that is when the secondary is short-circuited. Since no lines of flux can now link the secondary, no lines of

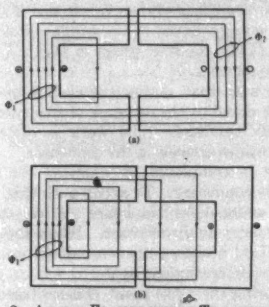


Fig. 2—Actual Fluxes in the Transformer
(a) Open circuit
(b) Short circuit

flux can follow the iron path around the secondary, consequently the flux-lines have to follow the path of minimum possible permeance (Fig. 2B). The stored energy is the maximum possible and is equal to $\Phi^2/\mathcal{P}_{min}$.

Let again the minimum stored energy be plotted as $\overline{A\,B}$ (Fig. 3A) and the maximum stored energy as $\overline{A\,C}$. Again $\overline{A\,B}$ is proportional to $\mathcal{P}_{min}$ and $\overline{A\,C}$ to $\mathcal{P}_{max}$.

Since reactance is proportional to the permeance of the path of the flux-lines, at short circuit the machine has a minimum possible reactance, $X_{SH}$, at open circuit it has a maximum possible reactance, $X_o$. With a variation of load the reactance of the machine varies, but only between these two values (in case of positive loads).

The constant flux will be subjected not only to a change of state, but also to a complete cycle. The cycle will consist of letting the lines of flux pass from the path of minimum permeance (short-circuited secondary) to the path of maximum permeance (open secondary) and back to the path of minimum permeance. This change

is effected by letting the impedance of the load pass through a cycle of change from zero to positive infinity and from negative infinity through *negative* values back to zero.

In this load cycle while the impedance of the load varies from zero to positive infinity, the amount of energy which disappears from the machine into the load is $\overline{BC}$ (Fig. 3A) and while the impedance of the load varies from negative infinity through negative values to zero, energy returns to the machine and the same amount $\overline{BC}$ comes back which has departed. Between short circuit and open circuit the energy disappeared $\overline{BC}$, or the work done is equal to the decrease

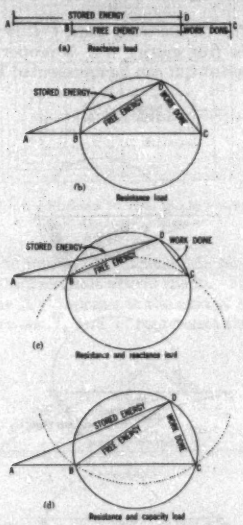


FIG. 3—ENERGY DIAGRAM OF THE TRANSFORMER

of free energy, consequently $\overline{BC}$ is the free energy of the system at short circuit.

During the load cycle the work done can be stored either in a reactance or in a resistance, or in a combination of the two. First it will be assumed that the load consists of a reactance.

As the reactance of the load increases, the current in the secondary decreases, the lines of flux pass into paths with higher permeances and the stored energy decreases. The energy disappeared is assumed to be stored in the reactance. This energy has disappeared from the machine at the expense of the free energy. Since the free energy before its disappearance is stored in the magnetic field as a reactive energy, after its disappearance from the machine is still stored as a reactive energy, therefore the energy disappeared, the work done, and the free energy are always in phase with each other, angle $B\,D\,C$ in Fig. 3A is 180 deg. and the locus of point $D$ is the horizontal line.

While the reactance of the load varies from zero to positive infinity, point $D$ moves from $C$ to $B$ along the horizontal line and while the load varies from negative infinity through negative values to zero, point $D$ moves from $B$ through $A$ along the horizontal line to negative infinity, then from positive infinity still along the same horizontal line back to $C$ completing a cycle.

When the load is a resistance, the work done is stored as an active energy. This energy has disappeared from the machine again at the expense of the free energy. Since the free energy before disappearance is stored in the magnetic field as a *reactive* energy, after its disappearance from the machine is stored in a resistance as an *active* energy, the energy disappeared, the work done, and the free energy have to be represented at right angles to each other (Fig. 3B).

As the resistance of the load increases, the work done, $\overline{CD}$ increases, the free energy, $\overline{BD}$, decreases, but the angle between them has to remain always 90 deg. Hence the locus of point $D$ is a circle with its center on line $\overline{BC}$. When the resistance is positive infinity or negative infinity (these two values being equivalent) point $D$ is at $B$. With negative resistance it arrives back at its starting point $C$, completing a cycle.

When the load is divided between a resistance and a reactance whose ratio remains constant, the lines representing the work done and the free energy have to be at a constant angle $\alpha$ less than 90 deg. from each other, hence angle $B\,D\,C$ is 90 deg. $+\,\alpha$ (Fig. 3C) and the locus of point $D$ is again a circle passing through points $B$ and $C$ with center below the horizontal line.

With a load partly resistance and partly capacity (negative reactance) angle $B\,D\,C$ is less than 90 deg. (Fig. 3D) and the center of the circle lies above the horizontal line. With a pure capacity load point $D$ starts at $C$ toward positive infinity and from negative infinity through point $B$ comes back to $C$. Point $D$ travels in opposite direction as in the case of a pure reactance load. The straight line is of course a circle with infinitely large radius.

## VII. ENERGY IN THE ALTERNATOR

The only difference between a constant-potential transformer and an alternator is that the transformer has constant flux linking the primary, while the alternator has constant magnetomotive force in the primary. The case of the constant-current electromagnets is parallel to the case of an alternator.

In the alternator, when the secondary is open (Fig. 4A) the flux linking the primary follows the path of maximum permeance and when the secondary is short-circuited (Fig. 4B) the flux follows the path of minimum permeance. The number of lines of flux is proportional to the permeance, since the m. m. f. remains constant, hence at open circuit the number of lines of flux is a maximum possible, the stored energy is $(\Phi_{max})^2/\mathcal{P}_{max}$.

At short circuit the permeance of the flux path is minimum, the number of lines of flux is the minimum possible, and the stored energy is $(\Phi_{min})^2/\mathcal{P}_{min}$. The ratio (maximum stored energy)/(minimum stored energy) $= \mathcal{P}_{max}/\mathcal{P}_{min} = \Phi_{max}/\Phi_{min} = k$.

Let it be assumed again that it the impedance of the load passes through a cycle. When the impedance is zero, the secondary is short circuited and the minimum

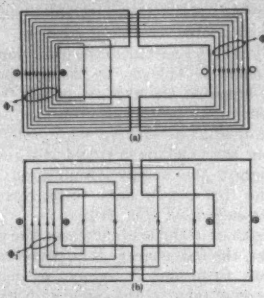


FIG. 4—ACTUAL FLUXES IN THE ALTERNATOR
(a) Open circuit
(b) Short circuit

stored energy is $\overline{AB}$ (Fig. 5A). As the impedance increases, work is done and the stored energy *increases*. Here also the increase of the stored energy is equal to the work done, while the work done is equal to the decrease of free energy (Fig. 1B).

If the load is for instance a resistance, the work done has to be at right angles to the free energy just as in case of a transformer, and the locus of point $D$ is again a circle (Fig. 5B).

The differences between Fig. 3, which refers to a transformer and Fig. 5, which refers to an alternator, are the following.

1. The lines for free energy and work done are interchanged.

2. In Fig. 3 point $D$ starts at $C$, in Fig. 5 it starts at $B$, both at the short-circuit point.

## The Generalized Vector Diagrams

### VIII. CONNECTIONS BETWEEN THE ENERGY AND THE FACTORS OF ENERGY

When the transformer is short circuited no lines of flux link the secondary. As work is done, some of the flux lines pass around the secondary and give up their free energy. Since each line of flux (or tube of flux) possesses the same amount of energy before linking the secondary and it also possesses the same amount afterward, the work done by each line of flux is the same, hence the work done is proportional to the number of lines of flux linking the secondary, $\Phi_2$.

As the secondary current of the transformer increases, it tends to produce flux. It can not send any flux through the primary winding, since the primary flux is constant, it sends flux through the path having a permeance $\mathcal{P}_{min}''$ (Fig. 6A). The number of lines thus produced is proportional to $I_2$. Since these lines combine with the lines already existing there, the resultant lines of flux appear as if the flux lines have been shifted from a path with maximum permeance to a path with minimum permeance (Fig. 6B). The number of flux lines thus shifted is proportional to $I_2$.

It has been seen above that when a flux line passed around the secondary it has lost its free energy. Hence when a flux line is shifted due to the increase of $I_2$, it acquires the same amount of free energy it has lost. Since the total free energy is proportional to the number of lines shifted, the free energy is also proportional to $I_2$.

Hence in Fig. 7A the work done, $\overline{CD}$ is proportional to $\Phi_2$, and the free energy $\overline{BD}$ is proportional to $I_2$. Since $\Phi_1$ is constant, it can be represented by $\overline{AC}$ while

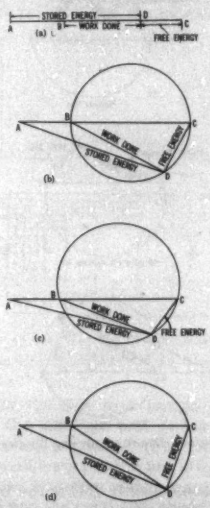


FIG. 5—ENERGY DIAGRAM OF THE ALTERNATOR
(a) Reactance load
(b) Resistance load
(c) Resistance and reactance load
(d) Resistance and capacity load

the stored energy $\overline{AD}$, which is equal to $I_1\Phi_1$, is proportional to $I_1$.

Similarly in the alternator diagram (Fig. 7B) the work done $\overline{BD}$ is proportional to $\Phi_2$, the free energy $\overline{DC}$ to $I_2$. Since $I_1$ is constant, it can be represented by $\overline{AC}$ while the stored energy, $\overline{AD}$ which is equal to $I_1\Phi_1$ is proportional to $\Phi_1$.

It can be seen that the energy diagrams of both transformer and alternator represent also the *actual* flux linkages and magnetomotive forces existing at any load. The scales will be determined below.

Comparing Figs. 7A and 7B, it is noticed that the lines representing $I_1$ and $\Phi_1$, also the lines representing $I_2$ and $\Phi_2$ are interchanged. Hence it can be concluded that *the theory of the polyphase alternator is identical with the theory of the polyphase transformer, except flux linkages and m. m. fs. are interchanged.*

It is interesting to note that for both the alternator and the transformer the four lines represent the phase

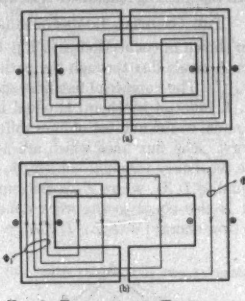


FIG. 6—FLUXES IN THE TRANSFORMER
(a) Component fluxes
(b) Actual fluxes

relations of the four actual measurable physical quantities not only in time, but also in space. For instance, if in Fig. 7B line $\overline{A\,C}$ represents the axis of the field pole, the angle between $I_1$ and $\Phi_1$ represents the space angle

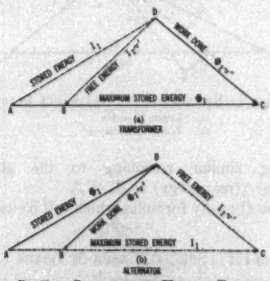


FIG. 7—THE GENERALIZED VECTOR DIAGRAMS
(a) Transformer
(b) Alternator

by which the total resultant field flux is shifted with respect to the axis of the field pole. In case of a pure reactive load point $D$ moves from $C$ toward $B$ as $I_2$ increases, $\Phi_1$ does not shift in space, only decreases ("demagnetizing effect"). With a pure capacity load point $D$ moves from $C$ away from $B$ and $\Phi_1$ increases ("magnetizing effect"). If the load contains resistance $\Phi_1$ shifts its position with respect to the axis of $I_1$ and the angle of shift in space is exactly equal to the angle of shift in time.

It can be seen also that the thermodynamic efficiency of both the alternator and transformer is the same as the efficiency of an electromagnet.

$$\eta = (\mathcal{P}_{max} - \mathcal{P}_{min})/\mathcal{P}_{max} = (X_e - X_{SH})/X_e$$

This constant $\eta$ is the most important characteristic of all electromagnetic machines. It shows how much of the maximum possible stored energy is free energy.

## IX. THE SCALES OF THE VECTORS

To find the scale for $\Phi_2$ let the case be considered when the machine is open and point $D$ is at $B$. At open circuit the flux linking the secondary is less than the flux linking the primary. Let at open circuit $\Phi_2 = \Phi_1 v'$, where $v'$ is less than unity. At open-circuit $\overline{C\,D} = \eta\,\Phi_1 = \eta\,\Phi_2/v'$. If $\eta/v' = v''$ then $\overline{C\,D} = \Phi_2 v''$.

Let $\overline{B\,D} = I_2 v$ and let one a-c. cycle be considered, that is the time while the applied voltage varies from zero through positive and negative maximum back to zero. During one a-c. cycle the amount of energy which did not return to the source $= (\Phi_1 I_1) \sin C\,A\,D$ = twice the area $A\,C\,D = (\Phi_2 I_2) \sin B\,D\,C = (\overline{C\,D}/v'')\,(\overline{B\,D}/v) \sin B\,D\,C = 1/v''v$ times twice the area $B\,D\,C$. Since

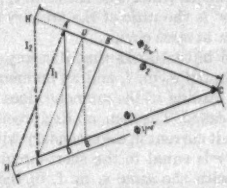

FIG. 8—ACTUAL CURRENTS AND FLUXES IN THE TRANSFORMER

area $A\,C\,D = \eta$ times area $B\,D\,C$, therefore $1/v''v = \eta$, from this $v = \eta/v'' = v'$.

Hence to determine the complete performance of the transformer or alternator one has to know the open-circuit reactance $X_e$ (or $\mathcal{P}_{max}$), the short-circuit reactance $X_{SH}$ (or $\mathcal{P}_{min}$), and the ratio of the secondary and primary voltages at open circuit $v'$. From these

$$\eta = (X_e - X_{SH})/X_e \text{ and } v'' = \eta/v'$$

In the following pages the scale on the diagrams will not be shown unless it is necessary.

## X. THE DESIGN CONSTANTS

Instead of introducing the ratio of the primary and secondary voltages at open circuit, it will be assumed that the voltage is impressed not on the primary side but on the secondary side. This determines different open-circuit and short-circuit reactances. When the e. m. f. is impressed on the primary the two reactances will be denoted by a prime $X_e'$, $X_{SH}'$ and when the e. m. f. is impressed on the secondary side they will be denoted by a double prime $X_e''$, $X_{SH}''$.

The relation between the four reactances can be found if the actual values of the currents and the fluxes are plotted. In Fig. 8 lines $A\,B\,C\,D$ represent the four

quantities of the transformer. If $\overline{A'C} = \overline{DC}/v''$ it is equal to $\Phi_2$. If $\overline{A'H}$ is drawn parallel to $\overline{DA}$ and $\overline{A'D'}$ to $\overline{DB}$, then it can be assumed that instead of $\overline{AD}$ line $\overline{HA'}$ represents $I_1$ and then $\overline{A'D'} = I_2 v'$. If $\overline{AH'}$ is drawn parallel to $\overline{D'A'}$ then $\overline{AC} = \overline{D'C}/v'$ hence $\overline{AH'} = I_2$.

The four heavy lines represent the four actual physical quantities in their proper magnitude and phase relation. (If fluxes and currents are interchanged, the four quantities of the alternator are found.)

Starting from the four lines representing the actual quantities, two different diagrams can be derived. If the e. m. f. is impressed on the primary, then point $D$ is selected as the common meeting point of three lines. If the e. m. f. is impressed on the secondary however, then point $D'$ has to be assumed as the common meeting point and then the four lines determined by points $A'B'C'D'$ represent the transformer diagram (where $\overline{D'B'}$ is parallel to $\overline{AD}$).

Two things can be observed if the e. m. f. is impressed in the secondary. First, that $\eta = \overline{B'C}/\overline{A'C} = \overline{BC}/\overline{AC}$, that is the thermodynamic efficiency is the same no matter which side the e. m. f. is impressed. Second, that $v''$ is the ratio of the primary and the secondary e. m. fs. at open circuit.

It is proved in textbooks that if in any complicated circuit a generated e. m. f. and an ammeter are interchanged, the reading of the ammeter does not change. (It is the so-called Theorem of Reciprocity.) Hence the short-circuit current in the secondary with an e. m. f. in the primary is equal to the short-circuit current of the primary with the same e. m. f. in the secondary. Hence if the e. m. f. is impressed on the primary, then $\overline{AC} = (I_2)_{SH}/v''$. If the e. m. f. is impressed on the secondary then $\overline{A'C} = (I_1)_{SH}/v''$. Since $(I_1)_{SH} = (I_2)_{SH}$, $\overline{AC}\,v'' = \overline{A'C}\,v'$ or $\overline{AC}/\overline{A'C} = v'/v''$. But $\overline{AC} = E_{imp}/X_{SH}'$ and $\overline{A'C} = E_{imp}/X_{SH}''$ therefore $X_{SH}''/X_{SH}' = v'/v''$. Similarly $X_o''/X_o' = v'/v''$.

Summarized, the performance of any electrical machine can be predetermined if any three of the four limiting reactances $X_o'$, $X_o''$, $X_{SH}'$, $X_{SH}''$ are known.

This is a particular case of a more general principle which states that the performance of any complicated circuit (transmission system) can be found if the open-circuit and short-circuit impedances measured from the source and from the load are known.

## XI. The Reactances under Load

a. *From the Secondary Side.* In the transformer the total resultant flux linking the primary is always constant. If energy is sent from the load towards the primary, no additional flux can link the primary, but additional current can flow through the primary. That is the primary behaves with respect to the secondary as if it were permanently short circuited. Hence the reactance of the transformer from the secondary side is always ($X_{SH}''$).

In the alternator the total current flowing through the primary is always constant. If energy is sent from the secondary towards the primary, no additional current can flow in the primary, but additional flux can appear at the terminals of the primary; that is, the primary behaves with respect to the secondary as if it were permanently open circuited. Hence the reactance of the alternator from the secondary side is always ($X_o''$).

b. *From the Primary Side.* In case of positive loads (resistance and reactance) the reactance of the machine varies between the limiting reactances $X_{SH}'$ and $X_o'$.

## XII. The General Load-Formula

It has been shown in connection with Fig. 6A that in a transformer $I_2$ sends flux through the path having a permeance $\mathcal{P}_{min}''$. The number of flux lines so produced (or the e. m. f. induced by them) is equal to $I_2 X_{SH}''$, which is also equal to the number of lines shifted and to the free energy. The flux lines which are not shifted appear as the secondary terminal-voltage, $\Phi_2$ and their number is equal to $I_2 Z_L$, where $Z_L$ is the impedance of the load. It is also equal to the work done. Hence (work done)/(free energy) $= I_2 Z_L/I_2 X_{SH}'' = Z_L/X_{SH}''$.

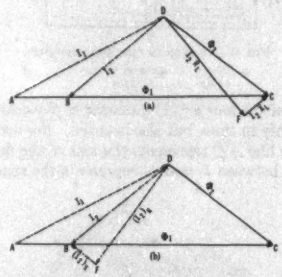


Fig. 9—Resistance and Reactance Load
(a) Loads in series
(b) Loads in parallel

Applying similar reasoning to the alternator, (work done)/(free energy) $= Z_L/X_o''$.

These are the only formulas which will be used in the article.

## XIII. Special Cases of Loads

(a) In case of short-circuits $Z_L = r_2$ and the alternator short-circuit current is determined by the point where $\overline{DB}/\overline{DC} = r_2/X_o''$ (Fig. 7B) and the transformer short-circuit current is determined by the point where $\overline{DC}/\overline{DB} = r_2/X_{SH}''$. (Fig. 7A.) $\overline{DC}$ is perpendicular to $\overline{DB}$.

(b) The load may consist of any combination of resistances and reactances. Let two simple cases be considered, a resistance and reactance in series and in parallel.

When in a transformer a resistance load is in *series* with a reactance load, the same $I$ flows through both of them, while the total secondary terminal voltage is divided between them. In Fig. 9A, $\overline{DF}$ is the voltage

across the resistance, $\overline{FC}$ across the reactance and they are at right angles to each other. Since $\overline{DF}$ represents the energy which disappeared in the resistance, $\overline{DF}$ has to be at right angles to the free energy $\overline{BD}$, while $\overline{FC}$ must be parallel to $\overline{BD}$. It can be also

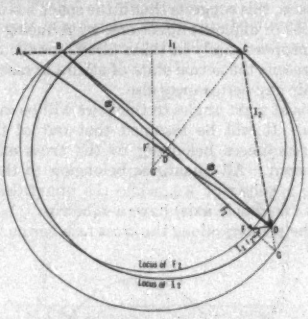


FIG. 10—LOCUS DIAGRAM OF THE ALTERNATOR

stated that $\overline{DF}/\overline{DB} = R_L/X_{SH}''$ also $\overline{FC}/\overline{DB} = X_L/X_{SH}''$ and $\overline{DC}/\overline{DB} = Z_L/X_{SH}''$.

When the load consists of a resistance in *parallel* with a reactance, the same voltage $\Phi_2$ is applied to both of

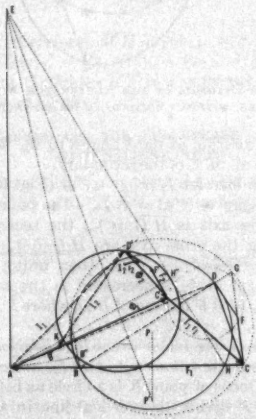

FIG. 11—LOCUS DIAGRAM OF THE CONSTANT POTENTIAL TRANSFORMER

them but $I_2$ divides between them (Fig. 9B). One part $\overline{DF}$ flows through the resistance, it is 90 deg. from $\Phi_2$, while $\overline{FB}$ flows in the reactance and is parallel to $\Phi_2$. The two currents are at right angles to each other. Here also $\overline{DC}/\overline{DF} = R_L/X_{SH}''$, $\overline{DC}/\overline{FB} = X_L/X_{SH}''$ and $\overline{DC}/\overline{DB} = Z_L/X_{SH}''$.

Similar relations hold true for an alternator, except $X_{SH}''$ is replaced by $X_s''$.

## Influence of the Boundary Conditions

### XIV. EFFECT OF THE SECONDARY RESISTANCE

The total resultant secondary flux, $\overline{DB}$ of the alternator (Fig. 10) can be divided into two parts. One part, $\overline{DF}$, represents $I_2 r_2$, it is always perpendicular to $I_2$ and $\overline{FD}/\overline{DC} = r_2/X_s''$. The other part, $\overline{BF}$ is the secondary terminal voltage $F_2$.

In the vector diagrams of the paper voltages are not represented, but fluxes producing those voltages.

At constant power factor the angle between $F_2$ and $I_2$ remains constant and the locus of point $G$ is a circle with center at $G'$. The loci of points $D$ and $F$ are also

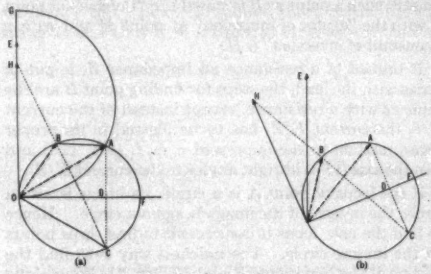

FIG. 12—EFFECT OF PRIMARY IMPEDANCE

(a) Resistance (b) Resistance and capacity

circles with center at $D'$ and $F'$. Point $F'$ lies on the vertical line through $G'$ and $\overline{D'F'}/\overline{D'C} = r_2/X_s''$.

If $F_2$ is plotted against $I_2$, the so-called Oelschläger-Ellipses are found.

In case of the transformer (Fig. 11) the reasoning is similar except $\overline{DF}/\overline{DB} = r_2/X_{SH}''$.

The scale for $F_2$ and $I_2 r_2$ is the same as for $\Phi_2$, that is $\overline{CF} = F_2 v''$.

### XV. EFFECT OF THE PRIMARY IMPEDANCE

Let current $\overline{OA}$ (Fig. 12A) flow in a circuit with impedance $Z_L$, where $\overline{OA} = E_{imp}/Z_L$. If the resistance alone had existed in the circuit, then the current which would flow through the resistance would be the diameter $\overline{OG}$ of the circle through $O$ and $A$ with center on $E_{imp}$. That is $\overline{OG} = E_{imp}/R_L$. If the reactance alone had existed, the current through it would be the diameter of the circle through $O$ and $A$ with center on a line at right angles to $E_{imp}$. That is $\overline{OF} = E_{imp}/X_L$.

An investigation will be made of how the current changes if an impedance $Z_1$ is placed between the load and the terminals.

With the introduction of $Z_1$ the apparent energy $\overline{OA}$ stored in $Z_L$ is divided into two parts. One part

$\overline{AB}$ is stored in $Z_1$ the other part $\overline{BO}$ is stored in $Z_L$. Hence $\overline{AB}/\overline{BO} = Z_1/Z_L$ and the current is $\overline{OB}$.

First it will be assumed that $Z_1$ is a resistance $r_1$. Point $B$ can be constructed the following way.

1. Draw circle through $O$ and $A$ with center on $\overline{OF}$
2. Find the image of point $A$ as $C$ where $\overline{AD} = \overline{DC}$
3. Plot the current $E_{imp}/r_1$ as $\overline{OH}$
4. Connect point $C$ with $H$

Point $B$ lies at the intersection of the circle and line $\overline{CH}$.

Angle $BAO$ = angle $BCO$ and angle $OBA$ = angle $HOC$ since they are drawn over equal arcs. Since $\overline{OC} = E_{imp}/Z_L$ and $\overline{OH} = E_{imp}/r_1$ therefore $\overline{OC}/\overline{OH} = r_1/Z_L$, hence $\overline{AB}/\overline{BO} = r_1/Z_L$ as required.

Angle $HOB$ = angle $OCB$ since both are drawn on the same arc $OB$, hence triangle $HOB$ is similar to $HCO$ and $\overline{HC}/\overline{HO} = \overline{HO}/\overline{HB}$. In Projective Geometry such a point as $B$ is called the "inverse" of point $C$ with the "center of inversion" at point $H$ and with a "constant of inversion" $\overline{OH}$.

If instead of a resistance an impedance $Z_1$ is put in series with the load, the steps for finding point $B$ are the same as with a resistance, except instead of the current $E/r_1$ the current $E/Z_1$ has to be plotted in its proper phase relation to the impressed e. m. f. (Fig. 12B) and also the axis $\overline{OF}$ is at right angles to the current $E/Z_1$.

If the locus of point $A$ is a circle, its image is also a circle, the inverse of the image is again a circle. Hence to find the new locus it is sufficient to find three points on the inverse circle. The quickest way is to find the inverse of the two points $B$ and $H$ (Fig. 11) lying along the axis by drawing $\overline{BE}$ and $\overline{HE}$ then erecting perpendiculars to these lines from point $A$. If the image $P'$ of the center of the circle $P$ is found, the center of the inverted circle lies along line $\overline{EP'}$.

If the locus of point $B$ is not a circle the inversion has to be made for each point.

If not only the current $\overline{OB}$ flowing in the circuit is known but all the other currents and fluxes existing among the different parts of the circuit, then with the introduction of $Z_1$ every other quantity changes its magnitude and direction in the same ratio as $\overline{OB}$.

## XVI. The Transformer with Primary Resistance

In case of the constant potential transformer with the introduction of the primary resistance the four points $BCDF$ (Fig. 11) change to $B'C'D'F'$ keeping their relative magnitude and phase relation. Hence after the introduction of $r_1$ $\overline{AC}$ = impressed e. m. f., $\overline{CC'} = I_1 r_1$, $\overline{AC'}$ = the total resultant flux linking the primary, etc.

It should be noticed that $\overline{CC'}$ $(I_1 r_1)$ is perpendicular to $\overline{AD'}$ $(I_1)$ and $\overline{CC'}/\overline{AD'} = r_1/X_{SM}'$. All the lines $\overline{D'B'}$ $(I_2)$ pass through point $K$ which lies at the intersection of the inverse circle and line $\overline{AH''}$, where point $H''$ is the inverse of point $H$.

## Special Problems of the Alternator

### XVII. The Salient-Pole Alternator Without Secondary Resistance

Since the four-line diagram represents the actual existing m. m. fs. and flux linkages not only in time but also in space, this suggests that if the space has different permeances in different directions, by reducing the flux linkages proportionally in those directions the diagram must represent the actual state of affairs in case of non-uniform air-gap permeances also.

The axis at right angles to the poles will be called the cross axis. It will be assumed that out of the four limiting reactances belonging to the cross axis, one, $X_o''$ is known. All quantities belonging to the cross-axis have a subscript $(\ )_c$ while the quantities of the main axis (field-pole axis) have a subscript $(\ )_m$.

Since the primary along the cross axis has no winding

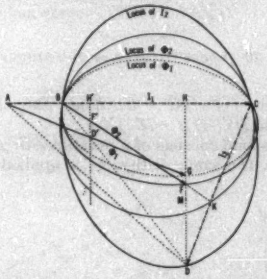


Fig. 13—Locus Diagram of the Alternator with Salient Poles, without Secondary Resistance

the only flux existing at right angles to the field pole is caused by the m. m. f. of the secondary.

At a certain load let $I_2\,(v')_m = \overline{CD}$ (Fig. 13). With a uniform air-gap $\Phi_2\,(v'')_m = \overline{BD}$. The m. m. f. acting along the cross-axis is $\overline{HD}/(v')_m$, the secondary flux linkages along the cross axis are $\overline{HD}/(v')_m$. If however, $(\mathcal{P}_{max}'')_c/(\mathcal{P}_{max}'')_m = p$ less than unity, then the cross-component of $\Phi_2$ is decreased in the same ratio, that is $\Phi_2\,(v'')_m = \overline{BF}$ instead of $\overline{BD}$, where $\overline{FH}/\overline{DH} = (\mathcal{P}_{max}'')_c/(\mathcal{P}_{max}'')_m = (X_o'')_c/(X_o'')_m = p$.

Hence if the power-factor of the load is given and $r_2$ is neglected, the angle between $\Phi_2$ and $I_2$, angle $BKC$ is constant, the locus of point $K$ is a circle as before, while point $D$ and $F$ divide the vertical line in a constant ratio $p$. Their loci are ellipses passing through points $B$ and $C$.

The steps for the construction of the ellipses are the following. First draw the original arc $CKB$ and any vertical line $\overline{H'D'}$. Then

1. Assume any line $\overline{BK}$.
2. Draw line $\overline{CKD}$.

3. Measure on line $\overline{H'D'}$ the distance $\overline{F'D'}$, where $\overline{F'H'}/\overline{D'H'} = p = (X_s'')_c/(X_s'')_m$.

4. Draw line $\overline{BD'D}$.

The intersection of $\overline{BD'}$ and $\overline{CK}$ determines point $D$.

The intersection of the vertical line $\overline{DH}$ and $\overline{BK}$ determines point $F$.

The cross component of $\Phi_1$ can be found by considering that $(\Phi_1)_c = (\Phi_2)_c\,(v'')_c$. Since $\overline{FH} =$

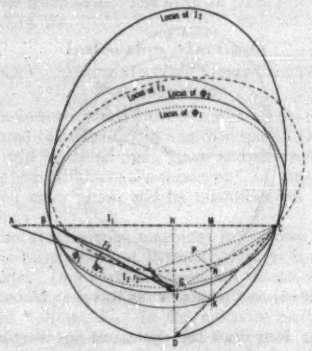


FIG. 14—LOCUS DIAGRAM OF THE ALTERNATOR WITH SALIENT POLES

$(\Phi_2)_c\,(v'')_m$ therefore $\overline{MH} = (\Phi_2)_c = \overline{FH}/(v'')_m$ and $\overline{GH} = \overline{MH}(v'')_c = (\Phi_2)_c(v'')_c = (\Phi_1)_c = \overline{FH}(v'')_c/v'')_m$. Hence point $G$ divides $\overline{HF}$ in a constant ratio and its locus is also an ellipse.

## XVIII. LOCUS OF THE POLYPHASE ALTERNATOR WITH SALIENT POLES

If the vector diagram is plotted in Fig. 14, $\Phi_2 = \overline{BF}$ can be divided into $\overline{FL} = I_2 r_2$, which is perpendicular

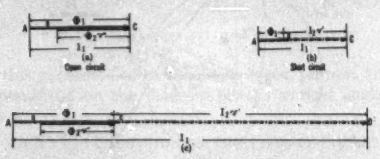


FIG. 15—SUDDEN SHORT CIRCUIT OF ALTERNATORS
(a) Open circuit (b) Permanent short circuit

to $I_2 = \overline{CD}$, where $\overline{FL}/\overline{DC} = r_2/(X_s'')$ and into $F_2 = \overline{BL}$. If the power factor of the load is constant, the angle between $F_2$ and $I_2$ remains constant and the locus of point $K$ is a circle, while the loci of points $D$, $F$, and $G$ are ellipses.

The steps for the construction of the three ellipses are the following: First draw the circle through $B\,K\,C$, then

1. Assume any line $\overline{CK}$
2. Draw $\overline{KB}$ and the vertical line $\overline{KM}$
3. Find point $N$ so that $\overline{NM}/\overline{KM} = (X_s'')_c/(X_s'')_m$
4. Draw $\overline{NP}$ perpendicular to $\overline{CK}$ so that $\overline{NP}/\overline{KC} = r_2/(X_s'')_m$
5. Draw lines $\overline{CNF}$ and $\overline{CPL}$
6. From point $L$ draw perpendicular to $\overline{CK}$
7. Through $F$ draw the vertical line $\overline{FD}$
8. Find point $G$ so that $\overline{GH}/\overline{FH} = (v'')_c/(v'')_m$.

## XIX. SUDDEN SHORT CIRCUIT OF ALTERNATORS

The case will be considered when an open-circuited alternator is suddenly short circuited.

When it is suddenly short circuited, the flux lines linking the primary and secondary cannot change instantaneously, but the m. m. fs. of the primary and secondary can. Since at sudden short circuit the existing $\Phi_1$ is $\overline{AC}/\overline{AB} = k$ times as large as it should be

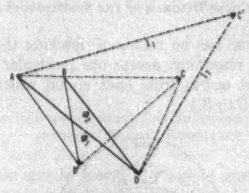


FIG. 16—VECTOR DIAGRAM OF THE ALTERNATOR WITH SUDDEN LOAD VARIATION

(Fig. 15) the primary m. m. f. has to change suddenly with the same ratio $k$ from $\overline{AC}$ to $\overline{AD}$.

That is the sudden short-circuit diagram is the same as the permanent short-circuit diagram with the following reservations:

1. The field m. m. f. $I_1$ increases in the ratio $\overline{AC}/\overline{AB}$ = (Actual $\Phi_1$)/(Permanent $\Phi_1$) = $\mathcal{P}_{max}'/\mathcal{P}_{min}'$

2. There is a superfluous $\Phi_2$ left in the alternator which slowly disappears while the whole diagram $A\,C\,D$ shrinks to its permanent size $A\,B\,C$.

That is the field m. m. f. increases with the ratio (short circuit current)/(open circuit current) if used as a transformer, or with $\mathcal{P}_{max}'/\mathcal{P}_{min}'$ or $X_s'/X_{sn}'$ while the secondary m. m. f. increases from zero to $I_1 v''$.

## XX. SUDDEN LOAD VARIATION OF ALTERNATORS

At a certain load let the alternator diagram be $A\,B\,C\,D$ (Fig. 16) and let the load change suddenly to such a value that after equilibrium is established the alternator diagram is $A\,B\,C\,D'$.

Again it is assumed that the flux linkages cannot change suddenly, only the m. m. fs.

Since $\Phi_1$ is larger than it should be by $\overline{AD}/\overline{AD'}$, therefore the primary m. m. f. $I_1$ changes suddenly in

the same ratio and phase-displacement from $\overline{AC}$ to $\overline{AC'}$ where $\overline{AC'}/\overline{AC} = \overline{AD}/\overline{AD'}$ and angle $DAD'$ = angle $C'AC$. $I_2 v'$ changes from $\overline{DC}$ to $\overline{DC'}$ just as in case of sudden short-circuit.

While point $D$ moves to $D'$, point $C'$ moves to $C$ when equilibrium is established.

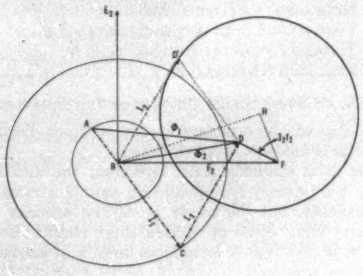

FIG. 17—LOCUS DIAGRAM OF THE SYNCHRONOUS MOTOR

(The writer has no means of checking the correctness of this reasoning, except one particular case, the sudden short circuit from open circuit when point $D$ moves from $C$ to $B$.)

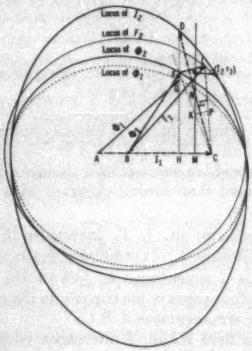

FIG. 18—LOCUS DIAGRAM OF THE SYNCHRONOUS MOTOR WITH SALIENT POLES

## Part II. Synchronous Machines

### XXI. THE SYNCHRONOUS MOTOR

Let the vector diagram of the alternator be Fig. 17. If it is assumed that $F_2$ is constant and $I_1$ is stationary, then the loci of points $F$ and $D$ are circles.

The diagram will be more familiar if instead of keeping $I_1$ stationary $F_2$ is kept stationary and $I_1$ is rotated around point $B$. The locus of point $C$ is a circle and that of $D'$ another circle with center at $H$ where $\overline{HF}/\overline{HB} = r_2/X_a''$.

### XXII. THE SYNCHRONOUS MOTOR WITH SALIENT POLES

Let the vector diagram of an alternator with salient poles be plotted in Fig. 18. If it is assumed that $F_2$ is constant the locus of point $L$ is a circle while points $F$ and $D$ move so that $\overline{FH}/\overline{DH} = (X_a'')_c/(X_a'')_m$, $\overline{FL}/\overline{DC} = r_2/(X_a'')_m$ and $\overline{FL}$ is perpendicular to $\overline{DC}$. The loci of points $D$, $F$, and $G$ will be ellipses.

The steps for the construction of the ellipses are the

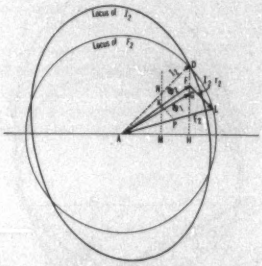

FIG. 19—LOCUS DIAGRAM OF THE REACTION MACHINE

following: First draw the circle and any vertical line $\overline{MN}$. Then

1. Assume any line $\overline{CN}$
2. Find point $K$ so that $\overline{KM}/\overline{NM} = (X_a'')_c/(X_a'')_m$
3. Draw line $\overline{CK}$
4. Draw $\overline{KP}$ perpendicular to $\overline{NC}$ so that $\overline{KP}/\overline{NC} = r_2/(X_a'')_m$
5. Draw line $CPL$
6. From $L$ draw a perpendicular to $\overline{NC}$
7. From point $F$ draw the vertical line $\overline{HFD}$
8. Find point $G$ so that $\overline{GH}/\overline{FH} = (v'')_c/(v'')_m$

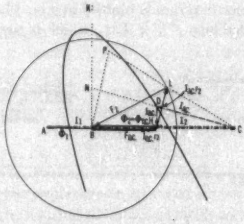

FIG. 20—LOCUS DIAGRAM OF THE SYNCHRONOUS CONVERTER

### XXIII. THE REACTION MACHINE

If it is assumed that the excitation of a synchronous motor with salient poles, $\overline{AC}$ (Fig. 18) is zero, the loci of points $D$ and $F$ are again ellipses, (Fig. 19). The angle between $I_2$ and $\Phi_2$ shows that torque is exerted by the rotor at all positions except when $\Phi_2$ is along the field axis or at right angles to it.

### XXIV. The Synchronous Converter

If brushes are put on a synchronous motor along the cross axis, the difference of potential appearing between the brushes is always equal to the component of $\Phi_2$ along the main axis, $\overline{BH}$ (Fig. 18). If current is taken out through the brushes, only that component of the rotor current can pass out which is in line with the brushes, that is $\overline{HD}$. The actual current flowing in the rotor is $\overline{CH}$, the actual $\Phi_2$ is $\overline{BH}$ and always lies along the main axis. The locus of point $D$ is again an ellipse (Fig. 20).

## Induction Machines

### XXV. Machines with Short-Circuited Secondaries

In the induction machines two separate phases will be considered to exist at right angles in space. One of the phases will be called main phase and all quantities belonging to it will have the subscript $(\ )_m$; the other will be called cross phase and its quantities will have the subscript $(\ )_c$.

In the synchronous machines it has been assumed that the total resultant secondary flux, $\Phi_2$ divides into two parts. One part represents the resistance drop in the secondary, $I_2 r_2$, the remaining part represents the terminal voltage, $F_2$. In the induction machines the secondary is permanently short circuited and $(\Phi_2)_m$ divides again into two parts. One part represents $I_2 r_2$, the remaining part represents a voltage generated in the secondary due to its rotation through a flux $(\Phi_2)_c$ linking it at right angles in space. The magnitude

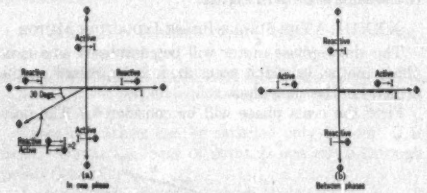


Fig. 21—Direction of the Flow of Energy

of this generated e. m. f. is $(\Phi_2)_c \times$ rev. per min. and is represented on the diagram always at right angles to $(\Phi_2)_c$.

### XXVI. Direction of the Flow of Energy

The angle between $\Phi_2$ and $I_2$ shows the relative magnitude and the direction of flow of the two types of energies between the machine and the load.

This relation can be generalized and stated that in any vector diagram the angle between *any* flux line and *any* current line shows the relative magnitude and the direction of the energies flowing between the circuit of the current and the space in which the flux resides.

If the current and the flux reside in the same phase, Fig. 21A should be consulted. The position of the current is assumed as a standard of reference and the flux is assumed to occupy different angles. The notation $\Phi \rightarrow I$ represents energy flowing from the space where $\Phi$ is stored *toward* the circuit in which $I$ flows. When the angles are multiples of 90 deg. only one type of energy flows. When $\Phi$ occupies some intermediary position between two perpendicular lines, both processes represented by the perpendiculars occur between $\Phi$ and $I$.

If the current and the flux reside in different phases, Fig. 21B should be consulted which is similar to Fig. 21A except the reference current is shifted 90 deg.

The knowledge of the direction of the flow of energy is especially important in variable-speed machines be-

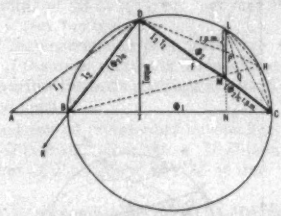


Fig. 22—Locus Diagram of the Polyphase Induction Motor without Primary Resistance

cause those speeds, where the flow of energy changes direction, have special importance.

### XXVII. The Polyphase Induction Motor

A two-phase motor will be assumed, in which the phases are identical in every respect. Since the impressed e. m. fs. are 90 deg. out of phase, to each flux and current in one phase corresponds an equal current and flux in the other phase but displaced 90 deg. in time. When in Fig. 22 $(\Phi_2)_m = \overline{DC}$ then $(\Phi_2)_c = \overline{DK}$ it is equal to $\overline{DC}$ but lags 90 deg.

$(\Phi_2)_m$ can be divided into two parts. One part $\overline{DF} = I_2 r_2$, it is at right angles to $I_2$ and $\overline{DF}/\overline{DB} = r_2/(X_{SH}'')$. The other part, $\overline{FC}$, is due to its rotation through $(\Phi_2)_c$, it is equal to $(\Phi_2)_c \times$ rev. per min. and is at right angles to $\overline{DK}$, that is it lies along $\overline{DC}$. Hence $(I_2)_m$ and $(\Phi_2)_m$ are always perpendicular and the locus of point $D$ is a circle with its center on $\overline{BC}$.

The load acts as a variable resistance $R_2$ and at any point $\overline{DC}\,\overline{D}/\overline{DB} = R_2/X_{SH}''$. But $\overline{DF}/\overline{DB} = r_2/X_{SH}''$ therefore $\overline{DF}/\overline{DC} = r_2/R_2 = \Phi_2(1 - \text{r.p.m.})/\Phi_2 = \text{slip} = s$. Hence $R_2 = r_2/s$.

*Locked Point.* At point $L$ where $\overline{CL}/\overline{LB} = r_2/X_{SH}''$ the motor is locked. The length of $\overline{FC}$ is zero, hence no energy comes from the cross phase.

*No-Load Point.* At point $B$ where $(\Phi_2)_m$ is at 180 deg. to $(I_1)_m$ the motor runs at no load, because no energy passes into the rotor.

*Motor Action.* Between points $L$ and $B$ the angle

$I_1 - \Phi_2$ shows that both active and reactive energies flow from the source toward the secondary.

*Generator Action.* Beyond point $B$ below the horizontal line to $C$ the angle $I_1 - \Phi_2$ shows that active energy flows from the rotor toward the source (hence rotor has to be driven) but still reactive energy flows from the source toward the secondary just as in case of motor action.

*Electric Brake Action.* If the rotor is driven in the negative direction, point $D$ moves beyond point $L$,

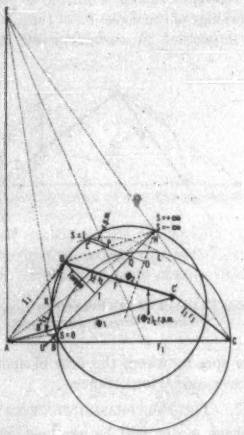

FIG. 23—LOCUS DIAGRAM OF THE POLYPHASE INDUCTION MOTOR

the voltage $\overline{FC}$ changes direction and the angle between $(\Phi_2)_m$ and $\overline{FC}$ shows that active energy comes from the cross phase into the secondary of the main phase. But angle $(I_1)_m - (\Phi_2)_m$ shows that active energy flows also from its primary into the secondary of the main phase. Both of these energies are dissipated in the secondary.

*Effect of Primary Resistance.* The effect of the primary resistance is taken care of by inverting the circle around point $E$, (Fig. 23) where $\overline{AE} = E/r_1$ or $\overline{AC}/\overline{AE} = r_1/X_{SH}'$ as shown before. The locked point $L$ is inverted to $L'$ by drawing a circle $LL'A$ with center on the horizontal line. $\overline{CC'}$ is perpendicular to $\overline{AD}$ and $\overline{CC'}/\overline{AD} = r_1/X_{SH}'$. The secondary currents always pass through point $K$ on line $\overline{AH}$.

*Speed Scale.* In Fig. 22 $\overline{FC} = (\Phi_2)_c \times$ rev. per min. and $\overline{DC} = (\Phi_2)_m$. Since $(\Phi_2)_c = (\Phi_2)_m$ therefore $\overline{FC}/\overline{DC}$ = rev. per min. (as a fraction of synchronous speed).

A scale for speed can be found by noticing that triangle $DFB$ is similar to $NCL$ (the ratio of the sides being $r_2/X_{SH}''$) and $DBC$ to $MNC$. From this it follows that point $M$ divides the line $\overline{LN}$ in the same ratio as point $F$ divides $\overline{DC}$. Hence rev. per min. = $\overline{LM}$, if $\overline{LN}$ = unity (Slip = $\overline{MN} = s$).

The significance of line $\overline{LN}$ can be seen from the following consideration. If the infinite-speed point, $C$, the locked point, $L$, and the synchronous-speed point $B$ are given, the speed for any point $D$ can be found in a different way. Assume any point $H$. Then line $\overline{DH}$ divides line $\overline{LQ}$ in the ratio rev. per min./syn. where line $\overline{LQ}$ is parallel to the line $\overline{HC}$. This is true because angle $DHB$ = angle $DCB$, also angle $LHD$ = angle $LCD$ and angle $LQH$ = angle $LNC$. Now if point $H$ coincides with the infinite speed point $C$, the speed-scale line $\overline{LQ}$ becomes parallel to the tangent at point $C$.

Hence on the inverted circle if the three characteristic speed points $HL'U$ (Fig. 23) are given, the speed scale line is found again by drawing a line $LQ$ parallel to the tangent at the infinite-speed point $H$ (or by drawing a perpendicular line to the diameter of the circle). As the primary current $\overline{AD}$ varies, line $\overline{DH}$ cuts off a distance $\overline{L'P}$ = rev. per min., if $\overline{L'Q}$ = unity. ($\overline{PQ}$ = slip)

*Torque.* The torque of each phase is equal to the product of the projection of $(I_1)_m$ on $(\Phi_1)_c$ with $(\Phi_1)_c$. Since on Fig. 22 $(\Phi_1)_c$ is vertical and constant, the vertical projection of $(I_1)_m$ multiplied by $(\Phi_1)_c$ is the torque. That is $\overline{DT}$ is proportional to the torque.

Since the torque is zero at infinite speed and at synchronous speed, the torque is represented by a line perpendicular to the line connecting the infinite speed point and the zero speed point. Hence in Fig. 23 line $\overline{DT}$, perpendicular to line $\overline{UH}$, represents the torque to the same scale as in Fig. 22.

## XXVIII. THE SINGLE-PHASE INDUCTION MOTOR

The single-phase motor will be considered as a two-phase motor, in which no e. m. f. is impressed on the primary of the cross phase.

First the cross phase will be considered. The only

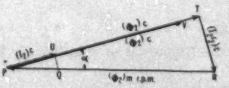

FIG. 24—CROSS PHASE OF THE SINGLE-PHASE INDUCTION MOTOR

e. m. f. generated in it is in its secondary and it is due to its rotation through $(\Phi_2)_m$. The value of this generated e. m. f. is equal to $(\Phi_2)_m \times$ rev. per min. The primary of the cross-phase is always open. In Fig. 24 let $\overline{PR}$ represent the e. m. f. $(\Phi_2)_m \times$ rev. per min., impressed on the secondary of the cross-phase. If $(r_2)_c$ were zero, then $(I_2)_c$ would be represented by $\overline{PQ}$ where $\overline{QR} = (\eta)_c\,\overline{PR}$ ($PQR$ is the standard four line diagram at open-circuit). Due to the presence of $(r_2)_c$ point $Q$ is inverted to $U$ where $\overline{UQ}/\overline{UP} = (r_2)_c/(X_s'')_c$. Every other quantity is reduced in the same proportion. Hence $\overline{PR}$ is the e. m. f. impressed on the secondary

$= (\Phi_2)_m \times$ rev. per min., $\overline{TR}$ is the resistance drop in the secondary while $\overline{PT}$ is the actual flux $(\Phi_2)_c$ linking the secondary. A part of this $\overline{PV} = (v'')_c\,(\Phi_2)_c$ is the flux $(\Phi_1)_c$ linking the primary of the cross phase. With the variation of the load only the length $\overline{PR}$ changes, but the configuration of all quantities remains the same.

Considering the vector diagram of the main phase in Fig. 25, let $\overline{AB} = E/(X_e')_m$ and $\overline{AC} = E/(X_{SH}')_m$. At any load $(\Phi_2)_m = \overline{DC}$ can be divided into two parts. One part $\overline{DF}$ is $(I_2\,r_2)_m$ is always 90 deg. from $(I_2)_m$ and $\overline{DF}/\overline{DB} = (r_2)_m/(X_{SH}'')_m$. The other part $\overline{FC}$ is the e. m. f. generated through its rotation through $(\Phi_2)_c$, it is equal to $(\Phi_2)_c \times$ rev. per min. and is always 90 deg. from $(\Phi_2)_c$. If the vector diagram of the cross phase is placed on this diagram then $(\Phi_2)_m \times$ rev. per min. is always 90 deg. from $(\Phi_2)_m$.

The motion of point $D$ is subjected to the following conditions.

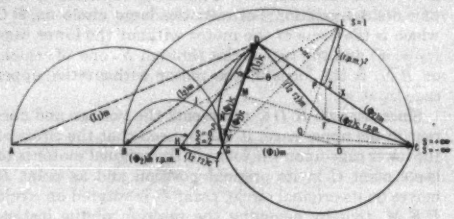


FIG. 25—LOCUS DIAGRAM OF THE SINGLE-PHASE INDUCTION MOTOR WITHOUT PRIMARY RESISTANCE

1. Angle $\alpha$ = constant, hence angle $\theta$ = constant, since $\alpha + \theta = 90$ deg.
2. Angle $CMG$ = constant = 90 deg.
3. $\overline{DF}$ is perpendicular to $\overline{DB}$ and $\overline{DF}/\overline{DB} = (r_2)_m/(X_{SH}'')_m$.

These conditions can be satisfied only if point $G$ is fixed. Hence the locus of point $D$ is a circle through points $G$ and $C$.

*Locked Point.* Point $L$, where angle $(I_2)_m - (\Phi_2)_m$ is 90 deg., is the locked point because $\overline{FC}$ is zero and $\overline{LC}/\overline{LB} = (r_2)_m/(X_{SH}'')_m$.

*Motor Action.* Between points $L$ and $N$ the angle $(I_1)_m - (\Phi)_c$ shows that active energy flows from the primary toward the cross phase.

*No-load Point.* At point $N$ where the angle $(I_1)_m = (\Phi_2)_c$ passes through 90 deg. the motor runs without load.

*Synchronous-Speed Point.* Between points $N$ and $S$ the angle $(I_1)_m - (\Phi_2)_c$ shows that now active energy flows from the cross flux toward the primary, but the angle $(I_2)_m - (\Phi_2)_c$ shows that active energy flows also from the secondary of the main phase toward the cross phase. That is between these points the copper loss in the secondary of the *cross* phase is supplied partly from the shaft and partly from the source. At point $S$, where $(I_2)_m$ is 90 deg. from $(\Phi_2)_c$ all the cross phase losses are supplied from the shaft.

*Generator Point.* Between points $S$ and $G$ the angles $(I_2)_m - (\Phi_2)_c$ and $(I_1)_m - (\Phi_2)_c$ show that the copper loss in the secondary of the *main* phase is supplied partly from the shaft and partly from the source. At point $G$ where $(I_1)_m$ is at 180 deg. from $(\Phi_2)_m$ all the rotor losses are supplied from the shaft and the only load is $(X_e'')_c$. Hence $\overline{GC}/\overline{GB} = (X_e'')_c/(X_{SH}'')_m$ and at point $G$ $(\Phi_2)_c = (\Phi_2)_m$.

*Generator Action.* Beyond point $G$ the angles $(I_1)_m - (\Phi_2)_m$ and $(I_1)_m - (\Phi_2)_c$ show that active energy passes into the source.

*Speed Scale.* $\overline{FC} = (\Phi_2)_c \times$ rev. per min. $= \overline{DT} \times$ rev. per min. $= (\Phi_2)_m \times$ rev. per min. $\times \cos\alpha$ rev. per min. $= \overline{MC} \times$ (rev. per min.)$^2$. Hence $\overline{FC}/\overline{MC} =$ (rev. per min.)$^2$.

Point $F$ may correspond to a positive or a negative speed and if the rotor rotates in the negative direction, point $D$ describes the same path again instead of moving to $C$ beyond point $L$.

The speed can be represented by one line. If a triangle $LOQ$ is drawn similar to $CMD$ then it can be proved that $\overline{LP}/\overline{LQ} = \overline{CF}/\overline{CM} =$ (rev. per min./syn.)$^2$.

Draw $\overline{FZ}$ perpendicular to $\overline{AC}$. Triangle $BDH$ is similar to triangle $DFZ$ since their sides are mutually perpendicular and $\overline{DZ}/\overline{DH} = r_2/(X_{SH}'')_m$. As in the polyphase motor $\overline{CZ}/\overline{CD} = \overline{LX}/\overline{LO}$. The triangle $LXP$ is similar to $CZF$, consequently $\overline{LP}/\overline{LQ} = \overline{CF}/\overline{CM} =$ (rev. per min.)$^2$.

The speed scale $\overline{LQ}$ is again perpendicular to the diameter of the circle and point $Q$ lies on the line connecting the synchronous-speed point $S$ and the infinite-speed point $H$.

*Torque.* Since there is only one primary current, torque $= (I_1)_m \times (\Phi_1)_c \times \cos ADV = \overline{AD} \times \overline{DV} \times \cos ADV/(v'')_m$.

The torque is zero at points $L$ and $H$, since $\overline{DV} = 0$, also at point $N$ where $\cos ADV = 0$.

*Effect of Primary Resistance.* The primary resistance is taken care of by inverting the diagram around point $E/r_1$. All quantities keep their configurations.

Similarly to the polyphase motor, all $(\Phi_2)_c$ lines pass through one point lying at the intersection of the locus and the line connecting the origin with the infinite-speed point.

## XXIX. THE DOUBLE SQUIRREL-CAGE INDUCTION MOTOR

In the double squirrel-cage induction motor another load is added in parallel to the ordinary induction motor load. This additional load is the reactance, $x_3$ of the lower cage (or of the tertiary winding) which also has a resistance $r_3$.

In Fig. 26 $\overline{AB} = E/X_e'$ and $\overline{AC} = E/X_{SH}'$ where $X_e'$ and $X_{SH}'$ are constants of the motor without the

lower cage. With any load the primary current is $\overline{AD}$, the total rotor current is $\overline{DB}$, and $\overline{DC}/\overline{DB} = Z_L/X_{SH}''$.

The total rotor current $\overline{DB}$ divides into two parts. One part $\overline{DK} = I_2$ flows in the upper cage, the other part $\overline{KB} = I_3$ flows in the lower cage.

The total resultant flux $\Phi_2$ linking the upper cage consists of two parts. One part $\overline{DT} = \Phi_3$ is the total resultant flux linking the lower cage, the other part, $\overline{CT}$ resides between the two cages. To each of these fluxes in the main phase corresponds an equal flux in the cross phase displaced 90 deg. in space as well as in time.

The upper cage behaves just as an ordinary induction motor. The total resultant secondary flux $\Phi_2 = \overline{DC}$

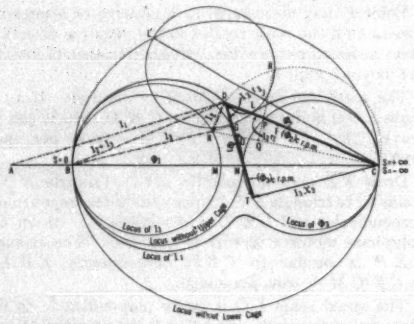


FIG. 26—LOCUS DIAGRAM OF THE DOUBLE SQUIRREL-CAGE INDUCTION MOTOR WITHOUT PRIMARY RESISTANCE

divides into two parts. One part is $\overline{DF} = I_2 r_2$, 90 deg. from $I_2$ where $\overline{DF}/\overline{DK} = r_2/X_{SH}''$. The other part is $FC = (\Phi_2)_c \times$ rev. per min., 90 deg. from $(\Phi_2)_c$, which lies along line $\overline{DK}$. Hence $\overline{DC}$ is always 90 deg. from $I_2$ and $\overline{DC}/\overline{DK} = R_2/X_{SH}'' = (r_2/s)/X_{SH}''$.

The lower cage which is in parallel with the upper cage and therefore has the same e. m. f. $\Phi_2$ impressed upon it, has in addition to $r_3$ and $(\Phi_2)_c$ and additional reactance $x_3$ in series. Hence $\Phi_2$ is divided now into three parts. One part, $\overline{CT}$ is the e. m. f. across the reactance $x_3$, is equal to $I_3 x_3$, is parallel to $I_3 = \overline{BK}$ and $\overline{CT}/\overline{BK} = x_3/X_{SH}''$. The other part, $\overline{DU}$ is the e. m. f. across $r_3$, is equal to $I_3 r_3$, is perpendicular to $I_3$ and $\overline{DU}/\overline{KB} = r_3/X_{SH}''$. The third part is $\overline{UT} = (\Phi_2)_c \times$ rev. per min., 90 deg. from $(\Phi_2)_c$ which lies along line $\overline{KB}$. Similarly to the upper cage $\overline{DU} + \overline{UT} = \overline{DT}$ lies 90 deg. from $\overline{BK}$ and $\overline{DT}/\overline{BK} = R_3/X_{SH}'' = (r_3/x)/X_{SH}''$.

Due to the perpendicular position of the currents and the fluxes the triangle $CDT$ is similar to triangle $KGD$. Since $\overline{DC} = \overline{DK} \times R_2/X_{SH}''$ each side of triangle $CDT$ is $R_2/X_{SH}''$ times as large as the sides of $KGD$. Since $\overline{DT}/\overline{BK} = R_3/X_{SH}'' = (\overline{KG}/\overline{BK})(R_2/X_{SH}'')$ therefore $\overline{BK}/\overline{KG} = R_2/R_3 = (r_2/s)(r_3/s) = r_2/r_3 =$ constant.

Since $\overline{CT}/\overline{KB} =$ constant and $\overline{GK}/\overline{KB} =$ constant, therefore $\overline{CT}/\overline{GB} =$ constant. Since $\overline{CT}$ and $\overline{GB}$ are also always parallel and $\overline{TG}$ is always perpendicular to both of them, triangles $BNG$ and $NTC$ are similar. $\overline{NC}/\overline{NB} =$ constant, hence the loci of the three points $K$, $G$, and $T$ are circles with their centers on line $\overline{BC}$, passing through points $M$ and $N$. These points are located between $B$ and $C$ such that $\overline{BM}/\overline{MN} = r_2/r_3$ and $\overline{NC}/\overline{BM} = x_3/X_{SH}''$.

If the three circles are drawn, for any assumed $I_3 = \overline{BK}$ the position of point $D$ is found at the intersection of line $\overline{NGD}$ and the semicircle on diameter $\overline{KC}$.

The locus of point $D$ is not a circle, hence each point of the locus has to be separately constructed.

With the variation of $r_2/r_3$ and $x_3$ point $D$ can assume any desired position between the large circle on $BC$ which is the locus of the motor without the lower cage ($r_3 = \infty$) and the two circles through $N$, one of which, on $\overline{BN}$, is the locus of the motor without the upper cage ($r_2 = \infty$).

Since triangle $KDC$ represents the voltage and current in the upper cage, it can be seen that the effect of the lower cage upon the locus of the original motor is to leave point $C$ in its original position and as point $D$ moves on its original circle, point $B$ is rotated on circle $BKM$, thereby changing the position of the instantaneous circle from load to load. That is each point of the original locus describes a circle, the diameter of each circle being proportional to the distance of that point from $C$.

*Locked Point.* This consideration immediately suggests how to find the locked point. Let the locked point of the motor without the lower cage be at $L'$, where $\overline{CL'}/\overline{L'B} = r_2/X_{SH}''$. If a circle is drawn through $L'$ on $\overline{L'C}$ with diameter $\overline{L'J}$ where $\overline{MJ}$ is parallel to $\overline{BL'}$, then the intersection of this circle with the locus is the locked point. Of course at this point $\overline{DC}/\overline{DK} = r_2/X_{SH}''$.

*Speed.* For any point $D$ on the locus the semicircle $KDRC$ represents the instantaneous locus of the upper cage, $R$ the locked point. Hence if a vertical line is drawn from $R$ to the diameter $\overline{KC}$, line $\overline{DC}$ divides it into two parts, such that rev. per min./syn. $= \overline{RP}/\overline{RQ}$ just as in an ordinary induction motor.

A second scale for speed is $\overline{FC}/\overline{DC} =$ rev. per min./syn. A third scale is $\overline{UT}/\overline{DT} =$ rev. per min./syn.

*Torque.* The projection of $(I_1)_m$ on $(\Phi_1)_c$ multiplied by $(\Phi_1)_c$ gives the torque of one phase. Hence just as in an induction motor the vertical component of $I_1$ is proportional to the torque.

*Effect of Primary Resistance.* Each point of the locus should be inverted around point $E/r_1$. All currents and fluxes will keep their relative configurations.

## XXX. The Repulsion Motor

The brush axis will be considered as the axis of the main phase.

Let the motor be short circuited and let (Fig. 27) $\overline{AB} = E/(X_s')_m$, $\overline{AC} = E/(X_{SH}')_m$. If the cross phase, which is always open circuited, is put in series with the main phase, line $\overline{AC}$ is inverted to $\overline{AC'}$ where $\overline{CC'}/\overline{C'A} = (X_s')_c/(X_{SH}')_m$.

Let $a$ = (number of cross turns)/(number of main turns).

When the motor is running, an e. m. f. $\overline{FR} = (\Phi_2)_c \times$ rev. per min.$/a$ is generated in the secondary of the main phase which is perpendicular to $\overline{RC}$. Also $\overline{AD}$ is parallel and proportional to $\overline{RC}$, since all the $(\Phi_1)_c$ is produced by $I_1$, that is $\overline{AD}/\overline{RC} = \overline{AC'}/\overline{C'C}$. Hence line $\overline{DR}$ always passes through point $C'$ which divides $\overline{DR}$ in the same ratio. The loci of points $D$ and $R$ are circles.

At infinite speed $(\Phi_1)_c = \overline{RC} = O$, $I_1 = O$ and $(\Phi_2)_c \times$ rev. per min.$/a$ lies at $\overline{F'C}$ where $\overline{AF'}/\overline{AB} = r_2/(X_{SH}'')_m$. The diameters of the circles are parallel to $\overline{F'C}$.

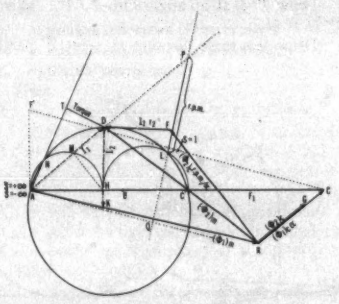

Fig. 27—Locus Diagram of the Repulsion Motor without Primary Resistance

Considering triangle $K\,D\,R$, the two stationary points $C'$ and $A$ divide two of the sides in constant ratios. Hence the third side $\overline{KD}$ also must be divided in a constant ratio by a stationary point $H$ lying along line $\overline{AC'}$. That is $I_2$ always passes through point $H$.

*Locked Point.* At point $L$ where $(I_2)_m$ is at right angles to $(\Phi_2)_m$, the motor is locked.

*No-Load Point.* At point $N$ where $I_2$ is perpendicular to $I_1$ no energy flows toward the secondary.

*Speed.* Just as in the polyphase induction motor, $\overline{LP}$, a perpendicular line to the diameter of the locus, is the speed scale.

*Torque.* The torque $I_1\,I_2 \cos\theta$ is proportional to $\overline{AD} \times \overline{MD}$ which is proportional to the perpendicular line $\overline{DT}$ drawn to line $\overline{AN}$.

*Effect of Primary Resistance.* Combine $(r_1)_m$ and $(r_1)_c$ into $r_1$ and invert the locus around point $E/r_1$.

## XXXI. The Condenser (or Split-Phase) Motor

The split-phase motor can be considered as the sum of two single-phase motors. The first motor exists if e. m. f. is impressed on the primary of one phase (main phase) while the primary of the other phase (cross phase) is short circuited. The second motor exists if e. m. f. is impressed on the primary of the cross phase, while the primary of the main phase is short circuited. If all currents and fluxes existing in each single-phase motor are added, the resultant represents all the actual currents and fluxes of the split-phase motor.

The actual current in the primary of the main-phase is the current flowing in the first case plus the short-circuit current in the second case. Similar relations hold for the cross phase. However, the Theorem of Reciprocity states that if in any circuit an applied voltage and an ammeter are interchanged, the reading of the ammeter does not change. That is the short-circuit current in the primary of the main phase is equal and opposite to the short-circuit current in the primary of the cross phase, hence they do not appear in the current coming from the line.

To find the locus diagram of the condenser motor, first the locus diagram of a single-phase motor with short-circuited cross phase has to be developed.

*The Single-Phase Motor with Short-Circuited Cross Phase.* Its theory is identical with the theory of the ordinary single-phase motor with open-circuited secondary, except the vector diagram of the cross phase (Fig. 28) differs from Fig. 24.

In Fig. 28 it is assumed that the cross phase has a resistance $(r_1)_c$ and a condenser $(x_1)_c$ in its primary. Also $a$ = (conductors in cross phase)/(conductors in main phase). The steps for constructing Fig. 28 are the following:

1. Assume any distance $\overline{DR}$ representing $(\Phi_2)_m \times$ rev. per min. $\times\, a$, the e. m. f. impressed on the secondary of the cross phase. $\overline{DR} = E/(X_{SH}'')_c$.
2. $\overline{BR} = (\eta)_c \times \overline{DR}$.
3. The loads are $(r_1)_c$ and $(x_1)_c$. If they were variable the locus would be a circle with center at $O$ where $\overline{OP}/\overline{PB} = (x_1)_c/(r_1)_c$.
4. The load, however, remains at a definite value at all speeds, hence the position of $(I_2)_c$ is always at a point $K$ where $\overline{KR}/\overline{KB} = (z_1)_c/(X_{SH}')_c$. To find this point draw a circle through $M$ and $B$ with its center along the vertical line at point $B$, where $\overline{MR}/\overline{MB} = (r_1)_c/(X_{SH}')_c$. [This circle is the locus of all loads with constant $(r_1)_c$.]
5. The effect of $(r_2)_c$ is taken care of by inverting point $K$ around point $E$ where $\overline{DE} = E/(r_2)_c$ or $\overline{DR}/\overline{DE} = (r_2)_c/(X_{SH}'')_c$. The other quantities can be drawn in as usual.

The vector diagram of the main phase is similarly constructed to Fig. 25. To find the locus, the only quantity needed from Fig. 28 is angle $\alpha$, because it determines the position of point $G$ in Fig. 25. It may happen with larger $(x_1)_c$ that angle $\alpha$ is negative. In

that case point $G$ lies to the left of point $B$. The construction of all quantities, however, remains the same. The center of circle $G\,C\,L$ lies below the horizontal line and no load occurs above synchronous speed.

Care should be taken in the speed scale. In Fig. 25 where $(\Phi_2)_c = \overline{R\,D} \cos \alpha$ the synchronous speed is represented by the distance $\overline{L\,Q}$. In Fig. 28, however, $(\Phi_2)_c$ is less than $\overline{R\,D} \times \cos \alpha$ by a constant ratio $\overline{D\,U}/\overline{D\,H} = b$, hence the synchronous speed is represented by $\overline{L\,Q} \times b$.

*The Condenser Motor.* The actual constants of each phase should be used. Let an e. m. f. be impressed on the primary of the main phase and let the primary of the

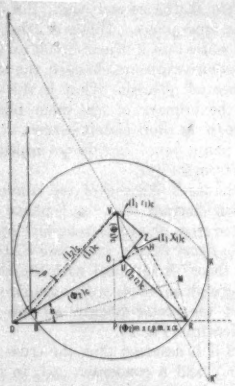

FIG. 28—SHORT-CIRCUITED CROSS PHASE OF THE SINGLE-PHASE INDUCTION MOTOR

cross phase be short circuited. The locus of the primary current in the main phase is the circle $L''\,S''\,K''$ in Fig. 29. Let the same e. m. f. be impressed on the primary of the cross phase and let the primary of the main phase be short circuited. The locus of the primary current in the cross phase is the circle $L'\,S'\,K'$. (The current scales should be identical.)

*Locus of the Line Current.* If the primary currents $\overline{A\,T''}$ and $\overline{A\,T'}$ corresponding to the same speeds are added, the locus of $I_{total}$ coming from the line is found to be again a circle $L\,T\,S\,K$. Hence it is sufficient to add three points, the infinite-speed points ($K''$ and $K'$) the synchronous-speed points ($S''$ and $S'$), and the locked points ($L''$ and $L'$) to determine the locus.

*Speed Scale.* It will be also noticed that the speed scale $\overline{L\,Q}$ for $I_{total}$ can be constructed in exactly the same way as in a single-phase motor. That is for any assumed $I_{total} = \overline{A\,T}$ the line $\overline{T\,K}$ cuts off from $\overline{L\,Q}$ a distance $\overline{L\,P}$ proportional to (rev. per min.)$^2$ ($\overline{L\,Q}$ = unity).

*Locus of the Phase Currents.* It is sufficient to find the short-circuited current in the cross phase. The steps are the following:

1. Draw any line $\overline{K''\,T''}$ and measure $\overline{L''\,P''}$ = (rev. per min.)$^2$
2. Draw line $\overline{K'\,T'}$ representing the same speed, that is $\overline{L'\,P'}$ = (rev. per min.)$^2$
3. Draw $\overline{H\,J}$ perpendicular to $\overline{A\,T''}$ where $\overline{H\,J}/\overline{A\,T''} = (r_1)_m/(X_{SH}')_m$ [$\overline{A\,H} = E/(X_{SH}')_m$] representing the resistance drop in the primary of the main phase when acts as a single-phase motor. Then $\overline{J\,T''} = (\Phi_2)_m$

In Fig. 28 the short-circuit current $\overline{T\,V}$ is always proportional to $(\Phi_2)_m \times$ rev. per min. and is always at a constant angle (90 deg. $- \beta$) from it. Let $\overline{T\,V}/\overline{D\,R} = d$. In Fig. 29 the number of volts corresponding to $(\Phi_2)_m = \overline{J\,T''} \times (X_{SH}')_m/(v'')_m$. [$\overline{J\,T''}$ in amperes] The number of volts generated in the secondary of the cross phase $= \overline{J\,T''}\,(X_{SH}')_m \times a \times$ rev. per min.$/(v'')_m$. This has to be equal to $\overline{T\,V} \times (v'')_c\,(X_{SH}'')_c/d$ = number of volts represented by $\overline{D\,R}$ in Fig. 28. Hence

4. Calculate $\overline{T''\,D}$ (in mm.) $= \overline{J\,T''}$ (in mm.) $\times$ rev. per min. $\times$ constant, where constant $= (X_{SH}')_m \times a \times d/(X_{SH}'')_c\,(v'')_m\,(v'')_c$
5. Draw $\overline{T''\,D}$ at an angle $\beta$ from $\overline{J\,T''}$. Then $\overline{A\,T''} + \overline{T''\,D} = (I_1)_m$
6. Draw this same distance at point $T'$ parallel to

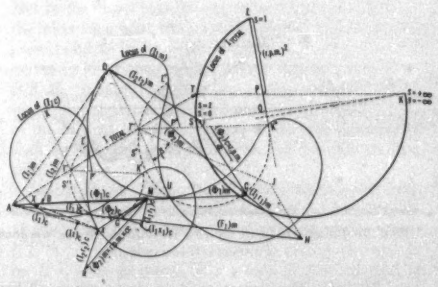

FIG. 29—LOCUS DIAGRAM OF THE CONDENSER MOTOR

itself in the opposite direction as $\overline{T'\,Z}$. Then $\overline{A\,T'} + \overline{T'\,Z} = (I_1)_c$

7. Reverse $\overline{T''\,D}$ and $\overline{T'\,Z}$ thereby finding two other points $U$ and $X$ on the loci corresponding to the same but negative speeds.

If the short-circuit current in the main phase is constructed instead of the short-circuit current in the cross phase, the same results are found.

It is interesting to note that if the motor is driven in the negative direction the phase currents have different values but $I_{total}$ describes again the same locus just as in a single-phase motor.

*Actual Currents and Fluxes.* $\overline{A\,H} = E/(X_{SH}')_m$ and $\overline{A\,G} = E/(X_{SH}')_c$. $\overline{H\,C} = (I_1\,r_1)_m$, is perpendicular to $\overline{A\,D}$ and $\overline{H\,C}/\overline{A\,D} = (r_1)_m/(X_{SH}')_m$. $\overline{B\,C}/\overline{A\,C} = (\eta)_m$,

$\overline{DF}/DB = (r_2)_m/(X_{SH}'')_m$. Similarly in the cross phase where in addition $\overline{GN}/\overline{AZ} = (x_1)_c/(X_{SH}')_c$, $\overline{GN}$ is parallel to $\overline{AZ}$ and represents the voltage across the condenser.

The correctness of the results is proved by the fact that $\overline{FC}$ representing the e. m. f. generated in the secondary of the main phase due to its rotation through $(\Phi_2)_c$, is always perpendicular to $\overline{ZM} = (\Phi_2)_c$ and is always equal to $(\Phi_2)_c \times$ rev. per min./$a$ (both expressed in volts). Similarly $\overline{MR}$ is also always perpendicular to $\overline{DC} = (\Phi_2)_m$ and is equal to $(\Phi_2)_m \times$ rev. per min. $\times\, a$, just as is required by the theory.

*Torque.* The total torque is the difference of the torques of the phases. In synchronous watts: torque $= (I_1)_m \times \cos MAD \times (AM/AG) \times E_{imp}/a - (I_1)_c \times \cos CAZ \times (AC/AH) \times E_{imp} \times a$.

If $(I_1)_m$ and $(I_1)_c$ are given, it is sufficient to draw only lines $\overline{HC}$ and $\overline{GM}$ for finding the torque.

## Appendix

### Connection between Design Constants

a. Let

$x_1$ = leakage reactance of the primary
$x_2$ = leakage reactance of the secondary
$x_m$ = mutual reactance

Then

$$X_o' = x_1 + x_m \quad X_{SH}' = x_1 + x_2\, x_m/(x_2 + x_m)$$
$$v' = x_m/(x_1 + x_m)$$
$$X_o'' = x_2 + x_m \quad X_{SH}'' = x_2 + x_1\, x_m/(x_1 + x_m)$$
$$v'' = x_m/(x_2 + x_m)$$

b. Let

$X_1$ = self-inductive reactance of the primary
$X_2$ = self-inductive reactance of the secondary
$K$ = coefficient of coupling

Then

$$X_o' = X_1 \quad X_{SH}' = X_1\,(1 - K^2) \quad \eta = K^2$$
$$X_o'' = X_2 \quad X_{SH}'' = X_2\,(1 - K^2)$$

### Acknowledgment

The writer wishes to acknowledge his indebtedness to Dr. W. J. Branson, who taught him the use of the open-circuit and the short-circuit reactances in the design of polyphase and the single-phase induction motor. Also, he wishes to thank Mr. E. E. Dreese for his suggestions and criticisms.

### Nomenclature

$X_o'$ = Open-circuit reactance, measured from the primary side
$X_o''$ = Open-circuit reactance, measured from the secondary side
$X_{SH}'$ = Ideal short-circuit reactance, measured from the primary side
$X_{SH}''$ = Ideal short-circuit reactance, measured from the secondary side
$\Phi_1$ = Total resultant flux linking the primary winding
$\Phi_2$ = Total resultant flux linking the secondary winding
$F_1$ = Difference of potential at the terminals of the primary winding
$F_2$ = Difference of potential at the terminals of the secondary winding
$r$ = Actual resistance
$R$ = Apparent resistance
$I_1$ = Primary current
$I_2$ = Secondary current
$\mathcal{P}_{max}'$ = Maximum possible permeance, measured from the primary side
$\mathcal{P}_{max}''$ = Maximum possible permeance, measured from the secondary side
$\mathcal{P}_{min}'$ = Minimum possible permeance, measured from the primary side
$\mathcal{P}_{min}''$ = Minimum possible permeance, measured from the secondary side
$(\ )_m$ = Quantity belonging to the main phase
$(\ )_c$ = Quantity belonging to the cross phase

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## Discussion

**R. H. Park:** The diagram (b) of Fig. 3 of the paper will look a little more familiar if we draw it as in Fig. 1 herewith. Let the circuit of Fig. 2 herewith represent the equivalent circuit of an induction motor. A certain amount of current $I_m$ flows in the magnetizing branch of the circuit, and a certain amount of

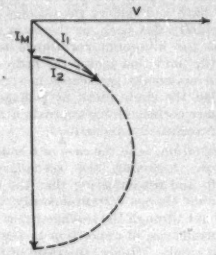


Fig. 1

current $I_2$ is coming out of the slip rings. If the slip rings are short circuited, the secondary current will be wholly reactive, and if the slip rings are feeding a resistance load, the locus of this secondary current will be a circle. The primary current $I_1$ is the vector sum of $I_m$ and $I_2$. Thus the lines on the diagram of Fig. 3b can be identified in conventional terms if desired.

Mr. Kron has introduced some entirely new names for these quantities—*i. e.*, vector stored energy, vector free energy, and vector work done. It is always possible to introduce new conceptions of this type and I hope that these new ones will help us

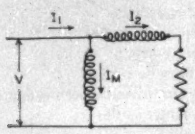


FIG. 2

in this sort of work. I notice that the projection of the stored energy vector does really represent the magnetically stored energy in the whole system.

**C. A. Adams:** In practically all of our textbooks, each type of electrical machine is considered largely as a separate problem with its own special type of treatment, although elements of similarity are often pointed out.

In so far as the author has succeeded in developing a generalized treatment that can be applied to any type of electrical machinery, he has rendered a very great service to the profession, and particularly to the education of our young engineers.

But Mr. Kron has created in considerable degree a new language and for most of us new languages are not easy to acquire.

In nearly every type of electrical machinery there are two or more m. m. fs. and there are many ways of dealing with these m. m. fs. and with the flux or fluxes produced by them, as well as with the e. m. fs. produced by the fluxes. In order to simplify the problem and to assist in visualization, we are accustomed to make certain approximations, and to simplify the picture we employ vector diagrams.

In my own teaching work, I have attempted for many years to generalize these diagrams and to make plain such distinctions as are necessary, for example, between time and space phase relations.

Instead of starting with m. m. fs., fluxes, e. m. fs., and currents, the author deals with energy, maximum stored energy, and free energy, and has labeled the ratio of the free energy to the maximum stored energy the thermodynamic efficiency, because of its analogy to that ratio. As a matter of fact, it is not efficiency at all as we understand it in connection with electrical machinery. It is really the ratio of the difference between the permeance of the primary flux path and that of the leakage path to the permeance of the primary flux path, or the ratio of the maximum permeance minus the minimum permeance to the maximum permeance. In the induction motor the ratio of the minimum permeance to the maximum permeance is approximately what is sometimes called the circle ratio, or leakage coefficient, the minimum permeance corresponding approximately to the leakage permeance as it is ordinarily understood.

As another illustration, take the case of a sudden short circuit on an alternator. Assuming the secondary or armature resistance to be 0, and remembering that the total flux linked with the field cannot change instantaneously, practically all of this flux is forced out through the leakage paths as both primary and secondary current rise in opposition to the point necessary to accomplish this result. Hence, the ratio of the sudden short circuit current to the full load current of the machine is practically the ratio of the permeance of the primary or field flux path to that of the leakage path.

These illustrations are given merely to indicate that the difference between the two methods is largely one of language.

However, there is one point in the author's method of analysis in which it is distinctly superior to the methods commonly represented by our more familiar vector diagrams; *i. e.*, where he deals with real and measurable permeances rather than with artificial permeances. For example, in the transformer as well as in the induction motor, we are accustomed to deal with the permeance of the flux path common to both primary and secondary, as if it were a real measurable quantity, when in fact it is not.

Finally, the question arises in the mind of the average designing engineer, "Is there any saving of labor in the actual quantitative computations involved in the analysis of the operation of a particular machine?" The author claims to use only two formulas, which, as a matter of fact, are sound and fundamental; but look at some of his vector diagrams and realize that the calculations must all be made graphically and to scale. I am wondering if the errors inevitably involved in this graphical work are not at least as great as those involved in the approximations connected with the ordinary mathematical methods.

I do not wish to leave the impression that Mr. Kron's method is not an excellent one for those who have not already learned another language. It may be that it portrays the relationships involved in a more satisfactory form, but I feel sure that it will be a long time before our more traditional methods are completely replaced.

**B. L. Robertson:** Mr. Kron makes the statement that in the sudden short circuit of an alternator, and in the sudden load variation of an alternator, the flux-linkages of the primary and secondary windings (defined as the stator and rotor windings respectively) cannot change instantaneously, but that the m. m. fs. of those windings can.

The first statement is in accordance with the principle known as the "constant linkage theorem" which states that in any closed circuit containing no live voltages and having zero resistance the sum of all of the flux-linkages of that circuit must remain a constant. This theorem was first recorded by Doherty, and later used by Franklin and Laffoon in solving alternator short circuit problems.

The second statement, however, that the m. m. fs. of the alternator circuits can change instantaneously is not in agreement with physical facts. The only way in which the flux-linkages of the alternator circuits can change is by a change in the armature or field currents under constant permeability conditions, by a change in permeability under constant current conditions, or by changes in both currents and permeability at the same time, so that their effects do not balance each other.

In the case of the alternator, the permeance of the magnetic circuit varies with the position of the rotor, and since the machine has a finite speed the change in permeance, and hence m. m. f., is not instantaneous. The flux-linkages being constant, and the permeance varying at a finite rate, the m. m. f. must change also at some definitely calculable rate. There is no change in any of the quantities of the machine at the very first instant of short circuit.

I should like to ask Mr. Kron if he can reconcile the two statements which have been made in the paper, or if I have misinterpreted his meaning.

All alternating quantities are in terms of effective values, hence it apparently follows that the diagrams do not lend themselves to the calculations of instantaneous values such as the cyclic variations of field and armature currents just following the sudden short circuit of an alternator. I believe it is for this reason that the usual analytical quantities do not appear, rather than that the four basic reactances given will take care of all conditions of machine performance at all instants of time.

The approach, as illustrated in the paper, to the solution of machinery problems is on the basis of energy relations. That is, the principle is borrowed from ordinary mechanics that if a problem can be solved from the standpoint of work and energy we usually have an easier means to its solution. The method outlined by Mr. Kron is valuable for this reason. It also gives us a different physical point of view of the electric machine.

**Gabriel Kron:** The paper introduces into electrical engineering a method of attack which is used already extensively and successfully in all branches of theoretical physics. It seems to be the tendency of physical problems to give easy solutions with the minimum effort when attacked from the energy point of view, while the consideration of the equilibrium of forces usually leads to complicated solutions. In the study of electrical machinery the method of equilibrium of forces (Kirchhoff's first law) is still used exclusively and as a consequence the physical theory of even comparatively simple machines, like the single-phase induction motor, becomes so complicated that only a surprizingly small number of engineers have any understanding of it.

Although the method of attack from the energy point of view is used in d-c. problems in a few isolated cases, its extension to a-c. problems has been handicapped by the fact that while d-c. force functions (e. m. fs., $I\ R$ drops) had been generalized for a-c. cases, no such generalization has been formulated yet for the different functions having the dimensions of energy. It is the purpose of the paper to define three such functions and to show that the generalized form of the so-called "Law of Free Energy," originated by Helmholtz for isothermal, reversible processes, gives the energy performance of the transformer and alternator, and at the same time introduces the most natural physical constants of a machine, the open-circuit and short-circuit reactances, which are the limiting cases of the only measurable quantity. Due to the length of the article I could only show during the presentation of the paper the extension of this law to the most general case of transmission networks by replacing reactances by impedances and scalars by vectors. The sudden short circuit analysis of the alternator was added only to show that not alone steady state but also transient problems have a tendency to give simple solutions by the use of energy relations.

The general formula $Z_L/Z_{SR}''$ gives not only a simple tool for finding the performance of complicated machines and networks, but it enables one to draw on the diagram, after the locus is found, all currents and fluxes existing inside the machine at any desired load without additional computations. Since these quantities are shown on all diagrams, some of them look complicated even to Professor Adams. Of course in the construction of the loci those lines are unnecessary and they are shown only for the sake of a physical picture.

Since only *resultant* fluxes are shown, the method is ideally suited for the analysis of machines in which saturation occurs.

Although the method of analysis was not worked out for the purpose of saving labor in the routine performance calculations, it took from five to ten times as long to plot the non circular loci from equivalent circuits or equations. The saving of time with the method presented in case of circular loci is of course not as apparent.

The method is still in its formative process, and I could eliminate at least half of the derivations if I rewrote the paper, due to simple relations existing between the actual quantities of the diagrams discovered since its writing. I just want to call attention to the fact that the extension of the four line diagram to any network eliminates the sections concerning the effect of resistances in the transformer and alternator, and at the same time introduces scales for input, output, loss, and efficiency.

Professor Adams notes that the thermodynamic efficiency is the same type of term as the circle coefficient of the induction motor. That is true, but while the circle coefficient refers to the accidental relation of a circular locus and it has no physical meaning with synchronous or commutator machines, the thermodynamic efficiency represents a fundamental property of a system of two magnetically interlinked windings just as the coefficient of coupling does, and it shows up in the vector diagrams of *all* machines. However I grant that the name is not very appropriate.

Professor Adams also mentions that the minimum possible permeance is approximately equal to the leakage permeance. The leakage permeance $(X_1 + X_2)$ is equal to the minimum permeance $X_1 + X_2 \cdot X_m/(X_2 + X_m)$ only in the limiting case when $X_m$ = infinity, and it is not desirable to interchange them, since approximate assumptions often lead to more involved results than the correct assumptions.

Professor Robertson calls attention to the incorrect use of the word "instantaneous." Instead "during the first cycle" should have been used. Lately I found that if the four-line diagram is considered as a *space* diagram, the four lines describe the actual position of the m. m. f. and flux waves *from instant to instant* after any type of sudden single-phase or polyphase short circuit in any single-phase or polyphase synchronous machine having smooth gap or salient poles. In view of this fact Figs. 15 and 16, representing only one instant, are superseded and the corresponding sections XIX and XX should be omitted.

Mr. Alger, who as Chairman of the Committee on Electrical Machinery had a chance to study the paper, finds the picture presenting a bird's eye view of a-c. machinery and networks, "very clear and complete." The aim in developing the theory was not only to build a clear physical picture, but to build it upon conceptions used by the parent of all applied sciences, theoretical physics, because only then can the method be applied successfully in future theoretical and practical developments.

# Transient Torque-Angle Characteristics of Synchronous Machines

BY W. V. LYON* and H. E. EDGERTON*
Associate, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—Mechanical oscillations of synchronous motors following the application of abrupt shaft loads have not been heretofore easily calculated for cases of large angular swings, taking into account the damping currents in the rotor, except by tedious point-by-point methods. The chief difficulty has been due to the form of the basic differential equation upon which the solution of hunting problems depends.*

*Within the last few years Dr. V. Bush and others at the Massachusetts Institute of Technology have devised the integraph which is capable of solving the equations of the synchronous motor. Into the integraph are put curves representing the non-linear differential equations and the boundary conditions. The desired results come from the integraph as curves.*

*In this paper the problem of sudden load on the non-salient pole alternator is solved by the integraph for enough different conditions so that the performance of practically any machine of this type may be easily predicted from the compiled results. Knowing the moments of inertia of the machine and its load, the characteristics of the machine running as a synchronous motor and as an induction motor, the maximum amount of sudden load for which the machine will remain in synchronism may be determined for different values of initial load. Other curves give the maximum angle of the first swing of the rotor and the time interval for the rotor to change from its initial position to this maximum angle.*

*The simplest type of equation representing an ideal synchronous machine is solved in this paper. The integraph is capable of solving problems of a much more complicated nature than those presented. The more complicated problems pertaining to machines with unsymmetrical excitation and salient-pole rotors will probably be the subjects of future papers.*

## Introduction

THE transient angular oscillations of synchronous machines are important to operating engineers, and within the last few years a number of papers devoted to this subject has appeared in our technical literature. Readjustment of steady-state operating conditions following changes of load or circuit causes the rotors of synchronous machines to swing in accordance with the dictates of mechanical and electrical requirements. The differential equations representing the constraints on the motions of the rotor have heretofore been unsolvable except by step-by-step analysis. The development of the integraph has made possible the solution of problems of the type encountered in studies of transient angle characteristics of synchronous machines. It will also be shown how the electromagnetic torque may be computed by the application of a well-known physical principle which heretofore has been little used for this purpose.

In this first paper there will be considered only the simplest case and therefore the following conditions will be imposed. The air-gap will be considered uniform and the permeabilities of all portions of the magnetic circuit treated as constant, *i. e.*, the effects of saturation will be neglected. Both the armature and field circuits will be taken as symmetrical with the windings so arranged that the space harmonics in the air-gap flux become negligible. The problem to be treated specifically is that of the sudden application of load to the shaft of a synchronous motor which is supplied with power from a balanced polyphase source of constant potential and frequency. In this problem the mutual inductance between the armature and rotor is the only circuit parameter which is variable.

If it be permissible to assume that both the hysteresis and eddy current losses vary directly with the frequency and the square of the maximum flux density, these losses can be taken into account by assigning the proper complex values to the self and mutual inductance. This, however, is a refinement which has been disregarded in the computation presented here.

The equation which determines the angle characteristics of a synchronous machine is

$$J \frac{d^2 \theta}{d t^2} + T_{em} + T = 0 \qquad (1)$$

where the first term represents the acceleration torque; the second, the electromagnetic torque developed between the stator and rotor, and the third, the mechanical torque on the shaft, including friction. $J$ is the moment of inertia and $\theta$ is the displacement angle of the rotor from some normal synchronous position.

It is first necessary to determine the expression for the electromagnetic torque. In addition to the conditions already assumed to exist, the currents in both the armature and field circuits are considered to be independent of the acceleration. That is to say, the currents at any moment are the same as would flow if the speed at that moment were to exist indefinitely. This additional assumption simplifies the problem. Results obtained with an induction motor having a rotor winding excited with direct current appear to justify this assumption for those cases in which the time constants of the stator and rotor windings are relatively small, or the moment of inertia large enough to assure small acceleration.

Equation (19) of Appendix I is a complete expression for the electromagnetic torque developed by the motor as a function of the terminal voltage $V$, the excitation voltage $E_1'$, the armature resistance $r_1$, the rotor resistance $r_2$, the synchronous reactance $x_s$, and the

*Massachusetts Institute of Technology, Cambridge, Mass.
*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

slip. The derivation of this equation, which is based upon the principle of superposition, is given in Appendix I. By this method the effects produced by the potential applied to the stator and that applied to the rotor are each found separately. Combination of these two effects gives the resulting conditions that exist in the motor. By neglecting the armature resistance $r_1$, the equation for the electromagnetic torque can be reduced to the form given in (20). This expression now substituted in 1, gives

$$J\frac{d^2\theta}{dt^2} + \frac{1}{(1)}\left[\frac{|E_1'||V|}{x_s}\sin\theta + \frac{1}{360f}\frac{|V|^2}{r_2}\frac{d\theta}{dt}\right] + T = 0 \qquad (2)$$

Since a power equation is more convenient than a torque equation, the above can be put in the power form by multiplying by unit speed (1), giving

$$P_j\frac{d^2\theta}{dt^2} + P_d\frac{d\theta}{dt} + P_m\sin\theta = P \qquad (3)$$

where

$\theta$ is the angle between the terminal potential and the e. m. f. induced in the armature by the action of the direct field voltage. (It is also approximately the space angle between the center line of the rotor and that of the same center line at no load.)

$P_j$ is the power per unit acceleration (at synchronous speed). $P_j = J\,(1)$.

$P_d$ is approximately (for small values of slip) the induction motor power per unit of change of angle with respect to time.

$$P_d = \frac{1}{360f}\frac{|V|^2}{r_2} \text{ (approximately).}$$

$P_m$ is the maximum static synchronous power.

$$P_m = \frac{|E_1'||V|}{x_s}.$$

$P$ is the shaft load on the motor which may be any function of time, angle or the rate of change of angle. $P = -T\,(1)$.

### Abrupt Application of Shaft Load

The particular problem considered in the integraph solutions of Equation (3) is that of the abrupt application of load to the shaft of a synchronous motor. Of especial interest is the maximum amount of abrupt load that can be suddenly applied without resulting in a loss of synchronism. This critical load will depend upon the relative sizes of the coefficients of Equation (3) and upon the initial load that exists when the sudden load is applied. It will also depend upon the initial acceleration and slip. Both of these last two factors have been considered to be zero in the integraph solutions. Such a consideration implies that the motor is operating in a steady-state condition at the time when the abrupt load is applied.

The load as a function of time for this specific problem is of the form,

$$P = P_o + P_L\mathbf{1} \qquad (5)$$

where $P_o$ is the initial shaft load.

$P_L$ is the abrupt shaft load.

$\mathbf{1}$ is Heaviside's unit function which indicates that the quantity to which it is applied is zero before time equals zero and is multiplied by one thereafter.

Substituting (5) in (3) gives (16), the complete differential equation including the initial conditions for the problem of abrupt shaft load, it being understood that the initial acceleration and slip are equal to zero.

$$P_j\frac{d^2\theta}{dt^2} + P_d\frac{d\theta}{dt} + P_m\sin\theta = P_o + P_L\mathbf{1} \qquad (6)$$

From this equation, it may be seen that there are five factors which influence the solution. The first factor $P_j$ depends upon the combined inertia of the motor and its connected load, and upon the synchronous speed of the motor. The next factor $P_d$ depends upon the induction motor characteristics of the synchronous machine when its field circuit is symmetrical[1] and short-circuited. For small values of slip it is approximately proportional to the slope of the slip-torque curve. Actually the coefficient $P_d$ is not constant but is the variable factor which when multiplied by the slip gives the correct value for this torque term. The third factor $P_m$ depends upon the synchronous motor characteristics. It is the pull-out power or maximum load that does not cause the motor to pull out of step if slowly applied. The fourth factor $P_o$ is the initial load. The last factor $P_L$ is the abrupt load that is applied at $t = 0$.

By a change of time scale the factors that influence the solution may be reduced to three which are:

1. $k = \dfrac{P_d}{\sqrt{P_m P_j}}$ = a "relative damping coefficient" which depends upon the induction and synchronous motor characteristics and the combined inertia of the motor and load.

(Although $k$ is a numeric it contains the dimensions of angle and is proportional to the square root of the magnitude of the unit used for measuring angle. The unit used for the solutions in this paper was the electrical degree. If electrical radians are used $k$ must be multiplied by the square root of $180/\pi$.)

2. $\dfrac{P_o}{P_m}$ = the initial load ratio.

3. $\dfrac{P_L}{P_m}$ = the abrupt load ratio.

1. This type of rotor was used in the experimental tests.

This reduction in the number of coefficients is accomplished by selecting a new variable which is related to the usual time scale by the following equation

$$t = t' \sqrt{\frac{P_j}{P_m}} \tag{7}$$

where $t'$ is the new variable. The substitution of (7) into (6) and the division of all terms by $P_m$ gives the most general form of Equation (6)

$$\frac{d^2\theta}{(d\,t')^2} + k\,\frac{d\,\theta}{d\,t'} + \sin\theta = \frac{P_o}{P_m} + \frac{P_L}{P_m}\,1 \tag{8}$$

This equation characteristizes the angular transients that follow a suddenly applied shaft load. It is the equation of a damped pendulum swinging through large amplitudes. Initially the angle must be of such a value that $\sin\theta_1 = P_o/P_m$. After a transient (in case synchronism is not lost) the final steady-state angle must be such that $\sin\theta_2 = (P_o + P_L)/P_m$.

If $k$ is zero then the equation represents undamped motion and the angular variation is an oscillation between the initial value and some maximum value. This equation is solvable for the critical load by a method of areas.[2] Also the maximum angle of swing for any load can be determined in the same manner. Should the maximum angle reach and slightly exceed the value of angle corresponding to this critical load in the unstable part of the power-angle characteristic, stability will be lost because the synchronizing torque is less than the load torque. Park and Bancker show a curve of $P_o/P_m$ against $P_L/P_m$ in Fig. 12 of their paper which gives the critical values that are just on the verge of instability. They also show curves of angular position against time for the undamped case which were calculated step-by-step.

The damping is not equal to zero when the induced rotor currents in the field windings and the amortisseur bars are appreciable. The relative damping coefficient $k$, becomes larger as the induction motor effect becomes greater. By analogy to the damped pendulum it will be seen that the motion represented by Equation (8) is beneficially influenced by increasing the value of $k$ since the damping term reduces the maximum angle of swing. In other words as the value of $k$ becomes larger, the amount of sudden load ratio that may be applied becomes larger with a constant initial load ratio. A limit, however, is reached when $k$ has such a value that the sudden load ratio plus the initial load ratio equals one. Further increase of the relative damping coefficient, $k$, cannot allow the motor to stand more sudden load because the final steady-state conditions are impossible. The value of $k$ that just allows the sudden load ratio plus the initial load ratio to equal one has been termed the "critical damping coefficient." This coefficient has different numerical values for different initial load ratios. It corresponds roughly to the critically damped $R$, $L$, and $C$ series electrical circuit.

The integraph (see Fig. 1) made it possible for many complete solutions of Equation (8), taking into account the damping term, to be made in a reasonable length of time. Reference to three previously published articles on the integraph describing its construction and operation are given in a footnote below Appendix II. Appendix II describes the methods employed in solving equations of the type of (8) on this device. Without the integraph a tedious point-by-point method would be necessary which would require a prohibitive amount of time.

The procedure used in systematizing the results of the integraph solutions follows. The relative damping coefficient $k$, and the initial load ratio, $P_o/P_m$, were given numerical values. Then the integraph was used

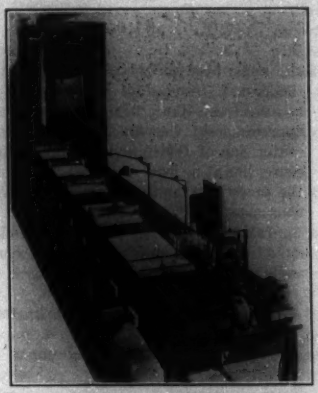

FIG. 1—A GENERAL VIEW OF THE INTEGRAPH

This device is the result of several years of intensive research at the Massachusetts Institute of Technology by Dr. V. Bush and others

to obtain solutions for the angular variation against time for different values of abrupt load ratio, $P_L/P_m$. Fig. 2 shows such a family of solutions. For these solutions the value of $k$ was equal to 0.022, and $P_o/P_m$ was equal to zero. The time scale is converted to seconds for any particular case by multiplying the numbers on the horizontal scale of Fig. 2 by $2\,\pi\sqrt{\frac{90\,P_j}{P_m}}$ or $59.6\sqrt{\frac{P_j}{P_m}}$. The factor $2\,\pi\sqrt{90}$, results from the way in which the integraph was calibrated using a linear second degree differential equation without a damping term. This method of calibration is explained in Appendix III.

Small sudden load ratios cause the angle-time solutions of Fig. 2 to resemble damped sinusoids and all

2. Fortescue, A. I. E. E. TRANS., Vol. 44, 1925, p. 984. Park and Bancker, A. I. E. E. TRANS., Vol. 48, Jan. 1929, p. 170.

2a. Summers and McClure, A. I. E. E. Quarterly TRANS., Vol. 49, Jan. 1930, p. 132. (Appendix VIII). The integraph was used for solutions of transient angle-time curves for the undamped case for ten values of initial load ratio and for many sudden load ratios up to 3. Ten charts are given.

have approximately the same frequency. For sudden load ratios larger than 0.4 the frequency of oscillation is considerably reduced, so that for a ratio of 0.79 the time required for one oscillation is doubled.

The integraph solution for the sudden load ratio of 0.80 on Fig. 2 shows there is no oscillation but the angular deviation of the rotor continues to increase and the motor falls out of step. The solution for the ratio of 0.79, however, shows that the angular deviation does reach a maximum value and then oscillates with decreasing amplitude about the final value. Between these values of sudden load ratio there is one for which the angular deviation would neither continue to increase nor decrease. This value is that which would cause the so-called "unstable equilibrium condition" for this particular equation. Physically such a solution means that the slip and acceleration of the rotor of a synchronous machine both become zero when the rotor reaches the angle giving an unstable steady-state solution. This angle is on the unstable portion of the

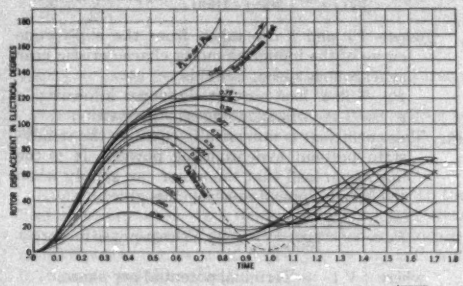


FIG. 2—CURVES SHOWING THE VARIATION OF ANGULAR DISPLACEMENT AGAINST TIME FOR VARIOUS SUDDENLY APPLIED SHAFT LOADS

Angle-time solutions of Equation (8) for a relative damping coefficient of 0.022 and no initial load

power-angle curve, thus being greater than 90 deg. The precision of the integraph was not sufficient to secure a plot of this condition. However, the integraph shows that the largest value of sudden load ratio that does not cause instability is greater than 0.79 and less than 0.80. This determination is sufficiently accurate for engineering purposes.

The results of many families of solutions such as those shown in Fig. 2 are compiled as a chart giving the relation between the relative damping coefficient and the maximum load ratio which does not result in instability. Such a chart, complete in that it gives the results of all the solutions, appears in Fig. 3. The solid points indicate that the integraph solution of Equation (8) with the coordinates of the point $k$ and $P_L/P_m$ is a stable one. The open points indicate that the integraph showed instability for the corresponding values, $k$ and $P_L/P_m$. Only a few values near the critical value are located on Fig. 3. Between the two types of solutions there is a boundary line which separates stable and unstable regions.

To get a complete relation between $\frac{P_e}{P_m}$, $\frac{P_L}{P_m}$, and $k$ the following procedure was used. For a particular value of $\frac{P_e}{P_m}$ $\left(\text{say } \frac{P_e}{P_m} = 0\right)$ the critical value of $\frac{P_L}{P_m}$ for a given $k$ was determined by several trial

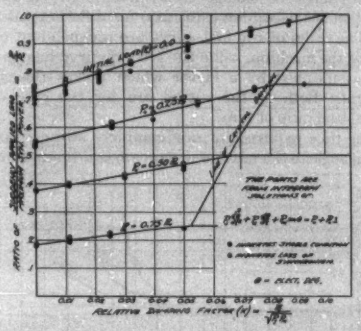


FIG. 3—CHARTS SHOWING ALL POSSIBLE SOLUTIONS OF THE TYPE DIFFERENTIAL EQUATION IN TERMS OF STABILITY

Points for this chart come from solutions similar to those of Fig. 2

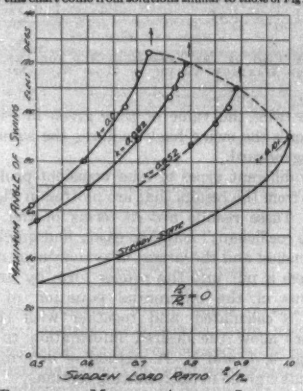


FIG. 4—PLOT OF THE MAXIMUM ANGLE OF SWING FOLLOWING A SUDDEN LOAD

(The arrows indicate that the angle continued to increase, thus showing instability)

solutions. This was repeated for several values of $k$, thus establishing the boundary curve marked "Initial Load, $P_e = 0.0\,P_m$" in Fig. 3. In the same way the

other three boundary curves for initial load ratios of 0.25, 0.50, and 0.75 were located on Fig. 3.

The "line of critical damping" on Fig. 3 is drawn through the points where the sum of the initial and sudden load ratios becomes unity. Relative damping factors larger than those for critical damping produce no beneficial effects but only slow up the rate of swinging. They do not allow greater loads to be applied without the loss of synchronism.

From the curves similar to Fig. 2, two other charts have been prepared. These are (Fig. 4) the maximum angle of swing plotted against the sudden load ratio for different values of $k$, and (Fig. 5) the time required for the angle to change to its maximum value as a function of the sudden load ratio for different values of $k$. The scales of the first curve are independent of the size of the machine, while the second curve has its time scale multiplied by a factor which makes the curves general. Both of the curves are for the case of an initial load ratio of zero.

The time required for one complete swing from the initial angle to the next minimum angle is approximately

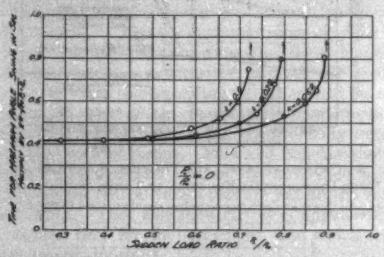


Fig. 5—Plot of the Time Required for the Angle to Reach its Maximum Value in Case Stability was not Lost

equal to twice the value of time given in Fig. 5. In other words the swing back requires the same time as the swing forward.

Many different types of load transient problems are solvable from the results that are plotted in Figs. 2, 3, 4, and 5. These results are in terms of the "relative damping coefficient," $k$ and so easily and quickly apply to the smallest and the largest of synchronous machines. A problem is put into the proper form by finding the coefficients of the differential equation of torques. Then $k$ is calculated, and together with the initial conditions allow the desired information to be read from Figs. 3, 4, and 5. A method of determining the coefficients is given in the following section.

## Determination of the Coefficients

To apply the graphical results of Figs. 3, 4, and 5 to a synchronous motor requires the determination of the three coefficients, $P_j$, $P_d$, and $P_m$. The integraph solutions are in terms of electrical degrees and so this unit of angle must be used for the coefficients. The unit of power used does not influence the solution. Kilowatts is the unit used below.

$P_j$. This coefficient is numerically equal to the power per unit of acceleration in electrical degrees per second per second at synchronous speed. Carrying through the conversion factors it is equal to

$$P_j = \frac{18.6\,(WR^2)f}{p^2} \times 10^{-6}$$

$(WR^2)$ = the moment of inertia in lb. ft.$^2$
$f$ = Frequency of terminal potential (cycles/sec.).
$p$ = The number of poles.

$P_d$. The numerical value of this coefficient is approximately equal to the power per unit rate of change of angle in electrical degrees per second, at synchronous speed (for small values of slip). That is

$$P_d = \frac{P_L}{360\,f\,s} \text{ or } \frac{1}{360\,f}\,\frac{|V|^2}{1000\,r_1} \text{ (approximately)}$$

where $P_L$ and $s$ are taken from the slip-torque curve of the induction motor characteristic near synchronous speed. In this
$P_L$ = The load in synchronous kilowatts.
$s$ = The corresponding slip (per unit).

$P_m$. This coefficient is numerically equal to the steady-state pull-out synchronizing power. It is the maximum load that the motor can supply when this load is applied slowly. It is given by

$$P_m = \frac{3\,|V|\,|E_1'|}{1000\,x_s} \text{ (for a three-phase motor)}$$

where $|V|$ = Terminal potential per phase.
$|E_1'|$ = Induced potential per phase.
$x_s$ = Synchronous reactance per phase.

The three above coefficients determine the relative damping coefficient, $k$.

$$k = \frac{P_d}{\sqrt{P_m P_j}}$$

The probable values of $k$ will be from 0.03 to 0.10, the larger value giving the best transient characteristics of the motor with respect to hunting.

## Experimental Results

Tests were made on a 5-kw. synchronous machine run as a motor to determine angle-time curves and power-angle curves following an abrupt change of load on the shaft. A d-c. generator on the same shaft furnished the sudden load by having a resistance load connected across its armature. Oscillograms showed that the time lag of this method of applying the load was negligible when compared to the relatively slow swinging of the synchronous motor.

The synchronous machine was built for a sine-wave generator and it has a cylindrical rotor with a distributed field winding. The coils that were not used

for the field were short-circuited so that the rotor was essentially symmetrical.

### Transient Angle-Time Curves

A steady-state power-angle test of this motor showed that the pull-out power was about 16.0 kw., for the values of field current that made the induced voltage equal to the terminal voltage. This determined the value of the coefficient $P_m$ for the field current used in the tests that are described.

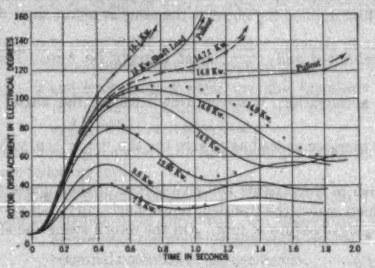


Fig. 6—Curves showing the Angular Variation against Time for a 5-Kw. Non-salient Pole Motor

Integraph solutions in solid lines. Experimental values indicated by points

$$P_m = 16.0 \text{ kw.}$$

Running the machine as an induction motor with the field short-circuited, data for a slip-torque curve were taken. The slope of this curve expressed in synchronous kilowatts per electrical degree per second is $P_d$ and in this case had the value,

$$P_d = 0.0128 \text{ kw. per electrical deg. per sec.}$$

A retardation test determined the available power per unit acceleration from the rotating parts when the speed was synchronous in kilowatts per electrical degree per second per second. This was found to be:

$P_I = 0.0041$ kw. per deg. per sec.$^2$ (at synchronous speed)

The integraph solution, Fig. 6, is the result of solving the equation determined by these three coefficients. The equation of the machine for this problem is:

$$0.0041 \frac{d^2\theta}{dt^2} + 0.0128 \frac{d\theta}{dt} + 16.0 \sin\theta = P_o + P_L 1 \qquad (12)$$

$P_o$, the initial load, was found to be about 1.3 kw. This was the windage and friction and the core loss of the three machines, the other synchronous machine being used to measure angular displacement.[3] Increasing values of $P_L 1$, were tried until the one that just did not cause instability was located. Oscillograms were taken for several values of load, both for stable and unstable conditions. Points from these oscillograms have been entered on the integraph solutions (Fig. 6) of the equation above. They show a very close agreement in the stable condition and check the point that

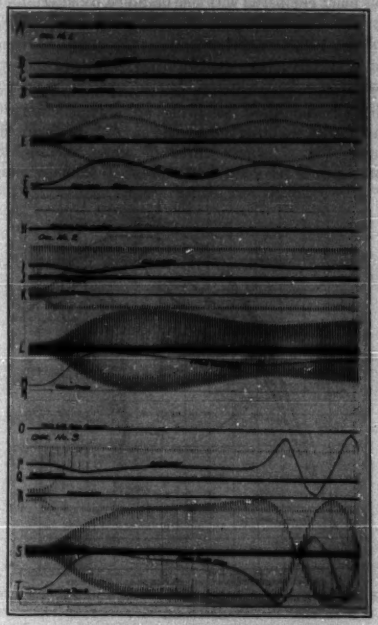

Fig. 7—Oscillograms for Three Sudden Loads

1. Relatively small load
2. Relatively large load
3. Load large enough to cause instability

*A, H, O* = Zero line for field current
*B, I, P* = Field current
*C, J, Q* = Line volts
*D, K, R* = Line current
*E, L, S* = Angle volts
*F, M, T* = Three-phase power input
*G, N, B* = Zero line for power

just causes instability within limits of experimental error. The specific oscillograms from which these points were taken are not reproduced in this paper, but the oscillograms in Fig. 7 are very similar to them.

The sudden load that could be applied can be seen to be about (14.6 − 1.3) kw. from Fig. 6. The portion of the maximum synchronizing power that can be suddenly applied is equal to

$$\frac{P_L}{P_m} = \frac{(14.6 - 1.3)}{16.0} = 0.832$$

3. The angular displacement was determined by an oscillograph vibrator connected to measure the difference between the terminal voltage and the open-circuit induced voltage of this extra synchronous machine. This later e. m. f. was in phase with the induced e. m. f. of the machine being tested.

The relative damping factor for this machine is

$$k = \frac{P_d}{\sqrt{P_s P_m}} = \frac{.0128}{\sqrt{0.0041 \times 16.0}} = 0.05$$

These values of $k$ and $P_L/P_m$ locate a point in Fig. 3 at which the initial load ratio is equal to 1.3/16.0 = 0.0813.

$$P_o = 0.0813\, P_m$$

This point compared with one obtained by interpolation between the curves for $P_o = 0.0$ and $P_o = 0.25\, P_m$ shows very close agreement.

### Transient Power-Angle Curves

The relationship between power and angle during the transient conditions following an abrupt change of shaft load were observed by the aid of a power oscillograph. Fig. 7 shows three of these oscillograms. Upon each is recorded field current, terminal voltage,

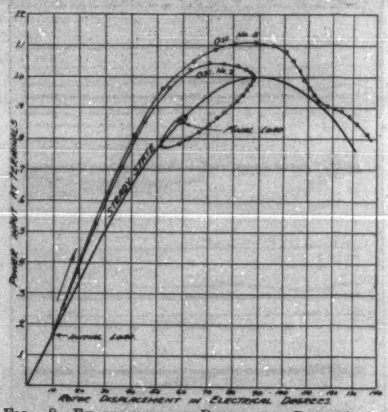


Fig. 8—Experimentally Determined Power Angle Diagram

(For suddenly applied load.)
Steady-state is for gradually applied load

armature current, angle voltage, and polyphase power input. These tests were made on a 5-kw. sine-wave generator which had essentially the same characteristics as the machine used in the previous tests of angle against time.

Oscillogram No. 1 in Fig. 7 shows the transients that occurred when a sudden load was applied by connecting the d-c. generator to a resistance load. The load was equal to about one-quarter of that necessary to pull the synchronous motor out of step, so the transients were similar to damped sinusoids.

Oscillogram No. 2 shows the resulting transient when the load was large enough to cause the maximum angle to approach that which would result in instability. Points from this oscillogram are plotted in Fig. 8. The time interval between points is 0.1 second, the readings being taken every six cycles. Fig. 8 shows the power-angle curve for the steady-state conditions also. The transient curve is approximately a plot of the sum of the two terms in the differential equation which give the electromagnetic torque. These terms are, in terms of power,

$$P_m \sin\theta + P_d \frac{d\theta}{dt}$$

It will be observed that the experimental transient power-angle curve satisfies this equation. When load is first applied the power is the same as before since $\theta$ is unchanged and $\frac{d\theta}{dt}$ must initially be zero. There is acceleration, however, which causes the angle, $\theta$, to increase as well as to give the slip, $\frac{d\theta}{dt}$, a value. Both of these terms will give torque in the same sense which makes the transient power-angle curve fall above the steady-state at first. On the return swing the slip, $\frac{d\theta}{dt}$, is in the opposite sense. This causes the transient curve to fall below the steady-state, as will be noticed in Fig. 8.

Oscillogram No. 3 shows the transients that follow the sudden application of a shaft load which is sufficient to cause the synchronous motor to fall out of step. Points one-tenth of a second apart are plotted on the steady-state power-angle diagram of Fig. 8. They show that the transient curve for the unstable case is always above the steady-state power-angle curve. The slip becomes large soon after the load is applied and then decreases to a minimum as the angle increases, the slip being proportional to the horizontal distance between successive time points. However, the slip does not reach zero and as the rotor swings still farther the decreasing magnitude of the synchronizing torque causes an increase in the slip.

For some slightly lower load the transient curve will just reach the steady-state curve. At this point the load will exactly equal the synchronizing power and equilibrium will exist. However, any change would result in either a loss of synchronism or a shift in angle back to the stable position on the rising portion of the power-angle curve. Synchronism would be lost if the load became a little larger than the synchronizing power and the stable operating point would be reached if the synchronizing power were slightly the greater.

### Differential Equations for Other Types of Synchronous Motors

The integraph solutions and the test results that have just been given apply only to an idealized synchronous machine having a cylindrical rotor with symmetrical excitation. The integraph, however, is capable of

solving the differential equations for the more usual type of synchronous machine also.

A cylindrical rotor machine with a single-phase field winding or a symmetrical field winding with unequal external impedances has a damping term which varies as a function of angle as well as being a function of the slip. It is probably of the form

Induction Motor Torque

$$= P_d\,[a \sin^2 (\theta + \alpha) + b \cos^2 (\theta + \alpha)] \frac{d\,\theta}{d\,t}$$

where $\alpha$ is some small angle that is a function of the impedances of the machine and the slip.

$a$ and $b$ are factors which are also functions of the rotor impedances and the slip. (For symmetrical excitation $b = a = 1$.)

The salient-pole alternator has a synchronizing term of the following form

Synchronous Motor Torque $= P_m\,(\sin\,\theta + c \sin 2\,\theta)$

where $c$ depends upon the direct and quadrature reactances of the machine and upon the ratio of terminal potential to the excitation.

The damping term of the salient-pole machine is probably similar to the damping of the unbalanced rotor machine which was previously given, since the salient-pole rotor is essentially single phase.

Some problems of the types mentioned above have been solved on the integraph by graduate students at the Massachusetts Institute of Technology. Undoubtedly further results will be published in the future using the more involved differential equations. However, as the complexity of the equations grows, so does the number of variables, thus making it impossible to resort to the same method as was used in this paper for reducing the number of variables and getting a general set of solutions.

## Appendix I

### Derivation of Electromagnetic Torque Equations by the Methods of Superposition

In any network whose parameters are not functions of the current, the current produced in any branch by the application of several electromotive forces to the network is the sum of the components current in that branch due to the individual action of the several e. m. fs. If this principle is applied to the synchronous machine when it is running without acceleration the currents in either the armature or field circuits may be considered as the sum of two component currents. The first component currents in both windings are those which would flow if excitation were applied to the field and the armature windings were short circuited, and the second are those which would flow if the field were short circuited and the desired potentials were applied to the armature. The first of these components are the direct exciting current in the field winding and the well known short-circuit currents in the armature windings which have a frequency determined by the speed of the rotor and a magnitude which is practically independent of that speed. The second of these components are the currents which flow when the machine is operating as a polyphase induction motor, or generator. The frequency of this component of armature current is that of the applied potentials and it is nearly independent of the acceleration of the rotor if this be not too great, and if the time constants of the stator and rotor windings are relatively small. The component in the field windings is of slip frequency. The advantage of having a field winding of the symmetrical polyphase type is evident, inasmuch as the reactions produced by a single-phase rotor winding, *i. e.*, the usual type of field winding, are somewhat more difficult to analyze.

This method of analysis gives a clear conception of the component currents which flow in both armature

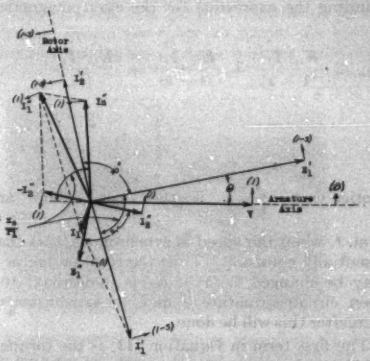


Fig. 9—Vector Diagram of a Non-salient Pole Synchronous Generator with a Symmetrical Polyphase Field when Running at a Constant Slip

and field windings of this type of synchronous machine when its speed is not synchronous.

The analysis can be embodied in a vector diagram. (See Fig. 9.) The subscripts 1 and 2 refer to the armature and field respectively and the primes and double primes to the first and second components respectively of currents and potentials as described above. $V$ is the applied terminal potential and $E_1'$ is the e. m. f. generated in the armature on open circuit by the action of the direct field current, $I_2'$. The e.m.f., $E_1''$, is that generated in the armature by the action of the second component of the field current, $I_2''$. The potential vectors represent rises in potential in a given direction through the windings and the current vectors represent the currents in the same direction through the windings. The vectors drawn at the ends of the potential and current vectors represent their relative angular velocities. Synchronous speed is taken as unity, and

the slip is represented by the letter $s$ as usual. The armature axis is fixed while the field axis rotates at a speed of $(1 - s)$. The instantaneous values of the field and armature currents are determined by the projections of the current vectors on their respective axes.

The electromagnetic torque developed by the action of a symmetrical polyphase current $I_1$ in the armature and a symmetrical polyphase current $I_2$ in the field is readily determined in the following manner. Let $E_1$ be the mutually induced e. m. f. in the first winding due to the rotating field produced by the current, $I_2$, which flows in the second winding. The power developed in the first winding by the action of the current in it and this e. m. f. is the real part of $E_{1c} I_1$, where $E_{1c}$ is the conjugate of $E_1$, and the corresponding torque is this power divided by the relative speed of the rotating field with respect to the first winding. Since there are in our problem two component currents in the armature winding the expression for the electromagnetic torque is

$$T_{em} = \frac{E_{1c}' I_1'}{(1-s)} + \frac{E_{1c}' I_1''}{(1-s)} + \frac{E_{1c}'' I_1'}{(1)} + \frac{E_{1c}'' I_1''}{(1)} \qquad (13)$$

Notice that $\frac{E_1'}{1-s}$ is the open circuit armature e. m. f. when the speed is synchronous, also that $I_1'$ is essentially constant. Thus the rotation factor $(1 - s)$ may be changed to (1) if $E_1'$ is understood to be the open circuit armature e. m. f. at synchronous speed. Hereafter this will be done.

The first term in Equation (13) is the torque due to the short-circuit armature current when the field current is $I_2'$. It is always positive. The last term is the torque due to induction motor action when the field winding is short circuited and the desired potential, $V$, is applied to the armature. The second and third terms are the torques due to the interaction of the "synchronous" and "induction" currents. The sum of these two terms is simplified if it is noted that

$$E_1'' = V + I_1'' Z_s \qquad (14)$$

and

$$I_1' = \frac{E_1'}{Z_s} \qquad (15)$$

The sum of these two terms may now be written

$$= \frac{E_{1c}' I_1''}{(1)} + \frac{V_c E_1'}{(1) Z_s} + \frac{E_1' I_{1c}'' (Z_s)_c}{(1) Z_s} \qquad (16)$$

In Equation (16) notice that $V_c$ equals $V$ if this vector is drawn along the horizontal axis as shown in Fig. 9.

The second term in Equation (16) is the synchronous torque under steady operating conditions. If the armature resistance is neglected, it can also be written in its most usual form as $\frac{|V|\,|E_1'|}{x_s} \sin\theta$. It is positive when $E_1'$ leads $V$ and negative when it lags. The first and third terms of Equation (16) if written with a common denominator are

$$\frac{E_{1c}' I_1'' Z_s + E_1' (I_1'' Z_s)_c}{(1) Z_s} \qquad (17)$$

The torque represented by this expression (17) is small if the resistance in the armature and external circuit is small compared with the sum of the synchronous and external reactances. An approximate value can then be obtained by noting that $I_1''$ is roughly equal to $V\left(\frac{s}{r_2} + j\frac{1}{x_s}\right)$ where $s$ is positive for a speed above synchronism and $r_2$ is the rotor resistance per phase. If this substitution is made the expression for this portion of the torque becomes,

$$-\frac{2\,|E_1'|\,|V|\,r_1}{(1)\,|Z_s|^2}\left[\left(1 - \frac{r_1 s}{r_2}\right)\cos\theta - \left(\frac{s x_s}{r_2} + \frac{r_1}{x_s}\right)\sin\theta\right] \qquad (18)$$

where $r_1$ is the resistance in the armature circuit, $|Z_s|$ is similarly the magnitude of the synchronous impedance, and $|E_1'|$ and $|V|$ now represent the magnitude only of these potentials. It will now be seen that this portion of the torque is small compared with the synchronous torque if the slip, $s$, is small and the stator resistance is small compared with the synchronous reactance. The integraph solutions that are here reported were obtained by neglecting both this torque and that due to the short-circuit armature current. The accuracy of the results justifies this neglect in this and similar cases.

The complete expression for the electromagnetic torque when the induction component of the stator current is taken as $V\left(\frac{s}{r_2} + j\frac{1}{x_s}\right)$ is:

$$T_{em} = \frac{1}{(1)}\left\{\frac{|E_1'|^2}{|Z_s|^2} r_1 + \frac{|E_1'|\,|V|}{x_s}\left[\left(1 + \frac{r_1^2}{|Z_s|^2}\right)\sin\theta - \frac{r_1 x_s}{|Z_s|^2}\cos\theta\right)\right] + \frac{2\,|E_1'|\,|V|\,r_2}{|Z_s|^2}\left(\frac{x_s}{r_2}\sin\theta + \frac{r_1}{r_2}\cos\theta\right)\frac{1}{360 f}\frac{d\theta}{dt} + \frac{1}{360 f}\frac{|V|^2}{r_2}\frac{d\theta}{dt}\right\} \qquad (19)$$

where $s = \frac{1}{360 f} \frac{d\theta}{dt}$

The last term in this expression is the torque due to the induction motor action alone and since in the integraph solution a graph of the torque is used it is not necessary to take the approximate linear function as is here given.

Since in this analysis the stator resistance is assumed to be negligibly small compared with the synchronous reactance the expression for the electromagnetic torque reduces to

$$T_m = \frac{1}{(1)} \left[ \frac{|E_1'||V|}{x_s} \sin\theta + \frac{1}{360 f} \frac{|V|^2}{r_2} \frac{d\theta}{dt} \right] \quad (20)$$

The first term of the electromagnetic torque is a sine function of the angular displacement. The other is a linear function of slip (change of angle with respect to time) when referred to a synchronously rotating reference. This second term has been shown to be the induction motor torque. The linear relation against slip is true only for small values of slip.

## Appendix II

*Methods Used by the Integraph.* The integraph is the result of several years of intensive development at the Massachusetts Institute of Technology by Dr. V. Bush and his associates. A general view of the integraph is shown in Fig. 1. This device adds, subtracts, multiplies, divides, and integrates the variables of a differential equation continuously and at the same time takes into account the boundary conditions. The form of the equation need not be linear or the coefficients constant. In fact, the occurrence of the non-linear differential equation in so many problems was one of the chief motives for developing the integraph.

The details of the electrical and mechanical construction will not be repeated here as they are adequately treated elsewhere.[4] However, the processes that the integraph uses and the operations of its various parts will be discussed with reference to the solutions made for this paper.[5]

Those who have employed "point-by-point" methods of solving non-linear differential equations will recognize immediately that the integraph employs exactly the same scheme except that the integraph uses infinitesimals, not increments. The method of solving a differential equation is quite straightforward and direct.

The equation to be solved is of the following form:

$$\frac{d^2\theta}{(dt')^2} + k\frac{d\theta}{dt'} + \sin\theta = \frac{P_e}{P_m} + \frac{P_L}{P_m} 1 \quad (21)$$

To see how this is solved on the integraph it can be put into an integral form by transposing and integrating twice, giving,

$$\theta = \int_0^{t'}\int_0^{t'} \left( \frac{P_e}{P_m} + \frac{P_L}{P_m} 1 - \sin\theta - k\frac{d\theta}{dt} \right) dt'\, dt' \quad (22)$$

The integraph has four movable platens as may be seen in the schematic diagram, Fig. 10. Platen 1 bears the resultant curve and it is moved continuously by the small synchronous motor. Upon platen 2, which is also driven continuously at a constant speed, is placed the function, $\left( \frac{P_e}{P_m} + \frac{P_L}{P_m} 1 \right)$ as a function of time.

The potentiometers (see the photograph, Fig. 11), are directly above platens, 1, 2, and 3. The pointers on the potentiometer sliders are made to follow the curves under them by turning the knobs or pushing the sliders.

Fig. 11—Photograph of a Potentiometer showing the Pointer which is Made to follow the Curve on the Platen

In this manner a voltage is obtained which is proportional to the term of the equation represented by the function on the platen. Thus the pointer above platen 2 is made to follow the constant value $\frac{P_e}{P_m}$ until the discontinuity, $\frac{P_L}{P_m} 1$, arrives, at which time the operator following the curve immediately shifts the pointer to the new value. In case any other load condition was of interest then that function would be plotted on the platen. It is of particular interest to note that any curve can be used whether it can be easily written mathematically or not.

Returning to Equation (22), the term $\left( \frac{P_e}{P_m} + \frac{P_L}{P_m} 1 \right)$ has two other terms subtracted from it. These are

4. V. Bush, F. D. Gage, and H. R. Stewart, "A Continuous Integraph," *Franklin Inst. Jl.*, January 1927, pp. 63-84. V. Bush and H. L. Hazen, "Integraph Solution of Differential Equations," *Franklin Inst. Jl.*, November 1927, pp. 575-615.

5. A somewhat similar problem considering a periodically impressed torque has been solved by L. Teplow on the integraph. *General Elec. Rev.*, June 1928.

$k \frac{d\theta}{dt'}$ and $\sin\theta$. Both are functions of the result, $\theta$.

These terms which are functions of the answer, $\theta$, are introduced into the solution by "back-coupling," that is, the mechanism which records the result, $\theta$, and its first derivative, $d\theta/dt'$, on platen 1 simultaneously

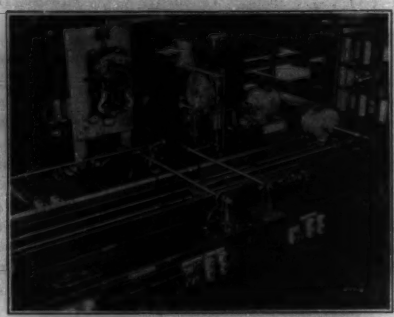

Fig. 12—View of the Electrical and Mechanical Integrating Devices, Also the Back-Coupling Arrangement

gives platens 3 and 4 displacements which are proportional respectively to these quantities. The diagrammatic drawing of the integraph, Fig. 10, shows how this back-coupling is accomplished, by the use of bevel gears and rack and pinion drives.

$k \frac{d\theta}{dt'}$. This voltage is connected in series with the voltage from platen 2 which represents the term $\frac{P_o}{P_m} + \frac{P_L}{P_m} 1$. The value of the voltage from the potentiometer above platen 3 is proportional to the damping torque or the induction motor effect that opposes a change of speed from synchronism.

Platen 4 is back-coupled to the result on platen 1. This gives platen 4 a back and forward movement such that its displacement is always proportional to the value of $\theta$. The differential equation shows that a sine function must be plotted on this platen because the synchronizing torque term is a sine function of the angular displacement. The voltage from the potentiometer is connected in series with the voltages from the other two potentiometers that are proportional to $k \frac{d\theta}{dt}$ and $\frac{P_o}{P_m} + \frac{P_L}{P_m} 1$, care being taken to have the relative polarities correct.

The total voltage from the three potentiometers is proportional to

$$\left(\frac{P_o}{P_m} + \frac{P_L}{P_m} 1\right) - k \frac{d\theta}{dt'} - \sin\theta$$

for all values of time, angle, or rate of change of angle with respect to time.

The watthour meter multiplies this voltage by a constant and then integrates the product with respect to time. The number of revolutions of the watthour meter

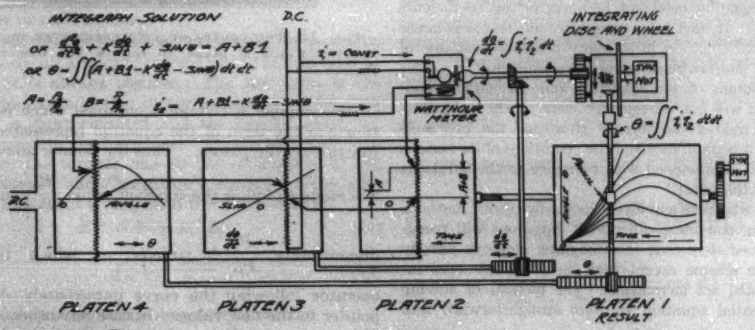


Fig. 10—Schematic Diagram of the Integraph showing the Method of Solving the Differential Equation of a Synchronous Machine

Upon platen 3 is plotted a straight line which has a slope depending upon the particular value of the coefficient $k$. As platen 3 moves back and forth its displacement always being proportional to $d\theta/dt'$ the potentiometer gives a voltage proportional to is proportional to the first integral of the voltage or to $\frac{d\theta}{dt'}$. This quantity is back-coupled to platen 3 and also operates the second integrating device which is a

mechanical integrating disk. The result of the second integration is proportional to the angular displacement, $\theta$, which is recorded by the pencil on the resultant platen No. 1. The various proportionality factors mentioned above are constants of the integraph which can be evaluated by a single calibration run.

The driving and integrating mechanisms are shown in Fig. 12. The resultant platen has been removed so that the back-coupling mechanism may be seen.

## Appendix III

### Calibration of the Integraph

In general there are two methods of calibrating the integraph. The first consists of solving an equation on the integraph which can also be easily solved analytically. By comparing these two solutions the scales are determined, suitable scales being found by trial and error. The second method makes use of two fundamental constants of the integraph and the approximate magnitudes of the variables in a computation of the gear ratios which will result in suitable scales. The first method was used for this problem.

A linear second degree differential equation was used to determine the time scale on the result platen and the slip scale on the platen which moves proportional to $d\,\theta/d\,t$ (see Fig. 10).

An equation that was used is given below

$$\frac{d^2\,\theta}{d\,t^2} + \frac{\theta}{90} = 0.5\,1$$

for which the solution is

$$\theta = 45\left(1 - \cos\frac{t}{\sqrt{90}}\right)$$

The time required for one cycle of oscillation is equal to

$$T_c = 2\,\pi\,\sqrt{90} \text{ seconds}$$

The slip as a function of time is

$$\frac{d\,\theta}{d\,t} = 0.5\,\sqrt{90}\,\sin\frac{1}{\sqrt{90}} \text{ electrical degrees per second.}$$

of which the maximum is

$$\left(\frac{d\,\theta}{d\,t}\right)_{max} = 0.5\,\sqrt{90} = 4.75 \text{ electrical degrees per second.}$$

For the solution of the equation on the integraph a straight line was drawn through the maximum of the sine curve and the origin on platen 4 (Fig. 10). This line is a plot of the term $\frac{\theta}{90}$ of the differential equation.

The platen which moves proportional to $d\,\theta/d\,t$ (platen 3, Fig. 10) was allowed to move as the solution was made but the potentiometer above it was set at zero.

The various gear ratios and adjustments of the integraph were set by trial and error so that one cycle of the solution would be drawn to a convenient scale on the result platen. The length of one cycle of the result was given a value of unity on the time scale. To get the time scale in seconds the scale must be multiplied by $2\,\pi\sqrt{90}$ which is the period of the oscillation of one cycle. The maximum deflection of the platen moving as $d\,\theta/d\,t$ was marked as 4.75 electrical degrees per second.

### Acknowledgment

The authors wish to acknowledge many helpful suggestions during this investigation by members of the Electrical Engineering Staff of the Massachusetts Institute of Technology, especially by Dr. V. Bush, Professors O. G. C. Dahl and M. F. Gardner, and Mr. H. L. Hazen. They also wish to thank Mr. P. L. Alger of the General Electric Company for his helpful advice. Mr. Charles Kingsley, Jr. assisted with the oscillograph work. Messrs. Frank Kear, T. S. Gray, J. B. Russell, Jr., all formerly of the Research Division, aided in making the integraph solutions.

### Nomenclature

$V$ = The applied potential to the armature. In all equations $V$ is taken on the real axis and is thus a real number in all the equations.

$E_1'$ = The induced e. m. f. in the armature due to the direct field current.

$E_1''$ = The induced e. m. f. in the armature due to the "induction motor" current in the symmetrical field circuit.

$I_1'$ = The armature current due to the $E_1'$ when $V = 0$. This is the short-circuit current of the stator.

$I_1''$ = The armature current due to $V$ when $E_1' = 0$. This is the stator current of the machine when run as an induction machine with the rotor short circuited.

$I_2'$ = The direct field current.

$I_2''$ = The "induction motor" current in the symmetrical field caused by relative motion between the rotating magnetic field of the armature and the rotor.

$I_1$ = The armature current $= I_1' + I_1''$. $I_1'$ and $I_1''$ do not have the same frequency except when the rotor is in synchronism.

$I_2$ = The rotor current $= I_2' + I_2''$.

$Z_s$ = Synchronous impedance in ohms per phase.

$x_s$ = Synchronous reactance in ohms per phase.

$r_1$ = Armature resistance per phase.

$r_2$ = Equivalent symmetrical rotor resistance per phase (referred to the stator).

$s$ = Slip $= \dfrac{\omega_s - \omega}{\omega_s}$ where $\omega_s$ = synchronous speed. $\omega$ = speed of the rotor.

(1) = Speed. The brackets indicate that the number which they inclose is proportional to synchronous speed.

$\theta$ = The angle between the applied terminal potential, $V$, and the induced e. m. f., $E_1'$, in the armature, in electrical degrees.

$\frac{d\theta}{dt}$ = The rate of change of angle with respect to time. If $\frac{d\theta}{dt}$ is to be expressed in electrical degrees per second as is done in this paper, it is related directly to slip by the equation

$$\frac{d\theta}{dt} = s\,(360\,f)$$

since $(360\,f)$ is synchronous speed in electrical degrees per second.

$\frac{d^2\theta}{dt^2}$ = The acceleration of the angle. The unit used in this paper was the electrical degree per second per second.

$P_i$ = The coefficient which multiplied by the acceleration gives the synchronous torque due to the inertia of the rotor. The unit here is the kw. per electrical degree per second per second.

$P_d$ = The coefficient which multiplied by the rate of change of angle gives the synchronous torque due to the induction motor effect of the induced field currents. The unit used is the kw. per electrical degree per second.

$P_m$ = The maximum power output for slowly applied load in kw.

$WR^2$ = The moment of inertia in lb. ft.$^2$

$J$ = A coefficient which multiplied by acceleration gives torque.

$f$ = The frequency of the voltage applied to the armature.

$p$ = The number of poles.

$T_m$ = The electromagnetic torque.

$T$ = The load torque.

$P$ = The load on the shaft of the motor in synchronous kw.

$P_o$ = The initial steady-state load in synchronous kw.

$P_L$ = The load that is suddenly applied in synchronous kw.

$\mathbf{1}$ = Heaviside's unit function.

$k$ = The relative damping factor $= \frac{P_d}{\sqrt{P_i\,P_m}}$

In order to use properly use the solutions of this paper the units for calculating $k$ must be in terms of electrical degrees.

$t'$ = An arbitrary variable selected so that the form of the differential equation of all sizes of motors correspond, thus reducing the number of variables.

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## Discussion

**R. H. Park:** I wish to say that we are fortunate in having this paper presented to us. I feel that it is exceedingly valuable, and that through an extension in the assumptions its usefulness may be increased. As it stands, however, it provides a solution of a particular type of equation which undoubtedly will apply to a large number of problems other than the particular one mentioned.

In the beginning of the paper Mr. Edgerton mentions the fact that the time constants in the rotor are assumed to be very fast. The same equation will apply if the time constants are assumed to be exceedingly slow. If we say that the field has zero resistance, the synchronizing torque term becomes the transient synchronizing power instead of the steady synchronizing power.

In the company with which I am associated we have made use of the solutions which have been developed and particularly we have made use of the chart shown in Fig. 3, by means of the artifice just mentioned; that is, we have replaced the steady synchronizing power by the transient synchronizing power and used the same curves to determine the load that can be thrown suddenly on a synchronous motor.

There is one problem of considerable importance which might form the obvious extension of the method shown here. I refer to the question of evaluating the usefulness of high-speed excitation. We have been trying by various calculations and tests to determine what is an optimum value for exciter speeds, in an effort to compromise between a desirable increase in stability and the undesirable effects of increased short-circuit current. These investigations have suffered from the fact that the machines tested are too small and their time constants are unduly small. The calculations have been exceedingly difficult, and it has been impossible to arrive at any very satisfactory conclusion. Now, I believe that the integraph is being extended so that more general equations can be handled, and when it becomes possible to treat fourth order equations, we should be able to investigate the problem that I have mentioned.

**I. H. Summers:** I recently had occasion to use the integraph at Massachusetts Institute of Technology to draw some two hundred and twenty-five curves in the solution of the same equation for which a solution is given in this paper except that damping was neglected. In doing this a record was kept of the amount of time consumed, compared to doing the same work by step-by-step methods of integration. It turned out that the man hours per curve for the curves done on the integraph were somewhat less than one-third of the corresponding figure for the calculated curves.

**H. E. Edgerton:** The charts and tabulations of our paper are limited to cylindrical rotor synchronous machines having symmetrical field circuits. These limitations were necessary

in order that number of variables of the problem could be reduced to three. This reduction of variables, accomplished by putting the equation into a dimensionless form, allowed the charts and curves to be general, that is, they apply to all sizes of machines. I mention this to emphasize the fact that the integraph did not impose the limitations. We have used and are using the integraph to solve the equations of salient pole machines and of machines having unsymmetrical field circuits.

A new integraph, entirely mechanical in principle, is at present being constructed at the Massachusetts Institute of Technology by Dr. Bush and Mr. Hazen. There will be six integrating stages on this integraph. Certain types of differential equations of the sixth order and involved differential equations of lower order than the sixth will be solvable. The present integraph, used for the solution of the problem in this paper, is limited to second degree differential equations.

I do not believe that the detrimental effect of a large moment of inertia upon the damping of a system has been emphasized before. To increase the moment of inertia means a slower oscillation of the rotor during load to transients and a reduction of the relative damping coefficient proportional to the square root of the moment of inertia, (see Fig. 3). However, large inertia is beneficial because the slow swinging gives the excitation systems more time to act. Also large inertia is necessary when slow governors are used, as on hydraulic turbines, to avoid excessive speeds when load is suddenly dropped.

Those who are interested in the problem of pulling into step of a synchronous motor which has been started as an induction motor will find of interest a paper by Mr. F. J. Zak and the writer, which has been accepted for publication by the Institution of Electrical Engineers, (London). This problem depends upon the same differential equation as used in this paper on the sudden load, but with different boundary conditions.

The integraph fills a gap in the computing devices which engineers have at their disposal. It will solve difficult differential equations which involve parameters and functions which may only be representable by curves. Furthermore, the solutions are complete since they take into account the boundary conditions. The integraph performs the various operations as dictated by the differential relationships and plots the result as a curve.

# Three-Phase Short Circuit Synchronous Machines—V

BY R. E. DOHERTY*
Member, A. I. E. E.

and

C. A. NICKLE*
Associate A. I. E. E.

***Synopsis.***—*This paper is the fifth of a series which the authors have presented on the subject of synchronous machines. Part I was an extension of the fundamental theory; Part II, a treatment of torque-angle characteristics under steady-state conditions; Part III, a study of torque-angle characteristics under transient conditions; and Part IV, an analysis of single-phase short circuits. In the present paper, equations for the currents in the armature phases and field under three-phase short circuit are developed.*

*The analysis is divided into three parts. The first covers the case of short circuit at no-load when the resistance is negligible in determining the magnitude of the current although it must naturally be considered in finding the decrement factors; the second considers the same case where the resistance does affect the magnitude of the current; the third covers the case of short circuit under load when resistance is negligible as in the first case.*

*The effect of the nature of the load, i. e., whether the power factor is lagging or leading, is studied and some interesting results are brought out. It is shown that short circuits under load may give less current than at no-load, and it is further developed that under certain practical operating conditions it is even possible to obtain substantially no fundamental current.*

*The paper is illustrated with comparisons of calculated curves and oscillograms showing the actual currents obtained in test. Some of the interesting points concerning the nature of the short-circuit currents and the manner in which they are influenced by the design of the machine are mentioned in the discussion of results.*

## Introduction

A historical treatment of special cases of short circuits was given in *Synchronous Machines IV*. It was mentioned there that the solution for three-phase short circuit of the cylindrical rotor machine, under the assumption of negligible saturation, had been published by other authors. Dreyfus,[14] Lyon,[13] Shimidzu and Ito,[8] Biermanns,[3] Bekku,[12] and Ku[16] have all given thorough mathematical treatment of this type of machine. A general expression for current on three-phase short circuit, covering the case of salient-poles, was included in a paper by Park (*Two-Reaction Theory of Synchronous Machines*,[15b]) presented at the 1929 Winter Convention.

The advance over the authors' previous studies of three-phase short circuits, which is made in the present analysis, is in its treatment of the salient-pole case. That is, the present analysis considers both cylindrical rotor and salient-pole machines, including the effect of load.

## Assumptions

*1. Negligible Saturation.* This assumption is, of course, a deviation from the practical machine. However, as explained in previous papers of this series, the results may nevertheless be used with judgment as an approximation.

*2. The Armature Phase M. M. F. is Sinusoidally Distributed.* This is practically true of most modern machines so that no appreciable error is involved on this score in applying the results to practical cases.*

*3. Only One Rotor Circuit.* The machine is assumed to have only one rotor circuit, *i. e.*, the main field winding in the direct axis.

## Part I

Part I covers the case of dead three-phase short circuit at the terminals of the machine. Only the internal resistance of the machine windings is involved and this is entirely negligible, in most cases, in determining the magnitude of the short-circuit currents.

The mathematical derivation of the equations, neglecting resistance, is given in Appendix A. The general method used is to set up the expressions for the magnetomotive forces, $A_d$ and $A_q$, in the direct and quadrature axes of the machine for any time $t$ after the short circuit occurs. This is done by summing up the m. m. fs. in each axis due to the phase currents, $i_a$, $i_b$, and $i_c$, each total phase m. m. f. being multiplied by a function of time to obtain the component acting at any particular instant. The flux linkages in each axis are then determined from the expressions for $A_d$ and $A_q$. In the next step the total flux linkages in each phase are found. These expressions for flux linkages at any instant after short circuit are then equated to the known linkages which existed at the instant of short circuit.

*General Electric Company, Schenectady, N. Y.

14. For numbered references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

*This assumption is equivalent to the following:

(a) That the mutual inductance of the armature and field circuits is a first harmonic only with respect to the electrical space angle.

(b) That the armature self and mutual inductance with respect to the field winding and other armature windings, contain only the zero and second harmonics.

(c) That the second harmonic of armature self-inductance is equal to the second harmonic of armature mutual inductance with respect to other phases. This follows from Equation (3), reference (15a).

This step is made according to the principle of constant linkages since the resistance is assumed to be negligible. The resulting three equations are then solved for the phase currents $i_a$, $i_b$, and $i_c$. This results in expressions for the currents, each made up of a d-c. component, a positive phase sequence fundamental, and a positive phase sequence second harmonic. Each of these components actually exists only at the initial instant of short circuit and the next step is, therefore, to determine the decrement factors which govern their decay. The positive phase sequence fundamental does not decay to zero but to the sustained value of current. This sustained current is found and subtracted from the expression for the fundamental component of the initial current so that the decrement factor may be applied to the remainder which decays to zero. To make the expressions for total currents hold true, the sustained current is then added so that the final expressions have four component parts, each in terms of $e_o$, the terminal voltage existing before short-circuit, $x_d$ and $x_q$, the synchronous reactances in the direct and quadrature axes, and $x_d'$, the transient reactance of the direct axis. These expressions are:

$$i_a = \frac{e_o}{x_d}\cos(t-\alpha) + e_o\frac{x_d - x_d'}{x_d x_d'}\epsilon^{-\sigma_f t}\cos(t-\alpha)$$

$$- e_o\frac{x_d' + x_q}{2\,x_d'\,x_q}\epsilon^{-\sigma_a t}\cos\alpha$$

$$+ e_o\frac{x_d' - x_q}{2\,x_d'\,x_q}\epsilon^{-\sigma_a t}\cos(2t-\alpha)$$

$$i_b = \frac{e_o}{x_d}\cos\left(t-\alpha-\frac{2\pi}{3}\right)$$

$$+ e_o\frac{(x_d - x_d')}{x_d x_d'}\epsilon^{-\sigma_f t}\cos\left(t-\alpha-\frac{2\pi}{3}\right)$$

$$- e_o\frac{(x_d' + x_q)}{2\,x_d'\,x_q}\epsilon^{-\sigma_a t}\cos\left(\alpha+\frac{2\pi}{3}\right)$$

$$+ e_o\frac{(x_d' - x_q)}{2\,x_d'\,x_q}\epsilon^{-\sigma_a t}\cos\left(2t-\alpha-\frac{2\pi}{3}\right)$$

$$i_c = \frac{e_o}{x_d}\cos\left(t-\alpha-\frac{4\pi}{3}\right)$$

$$+ e_o\frac{x_d - x_d'}{x_d x_d'}\epsilon^{-\sigma_f t}\cos\left(t-\alpha-\frac{4\pi}{3}\right)$$

$$- e_o\frac{(x_d' + x_q)}{2\,x_d'\,x_q}\epsilon^{-\sigma_a t}\cos\left(\alpha+\frac{4\pi}{3}\right)$$

$$+ e_o\frac{(x_d' - x_q)}{2\,x_d'\,x_q}\epsilon^{-\sigma_a t}\cos\left(2t-\alpha-\frac{4\pi}{3}\right)$$

An expression for the field current is obtained by finding the currents induced in the field winding by the m. m. f. in the direct axis. This is found in terms of the currents $i_a$, $i_b$, and $i_c$, whence the expressions given above are substituted to obtain the current in terms of $e_o$, $x_d$, and $x_d'$. The final expression is:

$$I = e_o\frac{x_d}{x_d'} - e_o\frac{x_d - x_d'}{x_d'}\cos t$$

## Part II

The results of Part I may be extended to cover the case of a short circuit occurring through external reactance simply by modifying the reactance coefficients of the machine. When the resistance is negligible the results will be accurate. It remains, however, to consider the case of short circuit occurring through external resistance which is not negligible. In the equations derived in this section of the paper, values of total resistance, including the internal resistance of the machine windings, may be used. Hence, Part II considers three-phase short circuit with armature resistance.

The effect of resistance is to cause the d-c. component and the second harmonic component which

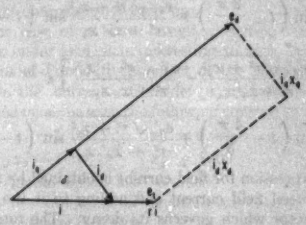


Fig. 1—Vector Diagram of a Salient-Pole Synchronous Machine Short-Circuited through External Resistance

appear in the short-circuit current to decay so rapidly that they have negligible effect on the total transient current. Therefore, an expression for the transient current on three-phase short circuit with armature resistance may be derived simply by determining the initial fundamental current from which the sustained current may be subtracted and a decrement factor applied to the remainder. This remainder plus the sustained current will then give an accurate expression for the total short-circuit current. This is only true, however, for a machine having a single rotor circuit, *i. e.*, a field winding in the direct axis. When rotor circuits are present in the quadrature axis the expression for total current becomes complicated. In this case the rotor current which sponstaneously arises in each axis will have two decrements since armature resistance, by displacing the armature m. m. f. from the rotor axes of symmetry, has the effect of furnishing coupling between the direct and quadrature axes of the rotor.

In Appendix B it is shown how expressions for the

initial fundamental current and the sustained current may be derived from the vector diagram of the salient-pole machine. Knowing these components of current an equation is obtained for the total short-circuit current by adding to the sustained current the difference between it and the initial fundamental current. This difference is multiplied by the field decrement factor. The result is the following set of equations which check test results remarkably well. $e_d'$ is the nominal voltage in the direct axis before short circuit and $r$ is the total armature resistance, internal plus external. The second harmonic and d-c. terms are not included, the justification for their omission having been given.

$$i_a = \left[ \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} - \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \right] \epsilon^{-\sigma_f t} \sin t + \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \sin t$$

$$i_b = \left[ \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} - \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \right] \epsilon^{-\sigma_f t} \sin\left(t - \frac{2\pi}{3}\right) + \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} \sin\left(t - \frac{2\pi}{3}\right)$$

$$i_c = \left[ \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} - \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \right] \epsilon^{-\sigma_f t} \sin\left(t - \frac{4\pi}{3}\right) + \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} \sin\left(t - \frac{4\pi}{3}\right)$$

An expression for field current is obtained by finding the induced field current and adding to it the decrement factor which governs its decay. The total field current is given by adding the steady-state current to the induced current. This gives the result, in the terms of the same constants which have already been described,

$$I = e_d' \left[ 1 + \frac{x_q (x_d - x_d')}{r^2 + x_d' x_q} \right]$$

## Part III

Part III covers the case of a dead short circuit at the terminals of a machine which is running under load. This is similar to a no-load short circuit, the only difference being in the initial conditions. When short circuit occurs a direct current spontaneously flows in the armature winding to maintain constant the entrapped flux. This current, and the second harmonic current which appears in conjunction with it, are independent of the fundamental of the alternating current. Consequently, the fundamental current, the direct current, and the second harmonic current, may be solved for separately. The direct current and the second harmonic current are functions of the flux entrapped in the armature and the machine reactances. Expressions for these currents have already been found in Appendix A (Equations (13), (14), and (15) ) for a short circuit under no-load conditions. It is only necessary to substitute the new value of the entrapped flux to make the expressions hold for a short circuit under conditions of load. The fundamental current may be found in simple fashion from the vector diagram for a salient-pole machine. This derivation is given in Appendix C. Having determined the total fundamental current, the sustained current is found and subtracted from it in order to get the transient component to which the field decrement factor may be applied. The total short-circuit current is then given by the sum of the sustained fundamental current, the transient fundamental current, the direct component, and the second harmonic current. This results in the following expressions, in which only two new constants appear, *i. e.*, $e_t'$, the terminal voltage in the direct axis before short circuit and $\delta$, the displacement angle between the direct axis nominal voltage and the terminal voltage.

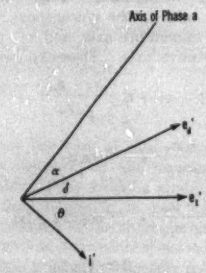


Fig. 2—Vector Diagram of a Salient-Pole Synchronous Machine under Conditions of Balanced Load

$$i_a = \frac{e_d'}{x_d} \cos(t - \alpha) + \left[ \frac{e_t' \cos\delta}{x_d'} - \frac{e_d'}{x_d} + i_d' \right] \epsilon^{-\sigma_f t} \cos(t - \alpha) - e_t' \frac{x_d' + x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos(\delta + \alpha) + e_t' \frac{x_d' - x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos\delta \cos(2t - \alpha) + e_t' \frac{x_d' - x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos(\delta + 90) \cos(2t - \alpha - 90)$$

$$i_b = \frac{e_d'}{x_d} \cos\left(t - \alpha - \frac{2\pi}{3}\right) + \left[ \frac{e_t' \cos\delta}{x_d'} - \frac{e_d'}{x_d} + i_d' \right] \epsilon^{-\sigma_f t} \cos\left(t - \alpha - \frac{2\pi}{3}\right)$$

$$- e_i' \frac{x_d' + x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos\left(\delta + \alpha + \frac{2\pi}{3}\right)$$

$$+ e_i' \frac{x_d' - x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos\delta \cos\left(2t - \alpha - \frac{2\pi}{3}\right)$$

$$+ e_i' \frac{x_d' - x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos(\delta + 90) \cos$$

$$\left(2t - \alpha - 90 - \frac{2\pi}{3}\right)$$

$$i_e = \frac{e_d'}{x_d} \cos\left(t - \alpha - \frac{4\pi}{3}\right) + \left[\frac{e_i' \cos\delta}{x_d'} - \frac{e_d'}{x_d} + i_d'\right] \epsilon^{-\sigma_f t} \cos\left(t - \alpha - \frac{4\pi}{3}\right)$$

$$- e_i' \frac{x_d' + x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos\left(\delta + \alpha + \frac{4\pi}{3}\right)$$

$$+ e_i' \frac{x_d - x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos\delta \cos\left(2t - \alpha - \frac{4\pi}{3}\right)$$

$$+ e_i' \frac{x_d' - x_q}{2\, x_d'\, x_q} \epsilon^{-\sigma_a t} \cos(\delta + 90) \cos$$

$$\left(2t - \alpha - 90 - \frac{4\pi}{3}\right)$$

The field current is given by the following expression, obtained by multiplying the direct axis component of the transient armature current by the difference between the synchronous and transient reactances of the direct axis,

$$I = e_d' + e_i' \cos\delta \left[\frac{x_d - x_d'}{x_d'}\right] \epsilon^{-\sigma_f t}$$

$$- e_i' \cos\delta \left[\frac{x_d - x_d'}{x_d'}\right] \epsilon^{-\sigma_a t} \cos t$$

## Discussion of Results

Although the results are based upon the premise that only one rotor circuit exists, expressions covering the case of machines having amortisseur windings can be developed. For instance, such equations will be obtained in the case of short circuit at no-load, where resistance is negligible, if the sub-transient reactances, $x_d''$ and $x_q''$, are used in the derivation instead of $x_d'$ and $x_q$. These expressions are identical with those given in Appendix A, Equations (**13**), (**14**), and (**15**), except that $x_d''$ and $x_q''$ replace $x_d'$ and $x_q$, respectively. It is immediately evident, from these expressions, that the second harmonic current depends upon the difference in the sub-transient reactances of the direct and quadrature axes and may be practically eliminated by the presence of a good amortisseur winding.

The expressions, in terms of the sub-transient reactances, give the maximum limit of the short-circuit current. This limit is never reached, in an actual case, since the current decrement has several components, some of which are of "high speed." These "high-speed" components decrease, to a large degree, before the first peak of the current wave has been reached.

The determination of an exact expression for the current and its decrement is difficult. In the case of a short circuit occurring when resistance is appreciable, the armature m. m. f. will be displaced from the rotor axes of symmetry causing mutual coupling of the rotor circuits in the two axes. When a short circuit occurs under conditions of load, flux initially exists in the quadrature axis. In any case, where more than one rotor circuit is present in either axis of the machine, these circuits are mutually coupled, causing additional components to appear in the decrement. Exact expressions may be obtained through a solution of the differential equations of the various circuits as has already been shown.[15b] Although these expressions have been developed, they are resorted to only when a particular case warrants their use.

In the case of a short circuit occurring with the machine under load, it is interesting to note, from the equations of Part III, the effect of the nature of the load on the current. Consider a cylindrical rotor laminated machine with the following constants,

$$x_d = 1.00 \qquad x_d'' = 0.30$$
$$x_q = 1.00 \qquad x_q'' = 1.00$$

Then for an initial load of rated kv-a. at normal voltage the fundamental short-circuit current as a function of power factor is,

| | P. F. | $e_d'$ | $\delta$ | $i_d'$ | $i_q'$ | $i$ |
|---|---|---|---|---|---|---|
| | 0 | 2.0 | 0 | 1.0 | 0. | 4.33 |
| Lag ↑ | 11.50 | 1.94 | 15 | 0.966 | 0.259 | 4.18 |
| | 1.00 | 1.414 | 45 | 0.707 | 0.707 | 3.064 |
| Lead ↓ | 0.50 | 0.517 | 75 | 0.259 | 0.966 | 1.123 |
| | 0 | 0 | 90 | 0 | 1.0 | 0 |

Thus in the practical case of a round rotor machine supplying the charging current of a line, it is possible to obtain substantially no fundamental current on short circuit.

It will also be noticed that for a unity power-factor load, the fundamental short-circuit current is less than for a short circuit at no-load. In the latter case the fundamental current would be $e_o/x_d'$ or 3.33 times normal. Hence, when the machine is initially under load, the total short-circuit current may be less than if the machine were carrying no load.

## Comparison of Calculated and Test Results

Calculations and tests were made on a 15-kv-a., 1800-rev. per min., 60-cycle, 220-volt, salient pole generator and a 20-hp., 1800-rev. per min., 60-cycle, 110-volt induction machine. The four major *per unit*

coefficients (measured) for the 20-hp. machine on the basis of 4.3 kv-a., three-phase, 52 volts, line-to-neutral, are:

$$x_d = 1.0 \quad x_d' = 0.0557 \quad x_q = 1.0 \quad x_q'' = 1.0$$

The auxiliary coefficients are:

$$r_a = 0.0252 \quad r_f = 0.0248 \quad x_f = 1.238$$
$$\sigma_a = 0.238 \quad \sigma_f = 0.360$$

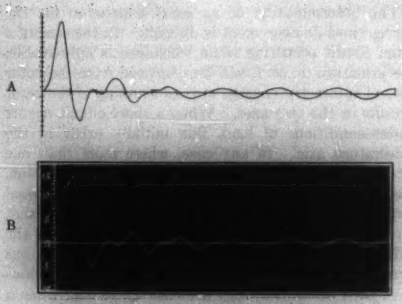


FIG. 3—TRANSIENT ARMATURE CURRENT IN PHASE *A* ON BALANCED THREE-PHASE SHORT CIRCUIT. APPROXIMATE ZERO FLUX LINKAGES WITH PHASE *A* ($\alpha$ = 80 DEG.) ROUND ROTOR MACHINE

Curve *A*. Calculated curve
Curve *B*. Test curve

Equation:

$$i_a = \cos(t + 80) + 16.95\, \epsilon^{-0.36\, t} \cos(t + 80) - 9.46 \cos(t + 80) - 8.47 \cos(2t + 80)$$

For the 15 kv-a. alternator the corresponding per unit coefficients based on 5.78 kv-a., three-phase, 60.7 volts line-to-neutral are:

$$x_d = 1.0 \quad x_d' = 0.157$$
$$x_q = 0.428 \quad x_q'' = 0.428$$
$$r_a = 0.0407 \quad r_f = 12.5$$
$$\sigma_a = 0.1773 \quad \sigma_f = 0.0658$$
$$x_f = 1208.0$$

A comparison of calculated and test results is shown in Figs. 3 to 16, inclusive. Each illustration shows:

(a) Calculated curve from the equations of the paper.

(b) Oscillograph record of test.

(c) Equation, with the numerical values substituted, from which the calculated curve was obtained.

A careful inspection of each of the illustrations shows a close agreement between the calculated and test curves, even in the minute details. The magnitude of the instantaneous current in amperes may be obtained by multiplying the ordinates of any curve by the unit peak current obtained from the kv-a. base to which the machine coefficients are referred. The actual short-circuit current may then be obtained by multiplying by the ratio of the normal kv-a. to the basis kv-a. The kv-a. base is chosen, in each case, so that the ordinate scales are marked with unit distance equal to the peak value of the sustained short-circuit current wave. In this way the peak value of current on the chosen kv-a. base is the maximum instantaneous value of the sustained wave.

ACKNOWLEDGMENTS

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## Appendix A

### THREE-PHASE SHORT CIRCUIT WITHOUT ARMATURE RESISTANCE

At any instant after a three-phase short circuit occurs, certain currents will exist in the three phases, *a*, *b*, and *c*. Since no neutral currents can exist the sum of these currents must equal zero, *i. e.*,

$$i_a + i_b + i_c = 0 \qquad (1)$$

Assuming that the short circuit occurs when phase *a* is ahead of the poles by an angle $\alpha$, phase *b* by an angle $(\alpha + 2\pi/3)$, and phase c by an angle $(\alpha + 4\pi/3)$, then at any instant, *t*, after short circuit these angles are $(\alpha - t)$, $(\alpha + 2\pi/3 - t)$, and $(\alpha + 4\pi/3 - t)$ respectively.

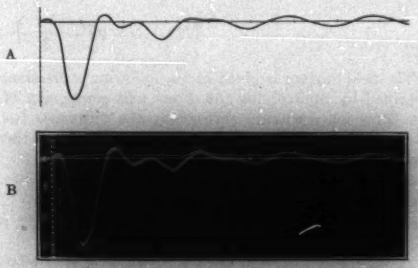


FIG. 4—TRANSIENT ARMATURE CURRENT IN PHASE *A* ON BALANCED THREE-PHASE SHORT CIRCUIT. MAXIMUM INITIAL FLUX LINKAGES WITH PHASE *A* ROUND ROTOR MACHINE

Curve *A*. Calculated curve
Curve *B*. Test curve

Equation:

$$i_a = \cos t + 16.95\, \epsilon^{-0.36t} \cos t - 9.46\, \epsilon^{-0.238t} - 8.47\, \epsilon^{-0.238t} \cos 2t$$

The m. m. f. in the direct axis is the sum of the components produced by $i_a$, $i_b$, and $i_c$ or,

$$A_d = \frac{2}{3}\left[i_a \cos(\alpha - t) + i_b \cos(\alpha + 2\pi/3 - t) + i_c \cos(\alpha\, 4\pi/3 - t)\right] \qquad (2)$$

and in the quadrature axis ahead of the pole,

$$A_q = \frac{2}{3}\left[i_a \cos(\alpha - t - \pi/2) + i_b \cos(\alpha + 2\pi/3 - t - \pi/2)\right.$$

$$+ i_c \cos(\alpha + 4\pi/3 - t - \pi/2)] \quad (3)$$

or,

$$A_q = \frac{2}{3}[i_a \sin(\alpha - t) + i_b \sin(\alpha + 2\pi/3 - t) + i_c \sin(\alpha + 4\pi/3 - t)] \quad (4)$$

The m. m. f., $A_d$, being of a transient nature produces flux linkages in the direct axis,

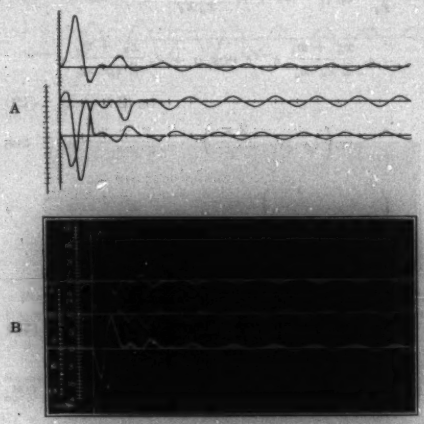


FIG. 5—TRANSIENT ARMATURE CURRENTS FOR BALANCED THREE-PHASE SHORT CIRCUIT. MAXIMUM INITIAL ARMATURE LINKAGES WITH PHASE-$B$ ROUND ROTOR MACHINE

Curves $A$. Calculated curves
Curves $B$ Test curves

Equations:

$$i_a = \cos t + 16.95\, \epsilon^{-0.36t} \cos(t - 120) + 4.73\, \epsilon^{-0.238t} - 8.45\, \epsilon^{0.238t} \cos(2t - 120)$$

$$i_b = \cos t + 16.95\, \epsilon^{-0.36t} \cos t - 9.46\, \epsilon^{-0.238t} - 8.45\, \epsilon^{0.238t} \cos 2t$$

$$i_c = \cos t + 16.95\, \epsilon^{-0.36t} \cos(t - 240) + 4.73\, \epsilon^{-0.238t} - 8.45\, \epsilon^{-0.238t} \cos(2t - 240)$$

$$\psi_{da} = \frac{2}{3} x_d' [i_a \cos(\alpha - t) + i_b \cos(\alpha + 2\pi/3 - t) + i_c \cos(\alpha + 4\pi/3 - t)] \quad (5)$$

and the m. m. f., $A_q$, produces flux linkages in the quadrature axis,

$$\psi_{qa} = \frac{2}{3} x_q [i_a \sin(\alpha - t) + i_b \sin(\alpha + 2\pi/3 - t) + i_c \sin(\alpha + 4\pi/3 - t)] \quad (6)$$

Hence the total flux linkages in phase $a$ are,

$$\psi_a = e_o \cos(\alpha - t) + \psi_{da} \cos(\alpha - t) + \psi_{qa} \sin(\alpha - t) \quad (7)$$

in phase $b$,

$$\psi_b = e_o \cos(\alpha + 2\pi/3 - t) + \psi_{da} \cos(\alpha + 2\pi/3 - t) + \psi_{qa} \sin(\alpha + 2\pi/3 - t) \quad (8)$$

in phase $c$,

$$\psi_c = e_o \cos(\alpha + 4\pi/3 - t) + \psi_{da} \cos(\alpha + 4\pi/3 - t) + \psi_{qa} \sin(\alpha + 4\pi/3 - t) \quad (9)$$

where $e_o$ is the open-circuit terminal voltage before short circuit.

In determining the initial short-circuit current resistance may be assumed equal to zero and the linkages $\psi_a$, $\psi_b$, and $\psi_c$ must at all instants be equal to their values which existed at the instant of short circuit. Hence,

$$\psi_a = e_o \cos(\alpha - t) + \psi_{da} \cos(\alpha - t) + \psi_{qa} \sin(\alpha - t) = e_o \cos\alpha \quad (10)$$

$$\psi_b = e_o \cos(\alpha + 2\pi/3 - t) + \psi_{da} \cos(\alpha + 2\pi/3 - t) + \psi_{qa} \sin(\alpha + 2\pi/3 - t) = e_o \cos(\alpha + 2\pi/3) \quad (11)$$

$$\psi_c = e_o \cos(\alpha + 4\pi/3 - t) + \psi_{da} \cos(\alpha + 4\pi/3 - t) + \psi_{qa} \sin(\alpha + 4\pi/3 - t) = e_o \cos(\alpha + 4\pi/3) \quad (12)$$

Substituting Equations (5) and (6) for $\psi_{da}$ and $\psi_{qa}$, gives three simultaneous equations in terms of the open-circuit terminal voltage $e_o$ and the currents $i_a$, $i_b$, and $i_c$. To solve for the currents the relation (1) is used to obtain three equations in terms of $i_b$ and $i_c$. Two of the three equations are chosen and the currents $i_b$ and $i_c$ solved for by determinants.

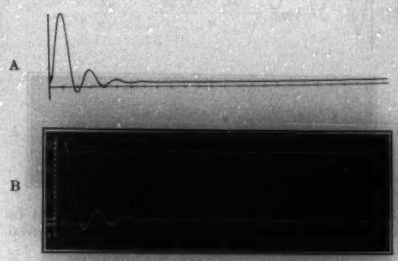


FIG. 6—TRANSIENT FIELD CURRENT ON BALANCED THREE-PHASE SHORT CIRCUIT. ROUND ROTOR MACHINE

Curve $A$. Calculated curve
Curve $B$. Test curve

Equation:

$$i_f = 1 + 16.95\, \epsilon^{-0.36t} - 16.95\, \epsilon^{-0.238t} \cos t$$

Then,

$$i_b = e_o \frac{x_d' + x_q}{2 x_d' x_q} \cos\left(\alpha + \frac{2\pi}{3}\right) - \frac{e_o}{x_d'} \cos\left(t - \alpha - \frac{2\pi}{3}\right) - e_o \frac{x_d' - x_q}{2 x_d' x_q} \cos\left(2t - \alpha - \frac{2\pi}{3}\right) \quad (13)$$

$$i_c = e_o \frac{x_d' + x_q}{2 x_d' x_q} \cos\left(\alpha + \frac{4\pi}{3}\right)$$

$$- \frac{e_o}{x_d'} \cos\left(t - \alpha - \frac{4\pi}{3}\right) - e_o \frac{x_d' - x_q}{2 x_d' x_q} \cos \left(2t - \alpha - \frac{4\pi}{3}\right) \quad (14)$$

$$i_a = - i_b - i_c = e_o \frac{x_d' + x_q}{2 x_d' x_q} \cos \alpha - \frac{e_o}{x_d'} \cos (t - \alpha) - e_o \frac{x_d' - x_q}{2 x_d' x_q} \cos (2t - \alpha) \quad (15)$$

Equations (13), (14), and (15), contain a d-c. component, a positive phase sequence fundamental, and a positive phase sequence second harmonic.

Under sustained short circuit the d-c. component and the second harmonic will have decayed to zero. The fundamental component is proportional at each instant to the average value of field current or nominal voltage. Immediately after short circuit the average value of nominal voltage is $e_o x_d/x_d'$ and under sustained short circuit this decays to $e_o$. Hence the sustained fundamental current in the armature will be $x_d'/x_d$ times the initial value or,

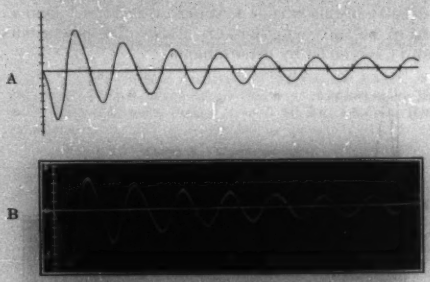


FIG. 7—TRANSIENT ARMATURE CURRENT IN PHASE $A$ ON BALANCED THREE-PHASE SHORT CIRCUIT. MINIMUM INITIAL FLUX LINKAGES WITH PHASE $A$. SALIENT POLE MACHINE

Curve $A$. Calculated curve
Curve $B$. Test curve

Equation:

$$i_a = \cos (t + 90) + 5.37 \cos (t + 90)\, \epsilon^{-0.0658t} - 2.02 \cos(2t + 90)\, \epsilon^{-0.1773t}$$

$$i_a = - \frac{e_o}{x_d} \cos (t - \alpha) \quad (16)$$

$$i_b = - \frac{e_o}{x_d} \cos\left(t - \alpha - \frac{2\pi}{3}\right) \quad (17)$$

$$i_c = - \frac{e_o}{x_d} \cos\left(t - \alpha - \frac{4\pi}{3}\right) \quad (18)$$

The values given by Equations (16), (17), and (18) are subtracted from the fundamental components of Equations (13), (14), and (15) respectively and each value is then added to the respective equation to maintain its equality. The three resulting equations contain four components each, three of which decay to zero; the fourth component is the sustained current which is, of course, constant. If $\sigma_a$ and $\sigma_f$ are the decrement factors for the armature and field circuits respectively, the armature currents are given by,

$$i_a = \frac{e_o}{x_d} \cos (t - \alpha) + e_o \frac{x_d - x_d'}{x_d x_d'} \epsilon^{-\sigma_f t} \cos (t - \alpha) - e_o \frac{x_d' + x_q}{2 x_d' x_q} \epsilon^{-\sigma_a t} \cos \alpha + e_o \frac{x_d' - x_q}{2 x_d' x_q} \epsilon^{-\sigma_a t} \cos (2t - \alpha) \quad (19)$$

$$i_b = \frac{e_o}{x_d} \cos\left(t - \alpha - \frac{2\pi}{3}\right) + e_o \frac{x_d - xd'}{x_d x_d'} \epsilon^{-\sigma_f t} \cos \left(t - \alpha - \frac{2\pi}{3}\right) - e_o \frac{x_d' + x_q}{2 x_d' x_q} \epsilon^{-\sigma_a t} \cos \left(\alpha + \frac{2\pi}{3}\right) + e_o \frac{x_d' - x_q}{2 x_d' x_q} \epsilon^{-\sigma_a t} \cos \left(2t - \alpha - \frac{2\pi}{3}\right) \quad (20)$$

$$i_c = \frac{e_o}{x_d} \cos\left(t - \alpha - \frac{4\pi}{3}\right) + e_o \frac{x_d - x_d'}{x_d x_d'} \epsilon^{-\sigma_f t} \cos \left(t - \alpha - \frac{4\pi}{3}\right) - e_o \frac{x_d' + x_q}{2 x_d' x_q} \epsilon^{-\sigma_a t} \cos \left(\alpha + \frac{4\pi}{3}\right) + e_o \frac{x_d' - x_q}{2 x_d' x_q} \epsilon^{-\sigma_a t} \cos \left(2t - \alpha - \frac{4\pi}{3}\right) \quad (21)$$

## DECREMENTS

Immediately after short circuit the average field current has risen from $e_o$ to $e_o x_d/x_d'$. Since this increase in the field current occurs in order that the flux linkages of the field circuit remain constant, it follows that with the armature short-circuited the effective inductance of the field winding is $x_d'/x_d$ times its value when the armature is open-circuited. Hence, if $T_{of}$ is the time constant of the field winding with the armature open-circuited, the time constant under short circuit is,

$$T_f = \frac{x_d'}{x_d} T_{of} \quad (22)$$

The decrement factor for the field circuit is therefore,

$$\sigma_f = \frac{x_d}{x_d'} \sigma_{of} \quad (23)$$

where $\sigma_{of}$ is the open-circuit field decrement factor, *i. e.*,

$$\sigma_{af} = \frac{R}{\omega L_{af}} \tag{24}$$

This is only true when the resistance of the armature circuit is small and when only one rotor circuit exists. The effect of armature resistance on the field decrement factor is mentioned in Part II and was discussed in Synchronous Machines IV.

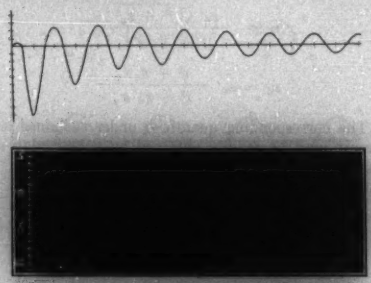


FIG. 8—TRANSIENT ARMATURE CURRENT IN PHASE *A* ON BALANCED THREE-PHASE SHORT CIRCUIT. MAXIMUM INITIAL FLUX LINKAGES WITH PHASE *A*. SALIENT-POLE MACHINE

Curve *A*. Calculated curve
Curve *B*. Test curve

Equation:

$$\cos t + 5.37\, \epsilon^{-0.0658t} \cos t - 4.35\, \epsilon^{-0.1773t} - 2.02\, \epsilon^{-0.1773t} \cos 2t$$

For the armature circuits, on short circuit, the direct component exists in order that the flux linkages be maintained constant. It is thus a measure of the average magnetic reluctance with respect to the armature. Hence, the average armature inductance is given by the reciprocal. From the derivation of Equations (19), (20), and (21) the direct component is:

$$\frac{x_d' + x_q}{2\, x_d'\, x_q} \tag{25}$$

times the per-unit entrapped flux.

The armature inductance expressed as a fraction of normal inductance is then,

$$l = \frac{2\, x_d'\, x_q}{x_d' + x_q} \tag{26}$$

The time constant under three-phase short-circuit conditions is therefore,

$$T_a = \frac{2\, x_d'\, x_q}{r_a\, (x_d' + x_q)} \tag{27}$$

Hence the decrement factor for the armature circuits is,

$$\sigma_a = \frac{r_a\, (x_d' + x_q)}{2\, x_d'\, x_q} \tag{28}$$

## FIELD CURRENT

The m. m. f. in the direct axis for the first few moments after short circuit occurs is given by Equation (2).

As already shown (Equation (5c), Synchronous Machines IV) an m. m. f. of a transient character will induce currents in the field winding in accordance with the equation,

$$\Delta I = -A_d\, (x_d - x_d') \tag{29}$$

Substituting the expression for $A_d$ given by Equation (2),

$$\Delta I = -\frac{2}{3}\, (x_d - x_d') \left[ i_a \cos (\alpha - t) + i_b \cos\left(\alpha + \frac{2\pi}{3} - t\right) + i_c \cos\left(\alpha + \frac{4\pi}{3} - t\right) \right] \tag{30}$$

Substituting for $i_a$, $i_b$, and $i_c$ from Equations (13), (14), and (15),

$$\Delta I = \frac{e_o\, (x_d - x_d')}{x_d'}\, (1 - \cos t) \tag{31}$$

The total field current is,

$$I = \frac{e_o\, (x_d - x_d')}{x_d'}\, (1 - \cos t) + e_o \tag{32}$$

$$= e_o \frac{x_d}{x_d'} - \frac{e_o\, (x_d - x_d')}{x_d'} \cos t \tag{33}$$

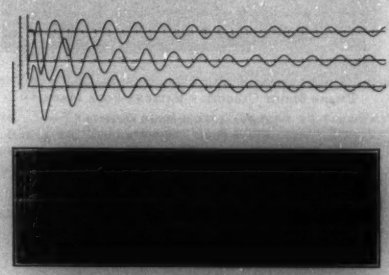


FIG. 9—TRANSIENT ARMATURE CURRENTS FOR BALANCED THREE-PHASE SHORT CIRCUIT. MAXIMUM INITIAL ARMATURE LINKAGES WITH PHASE-*A* SALIENT-POLE MACHINE

Curves *A*. Calculated curves
Curves *B*. Test curves

Equations:

$$i_a = \cos t + 5.37 \cos t\, \epsilon^{-0.0658t} - 4.35\, \epsilon^{-0.1773t} - 2.02 \cos 2t\, \epsilon^{-0.1773}$$

$$i_b = \cos (t - 120) + 5.37 \cos (t - 120)\, \epsilon^{-0.0658t} + 2.17\, \epsilon^{-0.1773t}\, 2.02 \cos (2t - 120)\, \epsilon^{-0.1773t}$$

$$i_c = -\cos (t - 240) - 5.37 \cos (t - 240)\, \epsilon^{-0.0658t} + 2.17\, \epsilon^{-0.1773t} + 2.02 \cos (2t - 240)\, \epsilon^{-0.1773t}$$

The alternating component of current in the field is due to the d-c. component in the armature and decays dependent upon the time constant of the armature. Hence, the final expression for field current is, from Equation (32),

$$I = e_o + e_o \frac{x_d - x_d'}{x_d'} \epsilon^{-\sigma_d t} - e_o \frac{x_d - x_d'}{x_d'} \epsilon^{-\sigma_d t} \cos t \qquad (34)$$

## Appendix B

### Three-Phase Short Circuit with Armature Resistance

Since the fundamental current is independent of the direct current and resultant harmonics, it may be derived separately. Considering the total resistance to be external to the machine, the vector diagram shown in Fig. I may be drawn.

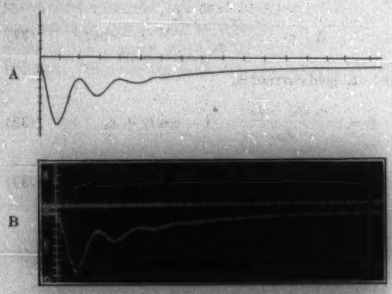


Fig. 10—Transient Field Current on Balanced Three-Phase Short Circuit. Salient-Pole Machine

Curve *A*. Calculated curve
Curve *B*. Test curve

Equation:

$$i_f = 1.0 + 5.37\ \epsilon^{-0.0658t} - 5.37\ \epsilon^{-0.1773t} \cos t$$

From Fig. 1,

$$i_d = i \sin \delta = \frac{e_t}{r} \sin \delta \qquad (1)$$

$$i_q = i \cos \delta = \frac{e_t}{r} \cos \delta \qquad (2)$$

$$e_t \cos \delta + i_d x_q = e_d = e_t \cos \delta + \frac{e_t x_d}{r} \sin \delta \qquad (3)$$

$$i_q \,.\, x_q = \frac{e_t x_q}{r} \cos \delta = e_t \sin \delta \qquad (4)$$

The nominal voltage $e_d$ is equal to that existing before short circuit and the component induced by armature reaction, *i. e.*, by the current component $i_d$. Hence,

$$e_d = e_d' + \frac{e_t}{r} \sin \delta \,(x_d - x_d') \qquad (5)$$

From Equation (4),

$$\tan \delta = \frac{x_q}{r} \qquad (6)$$

Solving (3), (5), and (6) simultaneously,

$$e_t = \frac{e_d' r \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} \qquad (7)$$

$$i = \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} \qquad (8)$$

$$e_d = e_d' \frac{r^2 + x_d x_q}{r^2 + x_d' x_q} \qquad (9)$$

The corresponding quantities under sustained short circuit may be readily obtained by substituting synchronous reactances for transient reactances in the equations just derived. Then,

$$e = \frac{e_d' r \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \qquad (10)$$

$$i = \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \qquad (11)$$

$$e_d = e_d' \qquad (12)$$

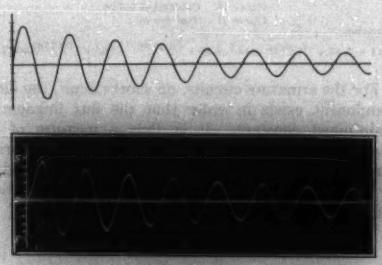


Fig. 11—Transient Armature Current in Phase *A* on Balanced Three-Phase Short Circuit. External Resistance in each Phase Equal to 13.2 Per Cent ($x_d$) Salient-Pole Machine

Curve *A*. Calculated curve
Curve *B*. Test curve

Equation:

$$i_a = (3.75\ \epsilon^{-0.0488t} + 1.008) \sin t$$

Expressions for the total currents in the three phases may readily be derived when armature resistance is present as the direct and second harmonic currents vanish quickly and need not be considered. The transient component of current is given by subtracting the sustained current, Equation (11), from the initial current, Equation (8). This transient current is multiplied by the decrement factor of the field circuit. The total current is then found by adding the sustained current, Equation (11), resulting in the following expressions,

$$i_a = \left[ \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} - \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \right] \epsilon^{-\sigma_f t} \sin t + \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \sin t \quad (13)$$

$$i_b = \left[ \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} - \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \right] \epsilon^{-\sigma_f t} \sin \left( t - \frac{2\pi}{3} \right) + \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \sin \left( t - \frac{2\pi}{3} \right) \quad (14)$$

$$i_c = \left[ \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d' x_q} - \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \right] \epsilon^{-\sigma_f t} \sin \left( t - \frac{4\pi}{3} \right) + \frac{e_d' \sqrt{r^2 + x_q^2}}{r^2 + x_d x_q} \sin \left( t - \frac{4\pi}{3} \right) \quad (15)$$

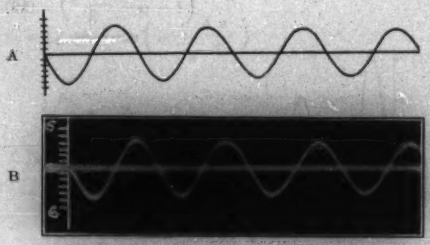


FIG. 12—TRANSIENT ARMATURE CURRENT IN PHASE $A$ ON BALANCED THREE-PHASE SHORT CIRCUIT. EXTERNAL RESISTANCE IN EACH PHASE EQUAL TO 46.4 PER CENT ($x_d$) SALIENT POLE MACHINE

Curve $A$. Calculated curve
Curve $B$. Test curve

Equation:

$$i_a = (1.086\ \epsilon^{-0.0219t} + 0.969) \sin t$$

The corresponding field current is obtained from Equations (5), (6), and (7) giving,

$$I = e_d' \left[ 1 + \frac{x_q (x_d - x_d')}{r^2 + x_d' x_q} \epsilon^{-\sigma_f t} \right] \quad (23)$$

The field decrement factor $\sigma_f$ is given by the open-circuit field decrement factor multiplied by the ratio of the average field current, which spontaneously appears at short circuit, to the value existing immediately before short circuit. This is purely a ratio of the open-circuit and short-circuit inductance of the field circuit, the theoretical basis for which is given in Synchronous Machines IV, Appendix H. Thus,

$$\sigma_f = \left[ 1 + \frac{x_q (x_d - x_d')}{r^2 + x_d' x_q} \right] \sigma_{of}$$

where $\sigma_{of}$ is given by Equation (24), Appendix A.

## Appendix C

### THREE-PHASE SHORT CIRCUIT UNDER LOAD

When a three-phase machine is operating under conditions of balanced load the vector diagram of Fig. 2 shows the relation between terminal voltage current, displacement angle, etc.

When the machine is short-circuited, a new current arises in the direct axis.* The difference between this current and the direct component of the pre-short-circuit, steady-state, current arises suddenly and induces a rotor current corresponding to the increment in nominal voltage,

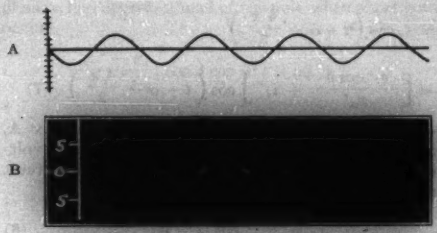


FIG. 13—TRANSIENT ARMATURE CURRENT IN ONE-PHASE ON BALANCED THREE-PHASE SHORT CIRCUIT. EXTERNAL RESISTANCE IN EACH PHASE EQUAL TO 89.8 PER CENT ($x_d$) SALIENT POLE MACHINE

Curve $A$. Calculated curve
Curve $B$. Test Curve

Equation:

$$i_a = (0.300\ \epsilon^{-0.0143t} + 0.788) \sin$$

$$\Delta e_d = (i_d - i_d')(x_d - x_d') \quad (1)$$

The fundamental armature current must be,

$$i_d = \frac{e_d}{x_d} \quad (2)$$

*With only one rotor circuit no new current of fundamental frequency can arise in the quadrature axis. In the general case, where an amortisseur winding exists, a current $i_q$ will arise, however, inducing a rotor current,

$$\Delta e_q = (i_q - i_q')(x_q - x_q'')$$

The current $i_q$ must be,

$$i_q = \frac{e_q}{x_q} = \frac{(i_q - i_q')(x_q - x_q'')}{x_q}$$

$$= -\frac{i_q'(x_q - x_q'')}{x_q''} = i_q' - \frac{e_d' \sin}{x_q''} \delta$$

This current is zero when $x_q = x_q''$.

or,

$$i_d = \frac{e_d' + (i_d - i_d')(x_d - x_d')}{x_d} \tag{3}$$

$$= \frac{e_d' - i_d'(x_d - x_d')}{x_d'} = \frac{e_t' \cos\delta}{x_d'} + i_d' \tag{4}$$

Considering the short circuit to occur when phase $a$ is ahead of the poles by an angle $\alpha$ the fundamental current in phase $a$ is,

$$i_a = i_d \cos(t - \alpha) = \left[\frac{e_t' \cos\delta}{x_d'} + i_d'\right] \cos(t - \alpha) \tag{5}$$

in phase $b$,

$$i_b = i_d \cos\left(t - \alpha - \frac{2\pi}{3}\right)$$

$$= \left[\frac{e_t' \cos\delta}{x_d'} + i_d'\right] \cos\left(t - \alpha - \frac{2\pi}{3}\right) \tag{6}$$

and in phase $c$,

$$i_c = i_d \cos\left(t - \alpha - \frac{4\pi}{3}\right)$$

$$= \left[\frac{e_t' \cos\delta}{x_d'} + i_d'\right] \cos\left(t - \alpha - \frac{4\pi}{3}\right) \tag{7}$$

From Equations (16), (17), and (18), Appendix A, where the steady-state, pre-short-circuit nominal voltage is now $e_d'$ instead of $e_o$, the sustained short-circuit current is, in phase $a$,

$$i_a = \frac{e_d'}{x_d} \cos(t - \alpha) \tag{8}$$

in phase $b$,

$$i_b = \frac{e_d'}{x_d} \cos\left(t - \alpha - \frac{2\pi}{3}\right) \tag{9}$$

and in phase $c$,

$$i_c = \frac{e_d'}{x_d} \cos\left(t - \alpha - \frac{4\pi}{3}\right) \tag{10}$$

Subtracting Equations (8), (9), and (10) from Equations (5), (6), and (7), and applying the decrement factor $\sigma_f$ to the remainder gives the transient component of the fundamental current which decays to zero. The total fundamental current is then obtained by adding the sustained currents to the transient currents respective of phase. This results in the following expressions:

$$i_a = \frac{e_d'}{x_d} \cos(t - \alpha)$$

$$+ \left[\frac{e_t' \cos\delta}{x_d'} - \frac{e_d'}{x_d} + i_d'\right] \epsilon^{-\sigma_f t} \cos(t - \alpha) \tag{11}$$

$$i_b = \frac{e_d'}{x_d} \cos\left(t - \alpha - \frac{2\pi}{3}\right)$$

$$+ \left[\frac{e_t' \cos\delta}{x_d'} - \frac{e_d'}{x_d} + i_d'\right] \epsilon^{-\sigma_f t} \cos\left(t - \alpha - \frac{2\pi}{3}\right) \tag{12}$$

$$i_c = \frac{e_d'}{x_d} \cos\left(t - \alpha - \frac{4\pi}{3}\right)$$

$$+ \left[\frac{e_t' \cos\delta}{x_d'} - \frac{e_d'}{x_d} + i_d'\right] \epsilon^{-\sigma_f t} \cos\left(t - \alpha - \frac{4\pi}{3}\right) \tag{13}$$

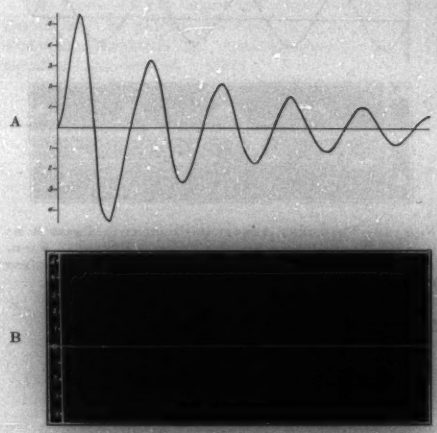


FIG. 14—TRANSIENT ARMATURE CURRENT IN PHASE $A$ ON BALANCED THREE-PHASE SHORT CIRCUIT FROM LOAD. MINIMUM INITIAL ARMATURE LINKAGES WITH PHASE $A$ SALIENT POLE MACHINE UNITY POWER FACTOR LOAD

Curve $A$. Calculated curve
Curve $B$. Test curve

Equation:

$$i_a = 1.31 \cos(t - 66.8) + 4.93\,\epsilon^{-0.0658t} \cos(t - 66.8) - 2.02\,\epsilon^{-0.1773t} \cos(2t - 90)$$

Spontaneously at short circuit a direct current flows in the armature to maintain the flux linkages which existed at the instant of short circuit. These linkages are always determined by the terminal voltage of the machine. In Appendix A, Equations (13), (14), and (15), the direct current was found to be

$$-\frac{x_d' + x_q}{2 x_d' x_q}$$

times the flux in the direct or quadrature axes of the particular phase considered, at the instant of short circuit. In the case of a short circuit occurring when the machine is under load this flux is, $e_t' \cos\delta$, in the

direct axis, and, $e_i' \cos(\delta + 90)$, in the quadrature axis, where $\delta$ is the displacement angle between the field poles and the rotating flux. Considering the short circuit to occur when the axis of phase $a$ is ahead of the pole by an angle $\alpha$, the total fluxes linking the three phases are,

$$e_a = e_i' \cos\delta \cos\alpha + e_i' \cos(\delta + 90) \cos(90 - \alpha) \quad (14)$$

$$e_b = e_i' \cos\delta \cos\left(\alpha + \frac{2\pi}{3}\right) + e_i' \cos(\delta + 90) \cos\left(90 - \alpha - \frac{2\pi}{3}\right) \quad (15)$$

$$e_c = e_i' \cos\delta \cos\left(\alpha + \frac{4\pi}{3}\right) + e_i' \cos(\delta + 90) \cos\left(90 - \alpha - \frac{2\pi}{3}\right) \quad (16)$$

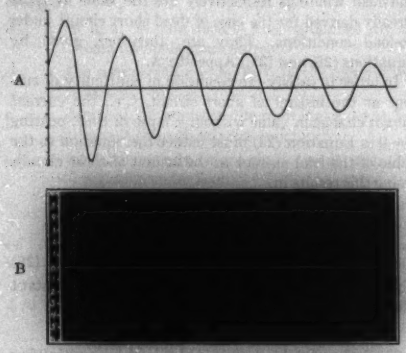


FIG. 15—TRANSIENT ARMATURE CURRENT IN PHASE $A$ ON BALANCED THREE-PHASE SHORT CIRCUIT FROM LOAD. MINIMUM INITIAL ARMATURE LINKAGES WITH PHASE $A$ SALIENT POLE MACHINE. ZERO POWER FACTOR LEADING LOAD

Curve $A$. Calculated curve
Curve $B$. Test curve

Equation:

$$i_a = 5.37\, \epsilon^{-0.0658t} \cos(t - 90) - 2.016\, \epsilon^{-0.1773t} \cos(2t - 90)$$

Hence, the direct currents which flow in the phases, $a$, $b$, and $c$ are respectively

$$i_a = -e_i' \frac{x_d' + x_q}{2 x_d' x_q} \cos(\delta + \alpha) \quad (17)$$

$$i_b = -e_i' \frac{x_d' + x_q}{2 x_d' x_q} \cos\left(\delta + \alpha + \frac{2\pi}{3}\right) \quad (18)$$

$$i_c = -e_i' \frac{x_d' + x_q}{2 x_d' x_q} \cos\left(\delta + \alpha + \frac{4\pi}{3}\right) \quad (19)$$

These direct currents hold the flux linkages constant in conjunction with a second harmonic current which is due to the variation in armature inductance as the poles rotate. This variation is caused by the variation in reluctance of the magnetic circuit, including the increase in reluctance which is due to the short-circuited field winding. Equation (15), Appendix $A$, shows that the variation in reluctance is

$$\frac{x_d' - x_q}{2 x_d' x_q} \cos(2t)$$

in the direct axis.

The variation in the quadrature axis, 90 deg. ahead of the pole, is obviously, starting at the same instant of short circuit,

$$-\frac{x_d' - x_q}{2 x_d' x_q} \cos(2t)$$

Multiplying the variations in reluctance by the flux which exists in each respective axis at the instant of short circuit, results in the following expressions for the second harmonic currents, assuming that the axis of phase $a$ is $\alpha$ degrees ahead of the pole when short circuit occurs.

$$i_a = e_i' \frac{x_d' - x_q}{2 x_d' x_q} \cos\delta \cos(2t - \alpha) - e_i' \frac{x_d' - x_q}{2 x_d' x_q} \cos(\delta + 90) \cos(2t - \alpha + 90) \quad (20)$$

$$i_b = e_i' \frac{x_d' - x_q}{2 x_d' x_q} \cos\delta \cos\left(2t - \alpha - \frac{2\pi}{3}\right) - e_i' \frac{x_d' - x_q}{2 x_d' x_q} \cos(\delta + 90) \cos\left(2t - \alpha + 90 - \frac{2\pi}{3}\right) \quad (21)$$

$$i_c = e_i' \frac{x_d' - x_q}{2 x_d' x_q} \cos\delta \cos\left(2t - \alpha - \frac{4\pi}{3}\right) - e_i' \frac{x_d' - x_q}{2 x_d' x_q} \cos(\delta + 90) \cos\left(2t - \alpha + 90 - \frac{4\pi}{3}\right) \quad (22)$$

The total current flowing on short circuit is then a summation of the fundamental current, Equations (11), (12), and (13), the direct current, Equations (17), (18), and (19), and the second harmonic current, Equations (20), (21), and (22). Adding these, with respect to phase, and applying the decrement factors $\sigma_a$ and $\sigma_f$ gives,

$$i_a = \frac{e_d'}{x_d} \cos(t - \alpha)$$

$$+\left[\frac{e_t'\cos\delta}{x_d'}-\frac{e_d'}{x_d}+i_d'\right]\epsilon^{-\sigma_f t}\cos(t-\alpha)$$

$$-e_t'\frac{x_d'+x_q}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos(\delta+\alpha)$$

$$+e_t'\frac{x_d'-x_q}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos\delta\cos(2t-\alpha)$$

$$-e_t'\frac{x_d'-x_q}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos(\delta+90)$$

$$\cos(2t-\alpha+90) \quad (23)$$

$$i_b=\frac{e_d'}{x_d}\cos\left(t-\alpha-\frac{2\pi}{3}\right)$$

$$+\left[\frac{e_t'\cos\delta}{x_d'}-\frac{e_d'}{x_d}+i_d'\right]\epsilon^{-\sigma_f t}\cos$$

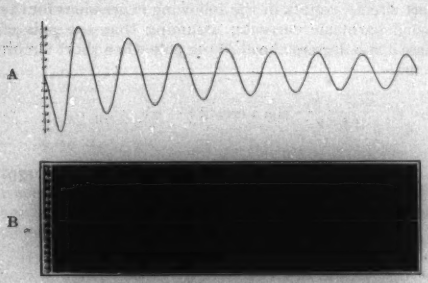


FIG. 16—TRANSIENT ARMATURE CURRENT IN PHASE $A$ ON BALANCED THREE-PHASE SHORT CIRCUIT FROM LOAD, MINIMUM INITIAL ARMATURE LINKAGES WITH PHASE $A$. SALIENT POLE MACHINE—LAGGING LOAD—0.208 POWER FACTOR $\delta$ = 3.5 DEG.

Curve $A$. Calculated curve
Curve $B$. Test curve

Equation:

$$i_a = 1.99\cos(t-86.5)+5.35\,\epsilon^{0.0658t}\cos(t-86.5) - 2.02\,\epsilon^{-0.1773t}\cos(2t-90)$$

$$\left(t-\alpha-\frac{2\pi}{3}\right)-e_t'\frac{x_d'+x_q}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos$$

$$\left(\delta+\alpha+\frac{2\pi}{3}\right)+e_t'\frac{x_d'-x_q}{2x_d'x_q}$$

$$\epsilon^{-\sigma_a t}\cos\delta\cos\left(2t-\alpha-\frac{2\pi}{3}\right)-e_t'\frac{x_d'-x_q}{2x_d'x_q}$$

$$\epsilon^{-\sigma_a t}\cos(\delta+90)\cos\left(2t-\alpha+90-\frac{2\pi}{3}\right). \quad (24)$$

$$i_c=\frac{e_d'}{x_d}\cos\left(t-\alpha-\frac{4\pi}{3}\right)$$

$$+\left[\frac{e_t'\cos\delta}{x_d'}-\frac{e_d'}{x_d}+i_d'\right]\epsilon^{-\sigma_f t}\cos$$

$$\left(t-\alpha-\frac{4\pi}{3}\right)-e_t'\frac{x_d'+x_q}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos$$

$$\left(\delta+\alpha+\frac{4\pi}{3}\right)+e_t'\frac{x_d'-x_q}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos\delta\cos$$

$$\left(2t-\alpha-\frac{4\pi}{3}\right)-e_t'\frac{x_d'-x_q}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos(\delta+90)\cos$$

$$\left(2t-\alpha+90-\frac{4\pi}{3}\right) \quad (25)$$

The decrement factors, $\sigma_a$ and $\sigma_f$, for the armature and field windings respectively are the same as those already derived for the case of dead short circuit under no-load conditions. They are, therefore, given by Equations (28) and (23), Appendix A.

In order to satisfy the condition of continuity of current at the instant of short circuit, *i. e.*, the current cannot change in value without a lapse of time, putting $t = 0$ in Equation (23) must reduce the equation to the value of the load current at the instant of short circuit. Doing this results in,

$$i_a = i_d'\cos\alpha+\frac{e_t'\sin\delta}{x_q}\sin\alpha$$

$$= i_d'\cos\alpha+i_q'\sin\alpha \quad (26)$$

which is the value of the load current at the instant when short circuit occurs.

## FIELD CURRENT

The induced field current is obtained by multiplying the direct axis components of the transient armature currents by the difference between the synchronous and transient reactances of the direct axis. That is, extracting the direct axis components of current from Equation (23) and multiplying by $(x_d - x_d')$ gives,

$$\Delta I=(x_d-x_d')\left\{\frac{e_t'\cos\delta}{x_d'}\epsilon^{-\sigma_f t}\right.$$

$$+e_t'\cos\delta\frac{(x_d'-x_q)}{2x_d'x_q}\epsilon^{-\sigma_a t}\cos t$$

$$\left.-e_t'\cos\delta\frac{(x_d'+x_q)}{2x_d'x_q}\epsilon^{-\sigma_a}\cos t\right\} \quad (28)$$

The direct and second harmonic terms of Equation (23) both represent m. m. fs. which pulsate over the poles in accordance with the variation, $\cos i$. This factor therefore, enters into the expression. Reducing (28) and adding the sustained current, $e_d'$, gives the total field current,

$$I=e_d'+e_t'\cos\delta\left\{\frac{x_d-x_d'}{x_d'}\right\}\epsilon^{-\sigma_f t}-e_t'\cos\delta$$

$$\left\{ \frac{x_d - x_d'}{x_d'} \right\} \epsilon^{-\sigma_a t} \cos t \qquad (29)$$

## Nomenclature

All armature currents are expressed as fractions of the peak value of normal armature current.

All field currents are expressed as fractions of the field current corresponding to open circuit, normal voltage at normal frequency.

All voltages are expressed as fractions of the peak value of normal voltage.

Time is expressed as a fraction of the time corresponding to one electrical radian at normal frequency.

Reactance and resistance are expressed as the ratio of the voltage drop due to normal current to normal voltage.

$A_d$ = m. m. f. in the direct axis, produced by a balanced polyphase current.

$A_q$ = the similar value of m. m. f. in the quadrature axis.

$e_t$ = terminal voltage with the machine under short circuit through external resistance.

$e_t'$ = terminal voltage before short circuit with the machine under load.

$e_o$ = open circuit terminal voltage before short circuit.

$e_d'$ = nominal voltage before short circuit.

$e_d$ = nominal voltage when the machine is short-circuited.

$\Delta e_d$ = increment in nominal voltage due to the suddenly induced field current when short circuit occurs.

$i$ = balanced three-phase armature current.

$i_a$ = armature current in phase $a$.

$i_b$ = armature current in phase $b$.

$i_c$ = armature current in phase $c$.

$i_d$ = component of short-circuit armature current in the direct axis.

$i_d'$ = armature current in the direct axis before short circuit.

$i_q$ = component of short-circuit armature current in the quadrature axis.

$i_q'$ = armature current in the quadrature axis before short circuit.

$I$ = field current.

$\Delta I$ = induced field current.

$l$ = inductance of the armature circuit, in general.

$L_o$ = inductance of the field circuit with the armature open-circuited.

$r$ = total resistance, internal and external, of the armature circuits.

$r_a$ = internal resistance of the armature.

$R$ = resistance of the field circuit.

$t$ = time (numerically equal to elapsed radians).

$T_a$ = time constant of the armature circuits.

$T_f$ = time constant of the field circuit.

$T_{of}$ = time constant of the field circuit with the armature open-circuited.

$x_d$ = three-phase, line-to-neutral, synchronous reactance, direct axis.

$x_d'$ = three-phase, line-to-neutral, transient reactance, direct axis.

$x_q$ = three-phase, line-to-neutral, synchronous reactance, quadrature axis.

$x_q''$ = three-phase, line-to-neutral, transient reactance, quadrature axis.

$\alpha$ = displacement between armature winding axis and axis of field pole at the instant of short circuit.

$\delta$ = displacement angle of the direct axis nominal voltage from the terminal voltage.

$\omega$ = $2\pi f$, where $f$ = normal frequency.

$\psi_a$ = flux-linkages in phase $a$.

$\psi_b$ = flux-linkages in phase $b$.

$\psi_c$ = flux-linkages in phase $c$.

$\psi_{da}$ = flux-linkages in the armature due to the m. m. f. in the direct axis.

$\psi_{qa}$ = flux-linkages in the armature due to the m. m. f. in the quadrature axis.

$\sigma_a$ = decrement factors of the armature circuit.

$\sigma_f$ = decrement factor of the field circuit with the armature short-circuited.

$\sigma_{of}$ = decrement factor of the field with the armature open-circuited.

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## Discussion

**L. A. Kilgore:** In this paper the authors have treated very thoroughly the case of three-phase short circuit of synchronous machines without dampers. The majority of machines, however, have damper windings or a solid rotor.

As the authors have suggested, it is possible to substitute direct and quadrature subtransient reactances for the transient values, in Equations (13), (14), and (15), Appendix A, in order to calculate the components of current at zero time. To determine the decay of the difference between initial and transient currents it is necessary to know a subtransient time constant. This complicates the theory further, but it is necessary if we are to extend this method to determine the short-circuit currents within the first few cycles for machines with dampers.

The method developed here for calculating three-phase short circuit from load has been used by the writer and has been extended to determine the current in the first few cycles for a machine with dampers. This can be done by adding a direct and quadrature axis subtransient currents to the transient currents calculated by the method described.

The components of the initial fundamental current are determined by the flux trapped by the direct and quadrature axis dampers and may be calculated as follows: The direct axis component will be the direct axis component of terminal voltage divided by the direct axis subtransient reactance plus the direct axis component of load current. The difference between the initial direct axis current and the transient component decays according to the direct axis subtransient time constant. The quadrature axis component is the quadrature axis synchronous reactance drop divided by the quadrature axis subtransient reactance, minus the quadrature axis load current. This component decays rapidly to zero according to the quadrature axis subtransient time constant. The resultant current at any time is of course the vector sum of the direct and quadrature axis components.

It is contemplated that the general method of calculating short circuit from load and some discussion of the effects of saturation will be given in a later paper.

In applying the method developed in this paper it is necessary to evaluate the effects of saturation of the main magnetic circuit. The effect on the initial values is negligible, and the effect on the sustained values can be readily calculated, but some judgment must be used in determining the effect on the rate of decay. I should like to ask the authors if they have a definite method of taking this factor into account.

**Sherwin Wright:** The results of this paper are very interesting, and are given in a decidedly comprehensive and concise manner. There is a characteristic difference between large and small capacity machines upon which I wish to comment, inasmuch as the tests and calculations were made on small capacity machines.

Fig. 3 shows the transient armature current for a 20-hp. round rotor machine, where $\alpha = 80$ deg. (approximately zero flux linkages). The irregularity of this current wave is striking; it is due mainly to (rapid) decrement of the transient component (caused by induced field current) and to the second harmonic component, which is caused by direct current in the armature reacting on the field, which in turn reacts on the armature to produce a second harmonic.

The decrement factor $\sigma_f$ of the transient component is the decrement factor of the field circuit with the armature short-circuited. Incidentally, decrement factor is simply the reciprocal of time constant. Now the decrement factor $\sigma_f$ of a large machine with relatively low field resistance will be only a fraction of that of a small one, hence the transient component will last much longer in a large capacity machine. The second harmonic current depends, as the authors say, "upon the difference in the sub-transient reactances of the direct and quadrature axes, and may be practically eliminated by the presence of a good amortisseur winding."

With the above items in mind, I wish to point out that a common example of a round-rotor machine, namely, a steam-turbine generator, will have a transient armature current wave quite different from that of the round-rotor machine tested. The short-circuit decrement factor for the turbine-generator is very much lower than that of the 20-hp. machine; hence the transient component of current lasts longer. The solid rotor (and its wedges) is in itself a good amortisseur winding, hence the second harmonic component is relatively small. The result of these two changes is that the current wave is not irregular as is the wave in Fig. 3.

The general method of analysis used by the authors is of course applicable to the large steam-turbine generators as well as to the small round-rotor machine; however, it is thought that some of the differences between such types of machines, and the reasons for these differences, are worthy of note.

**C. A. Nickle:** As pointed out by Mr. Wright in his discussion, the effect of a solid rotor in a turbine alternator is to make the subtransient reactance in the quadrature axis more nearly equal to the corresponding reactance in the direct axis than would be the case for a perfectly laminated rotor. This will of course reduce considerably the second harmonic currents which accompany the d-c. component.

A corresponding effect could also have been produced in the small round rotor machine cited in the paper by merely short circuiting the unexcited phase of the two-phase rotor. However, this machine was used to illustrate an extreme case in order that the correctness of the equations derived in the paper might be more effectively demonstrated.

The effect of saturation in the main magnetic circuit, as mentioned by Mr. Kilgore, is to change slightly the initial short circuit current and also to reduce the short circuit time constant of the field circuit. Information concerning the magnitude of the effect of saturation on the short-circuit time constant is rather meager and, as far as the writer is aware, has not been satisfactorily evaluated.

# Operating Characteristics of Turbine Governors*

BY T. E. PURCELL† and A. P. HAYWARD†
Non-Member Non-Member

*Synopsis.—Surging has occurred on power systems whose transmission distance is small and load density high. The Duquesne Light Company of Pittsburgh, Pennsylvania, has experienced these surges. This paper outlines tests conducted to determine the influence the steam turbine governors have in starting or sustaining a surge condition. The conclusions assumed are:*

*1. The governor system installed at Colfax Power Station will not start system surging.*

*2. The governor system will not sustain load oscillations.*

* * * * *

## Introduction

THE system of the Duquesne Light Company of Pittsburgh has developed periods of severe surging on several occasions. During these surges, indications have been that one or more generators were out of synchronism for periods of time lasting from a few seconds to several minutes. These surges have sometimes followed severe faults on the 66-kv. transmission system, the generators apparently drifting apart during the low-voltage period, resulting in severe surges during recovery of voltage and at other times have followed the loss of excitation due to exciter failure or regulator action.

This condition is not peculiar, we are informed, to the Duquesne Light Company system, but is experienced on many others. Review of the experience of other operating companies gives the reported causes of similar disturbances as loss of excitation, loss of a unit with absence of reserve capacity, and in one case as governor action.

The Duquesne Light system (Fig. 1) has two major power stations located approximately 18 mi. apart. These stations are connected by a 66-kv. ring transmission system. Colfax Power Station of 260,000-kw. capacity supplies all of its output to the ring at 66 kv. This power is transmitted through the ring to various step-down substations which feed the distribution substations at 22 kv.

Brunot Island Power Station of 116,000-kw. capacity is located near downtown Pittsburgh. This station and the 66-kv. transmission ring are paralleled on an 11-kv. bus from which the power is distributed mainly through an 11-kv. cable system.

At the time the tests outlined herein were made, the 66-kv. busses at both Colfax and Brunot Island were tied together solidly. Later, 11-kv. synchronizing busses were installed at both stations. Since then, the north and south sections of the 66-kv. ring have been sectionalized at the power stations, the tie being made through the 11-kv. generator busses and the synchronizing busses.

The original turbine governors at Colfax Power Station were of the flyball type with a single oil relay actuating the primary valve mechanism. A system disturbance causing loss of a major portion of the Colfax load would result in the operation of the overspeed trips on the turbines, resulting in loss of the entire load.

The governors at the Brunot Island Power Station are of the same type. Faults on a section near Brunot Island do not cause severe overspeeding, due to the large number of 11-kv. feeders and bus reactors preventing a major loss of load.

The present governors installed at Colfax Power Station are the result of much experimental work on the part of the Westinghouse Electric & Manufacturing Company and Duquesne Light Company engineers. As a result of many load dumping tests,[1] the governors

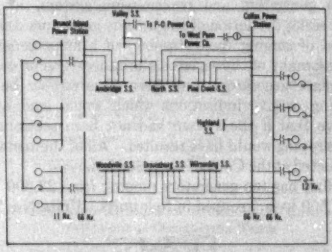


FIG. 1—SCHEMATIC DIAGRAM OF TRANSMISSION SYSTEM

were finally modified from the original type to the present type which consists of the flyball mechanism, an oil relay which in turn actuates a larger oil relay, giving the force to the mechanism of the primary valve. (Fig. 2.) Oil accumulators were added to the governor oil system to insure an adequate supply of oil at constant pressure during the period when the primary valve relays were operating. The net results of these changes have been to reduce the load on the flyball governor when tending to correct the valve setting and insuring an adequate oil supply to carry through the movement required for a change in speed conditions. (Fig. 3.) The reduction of duty on the flyballs has resulted in a much faster and more accurate following of the speed changes, allowing the governors to hold the turbines below the limit of the auto-stop setting.

During the course of several periods of severe system surging, the turbine operators have noted an apparent

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1. For references see Bibliography.

hunting of the governor mechanisms. This has been so noticeable at times that the operators have held the governor linkage and attempted by manual means to steady the surging. The governors having been made rather sensitive and in view of the observation of apparent hunting during system disturbances, it seemed reasonable and logical to determine if the governors were responsible or contributed in any way to sustaining or starting the surge conditions that have been noted.

It was the purpose of the tests described in this paper to determine the effect of the governors during observed periods of surging. The following tests were set up to either reproduce or indicate the true action of the governors.

The determination of the effect of the governors during periods of severe surging involved the knowledge of the natural period of oscillation of the governor system and the natural period of oscillation of the complete system. The first series of tests was conducted with the view of determining the natural periods of the turbine governors, the second series, the natural period of oscillation of the complete system, *i. e.*, the combined turbo generators and transmission system, and the third series the action of the turbine governors during a period of surging (pole slipping) of a main generator. During many of the severe disturbances, one or more of the main generators have been observed to be pole slipping or give indications which would lead one to believe that if the system had not been sectionalized pole slipping would have resulted. All of the tests were conducted at the Colfax Power Station.

Colfax has ten generators ranging from 23,600 kv-a. to 48,500 kv-a. grouped in four units. Units No. 1 and

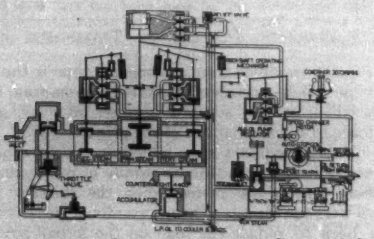
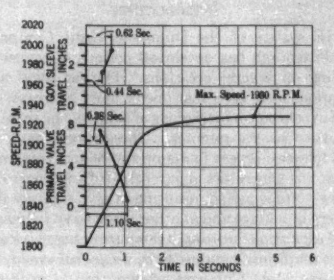


Fig. 2—Schematic Diagram of Flyball Governor System

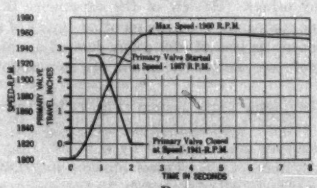
No. 2 each consist of a high-pressure turbine, exhausting to two low-pressure turbines, each having a generator of 23,600 kv-a. connected to it. The high-pressure turbine governor normally controls the load for the entire unit. Units No. 3 and No. 4 each have two single shaft turbo generators of 35,300 and 48,500 kv-a. respectively, Unit No. 4 having the oil relay type of governor[2] (Figs. 4 and 5).

Brunot Island has seven generators, five single shaft turbo generators having a capacity of 18,000 kv-a. each and one cross compound of 47,200-kv-a. capacity. Each element of the compound unit is rated at 23,600 kv-a.

The natural period of the governor was found in the following manner. A turbo generator was loaded to a predetermined value varying from one-quarter to full load. With the load adjusted and all other conditions normal, the turbine operator would grasp the governor sleeve linkage and depress it until the load on the




A




B

Fig. 3

A—Flyball Governor Performance—Load Dumping Test

Test on 3-B element, rating 35,300-kv-a., 85 per cent power factor, 12,000 volts, 1800 rev. per min., governor regulation, 4 per cent, 40,000-kw. load dropped by opening the generator oil circuit breaker, zero time on curve.

Load, 40,000 kw.
Throttle steam pressure, 260 lb. ga.
Throttle steam temperature, 650 deg. fahr.
Primary steam pressure, 252 lb. ga.
Secondary steam pressure, 248 lb. ga.
Tertiary steam pressure, 248 lb. ga.
Vacuum, 28.09 in.
Exhaust temperature, 80 deg. fahr.
Governor oil pressure, 78.7 lb. ga.
Bearing oil pressure, 13.2 lb. ga.
Aux. spring setting, $3\frac{1}{2}$ in.
All (four) heaters and evaporators are out of service

B—Oil Relay Governor Performance—Load Dumping Test

Test on 4-A element, rating 48,500-kv-a., 85 per cent power factor, 12,000 volts, 1800 rev. per min., governor regulation 4.5 per cent, 45,000-kw. load dropped by opening the generator oil circuit breaker, zero time on curve

Throttle pressure, 256 lb. ga.
Primary steam pressure, 250 lb. ga.
Secondary steam pressure, 246 lb. ga.
Vacuum, 28.1 in.
No. 1 heater steam pressure, 156 lb. ga.
No. 2 heater steam pressure, 52.3 lb. ga.
No. 3 heater steam pressure, 15 lb. ga.
No. 4 heater steam pressure, − 21.3 in.
Speed changer oil pressure, 32 lb. ga.

machine had increased approximately 10,000 kw. beyond the load setting of the governor. The governor flyballs would then adjust themselves to counteract the external force applied and the primary valve would adjust itself to a new position. The release of this external force resulted in a change of position of the flyballs with a tendency to oscillate about their new position until a state of equilibrium had been reached. This change in

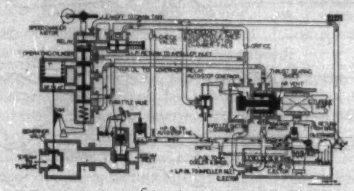


Fig. 4—Schematic Diagram of Oil Relay Governor

governor position reduced the amount of steam delivered to the turbine, resulting in a load swing on the generator. It was believed if this load swing on the generator and the natural period of oscillation of the turbine governor corresponded in the proper phase and time, it would be possible for such a disturbance to amplify itself to such a degree as to cause the generator either to pole slip or start severe surging of the entire system.

An oscillograph was used to record the oscillation and power output of the various units during the test.

Slide wire potential dividers were connected to the governor sleeves and primary valve pistons of all of the typical units in the station. The movement of the

Fig. 5—48,500-Kv-a. Turbo Generator, Showing Oil Relay Governor

various parts resulted in a change of potential across a circuit which being connected to an oscillograph element would properly record the increment. Other quantities recorded were single-phase output, bus voltage, and field amperes of the generator under test. The set-up was so arranged that the action of the governor on one unit might be recorded on the same film with the corresponding reaction of the governors on the adjacent units, (Fig. 6).

The results of these tests indicated that on Units No. 1 and No. 2, the governor period varied from 100 to 135 cycles per minute and the load swing period from 80 to 87.8 cycles per minute. Units No. 3 and No. 4 indicated an average period of 143 cycles per minute for the governor oscillation and 62.2 cycles per minute for the load swing. The discrepancy between the period of the load swing for Units No. 1 and No. 2 and Units No. 3 and No. 4 can be accounted for by the difference in moments of inertia of the revolving masses. The moments of inertia of 1-B and 2-B are 220,800 lb. ft.,$^2$ 3-A and 3-B have a moment of inertia of 560,000 lb. ft.,$^2$ and 4-A and 4-B have moments of inertia of 586,000 lb. ft.$^2$

The ratio of the governor period of oscillation to the load oscillation for units 1 and 2 is 1.45 to 1. For units 3 and 4, the ratio is 2.3 to 1. In order for one system to support an oscillation in another system, the two must be in resonance, that is, have the same period; also, the two oscillations must have a phase displacement of 180 deg. This condition can be met on the turbine if the natural period of the governor is the same as the natural

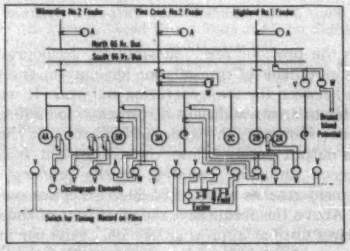


Fig. 6—Schematic Diagram of Oscillograph Connections —Governor Oscillation Tests

period of the rotor and the time lag between the governor action and the effect of the steam on the rotor equals one-half of this period. If it is assumed that the governors oscillate at their natural period, the effect on the turbine due to the variation in steam flow would not tend to sustain oscillation of the generator output, due to the difference in frequency between the governor and rotor periods. Also the tests indicate that the governor mechanism comes to its position of equilibrium after an impulse within one and one-half cycles of governor oscillation. (Fig. 7.)

The second series of tests was devised as a means of checking the natural period of the complete system. A device was constructed and installed on element 3-B which replaced the link between the primary valve oil relay and the link from the governor oil relay. This arrangement allowed the primary valve to be moved from one extreme to another independent of the governor setting or condition on the governor system. It was believed that if a load oscillation having the same frequency as the complete system could be established on one of the main units, surging would result and could

be readily recorded. The possibility of introducing a surge on the system such as might result in a major disturbance was considered. To avoid this, the oscillator mechanism was constructed so that both the load swing and the frequency of the swing could be manually controlled. The test was conducted by introducing a load swing of approximately 10,000 kw., the frequency of this swing being varied from 30 cycles per minute to over 130 cycles per minute.

The same set-up records were obtained on this test

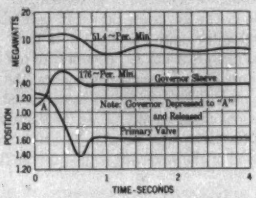



Fig. 7—Governor Period Test—3-B Element

as on the previous one. In addition, oscillograph records were made of transmission line current and phase angle between the two generating stations. It was not possible to create sufficient disturbance to oscillate the system. However, the tests did indicate that the generator output closely follows the steam input from low frequency until the variation in the primary valve movement reaches a period of 60 to 70 cycles per minute. Above this frequency, the amplitude of the swing decreases until at approximately 100 cycles per minute the steam variation becomes too fast to effect the output (Fig. 8). This point checks the statement made as a result of the previous tests that if the governors did

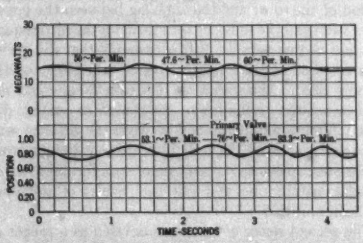



Fig. 8—Curves Obtained on System Oscillation Tests

oscillate, their period would be too fast to have any appreciable effect on a load swing.

The third series of tests was conducted to determine the governor action during pole slipping of a main unit. The resulting system disturbance was recorded with records of field amperes, field voltage, stator amperes, single-phase watt output, transmission line current, high-tension bus voltages, phase angle between generating stations, and governor action on adjacent units. The pole slipping was accomplished by adjusting the field current until the generator at full rated load, had unity power factor. The field was then gradually lowered by means of the face-plate rheostat until the

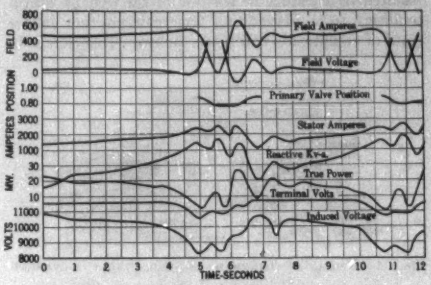



Fig. 9—Curves Obtained from Pole-Slip Test

current from the stator tended to increase at a rapid rate, indicating the start of a pole slip. The field was then given a slightly lower value and all adjustments discontinued. Approximately ⅛ to ½ of the field rheostat was in series with the field during the pole slipping. In every case of this nature, the first pole slip would take place very slowly, then there would be an appreciable time or interval during which no surging would occur, then a second slip would take place. The

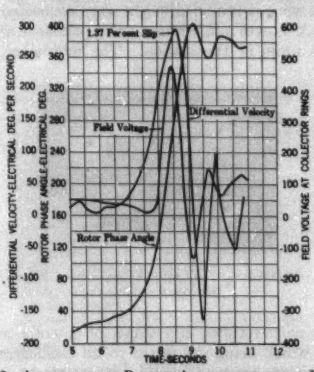



Fig. 10—Analysis of Phase Angle between Induced Voltage and System

third slip would occur at a shorter interval, the period gradually decreasing, (Fig. 9). During operations of this type, strengthening of the field during the period of steady operation resulted in the machine's pulling into step and remaining in step. It was also found, by trial, that tripping the turbine throttle allowed the generator

to pull into step. The torque produced by the turbine having been removed, the generator synchronizing torque notwithstanding its weak field, was sufficient to pull the rotor into step with the system and continue to operate in synchronism. Two factors were determined, first, that a large turbo generator out of synchronism may be pulled back onto the system without a reduction in throttle setting by carefully increasing the field current at the proper time, provided the surging has not become too rapid. Second, that a generator which is pole slipping may clear itself of that condition if the turbine torque is removed or reduced.

The records taken of these tests were with the same oscillograph set-up used for the second series of tests. In addition, recording wattmeters, ammeters, and voltmeters were installed on a common panel, high-speed motion pictures being taken of the assembled instruments. From a technical standpoint, little could be gained by attempting to analyze the performance of indicating meters. It is well known that the values of surge current are so high and the frequency is so rapid, that the meters do nothing but swing back and forth from zero to perhaps full scale. However, during periods of surging, meters are the only indication the operator has to tell him what is happening to the equipment. Therefore, it seemed advisable to take the motion picture records and to compare the visual observations of the operator with the oscillograph records. The oscillograph records substantiated observations, proving that during pole slipping, the power factor changes from lead to lag. This is true of a distributed field turbo alternator and is caused by the induction generator effect which prevents the power output from approaching zero during pole slipping conditions.

Of the records obtained during the pole slipping tests, those showing the angle between the rotor and the field of the stator are of interest. (Fig. 10.) An analysis of this displacement angle gives an indication of the rate of change of speed of the rotor during the pole slipping period. Also, when compared with the kw. output from the stator and the position of the primary valve, it gives a very definite indication of the true governor action during pole slipping of the unit.

From the oscillograph records, it appears that there is a positive power output at the time of maximum slip or differential velocity between the stator field and the rotor, and at this instant, the governor valve is at its minimum opening. The maximum power output, however, occurs at the instant the rotor passes through its next in phase position. At this instant, it is seen that the governor valve is just beginning to open. This condition indicates that the governors on the turbines follow the speed changes caused by pole slipping and attempt to reduce the steam input. Therefore, it seems that the governor by reducing the torque, will allow the generator to pull back into step and attempt to recover its load, but if at this instant, the cause of the original disturbance has not been removed, the generator will again poleslip.

## Conclusions

The period of the governor oscillation and the load oscillation on the generators do not have a time phase that would sustain a surge.

The natural governor period is fast enough to eliminate the effect of the variation in steam input on the load output.

The governors are sensitive enough to hold the turbine from overspeeding and tend to check the speed of the turbine during a pole slip.

The above conclusions are based on observations during a staged test. From these tests it seems fair to assume that on the turbo generators at Colfax, the governor oscillation can have no effect on the load output and the oscillation frequency of the load and governors are so far apart that the governor will not assist in sustaining a surge.

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## Discussion

**W. P. Dryer:** This paper, together with a preliminary article bearing on the same subject written last year by Mr. Purcell, sheds a welcome light on a somewhat hidden aspect of power system stability, the governing characteristics of large steam turbines during disturbances,—an aspect of system stability which hitherto has had little illumination.

After investigating during a period of some years the reports regarding the performance during system surges of the large steam units in this country, and after personally watching in actual service the governing actions of many such units during violent load changes, it became apparent to me that in times of such disturbances, there were going on at the steam end of the machine, governing changes that were somewhat analogous to the electrical transients occurring simultaneously in the alternator. In both cases unbalanced and fleeting conditions arise when a disturbance is made of an equilibrium previously existing between energy supplied and energy required. In the alternator a fugitive voltage develops and in the turbine, a fugitive speed. The characteristics of both transients are functions of time constants inherent in the design of the apparatus and are functions of the changes in energy.

On account of the similarity of those actions, I designate the governing processes going on during violent changes in a steam turbine as "Governing Transients," and six years ago inaugurated what I believe to be the first experiments on a large steam turbine alternator to determine the characteristics of these

transients. The unit selected for the experiments was a 30,000-kw., 17-stage machine. The general governing qualities of the unit were fairly well known, as several dozen similar units had been in service for some time. Instead of running the unit under actual load, it was decided in the experiments to simulate the load and to control all the factors so that an accurate history could be obtained of the transient conditions immediately subsequent to throwing on and off large blocks of load.

These experiments proved useful, as they showed what were the maximum speeds attained when different loads were suddenly thrown on and off the unit, and they showed how long was the period elapsing until conditions of equilibrium or steady running were resumed.

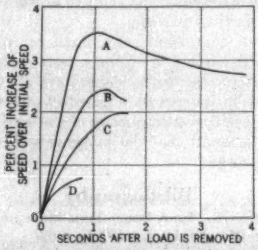


Fig. 1—30,000-Kw. Unit Running Steadily with 30,000 Kw. Load Before Removal of Loads

A—All load removed suddenly
B—22,500 kw. removed suddenly
C—15,000 kw. removed suddenly
D— 7,500 kw. removed suddenly

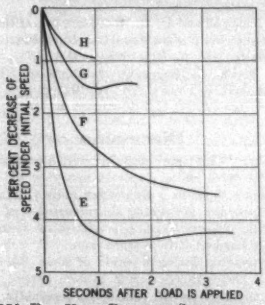


Fig. 2—30,000 Kw. Unit Running Steadily with No Load Before Application of Loads

E—30,000 kw. suddenly applied
F—22,500 kw. suddenly applied
G—15,000 kw. suddenly applied
H— 7,500 kw. suddenly applied

Briefly the experiments showed these facts, which are illustrated in Figs. 1 and 2:

1. That with the unit running steadily and fully loaded to 30,000-kw., on suddenly opening the generator circuit breaker, the turbine would accelerate quicker than the control valves could cut off the steam supply; in other words, that the unit would increase its speed by 3½ per cent in one second, and thereafter, it would proceed to slow down so that 2.8 seconds later it would run steadily, unloaded, and on the governor at a speed 2¾ per cent above initial speed. The governor regulation was 2¾ per cent.

2. That with the unit running steadily and fully loaded to 30,000 kw., on suddenly dropping off 15,000 kw., leaving 15,000 kw. load remaining on the unit, the turbine would not accelerate quicker than the valve could cut off the steam supply; in other words, the unit would increase its speed by 2 per cent in 1.6 seconds, when it would continue to run steadily on the governor at 2 per cent above initial speed.

3. That with the unit running steadily with no load, the sudden application of blocks of load allowed the unit to slow down to a slightly greater extent than the speed was increased when similar blocks of load were removed.

Most turbines, I realize, overshoot their governor regulation to a greater extent than is shown by the tests described above. However, to the extent that the changes in speed can be limited by proper governor design, to that extent will the units be able to handle themselves satisfactorily when system disturbances need every stabilizing influence on them that can be offered.

It would be well to enunciate here some basic requirements underlying the design of governing and valve systems of large steam turbines so as to enable them to carry the unit through violent system disturbances without the unit itself aggravating the trouble:

1. An accurate and instantly responsive speed indicator to move the pilot or relay valve.

2. A powerful and rapidly acting engine to move the control valves.

3. A proportioning or compensating device moved by the engine and reclosing the pilot or relay valve.

To meet the requirements outlined above, I have designed governor systems on the mechanical principles outlined below, and the subsequent operating performance of many of the largest units in this country so designed confirms my opinion of the soundness of these principles, and of the ability of such governing designs to take care of the turbines in times of system stress:

1. The speed indicator can be extremely accurate when made of the fly-ball type with a very powerful spring, and with knife edges for all the large forces. For the largest machines I used a governor spring having a tension of 4500 lb. With such a spring, and heavy fly-balls, the governor can be made instantly responsive, and need have no dashpot, which would necessarily tend to restrict the free action of the governor.

2. The engine for moving the control valves can be actuated wholly by oil or partly by oil and partly by springs. In order that this engine may act rapidly, it should have enough power to enable it to traverse its whole stroke completely closing or opening all of the control valves in one second or less, from the instant the pilot valve is suddenly thrown wide open. To obtain that rapidity of operation, I used oil pump pressures of 100 lb. to 125 lb. per sq. in., pumps of the greatest possible capacity and oil passages of very large cross sectional area.

3. The mechanism connecting the governors to the hydraulic system and connecting the hydraulic system to the control valves should be of the simplest possible arrangement, and should have very few parts.

One interesting innovation in the governor system used in the unit tested by the authors of this paper is the oil accumulator. It is my belief that some such device will have to be adopted for very large units to enable them to govern to the best advantage. The performance of one of the largest units recently installed in this country confirms this opinion. In this connection, I have believed for several years that it would be well to consider whether for large units it should not be better to take the oil pump off the unit itself and supply the oil from a central pressure storage system. Thereby, the governor could be made much more rapid, and so be able to better look after surges. Moreover, by that arrangement, the shutdowns due to pump and gear trouble could be eliminated, or at least minimized.

As the capacity of steam turbine alternators increases, it becomes more imperative to improve the inherent stability of operation, electrically and mechanically. I believe that governor designers should have a clearer appreciation of what is occurring

in their governing systems during the time of surges and before the governor takes complete and stable control.

**T. C. Rathbone:** The visible action of the governors during surges naturally led to the belief that they played a part in producing the unstable condition, because of the possibility of a resonance existing between the natural governor frequency and the electromechanical oscillation frequency of the system. We were particularly concerned because we had previously eliminated all possible damping to produce quick governor response in the effort to hold down the speed jump on sudden removal of full load. Among other things, the gag-pot and oscillator mechanism had been removed.

In the event that some damping would be found necessary to discourage governor oscillation, we had up our sleeve a one-way type of gag-pot so arranged that while permitting quick response during load removal, considerable friction would be developed in the other direction: There also existed the possibility of changing the natural frequencies of the governors, by altering the masses and elastic scales involved, thereby tuning them away from any given system oscillation frequency. In such a system involving several connected units, it is probable that the governors oscillate independently of each other, the maximum effect obtaining when several have the same frequency. That is to say, the masses and scales of the several governors do not constitute a compound elastic system in which each unit system plays a part in fixing the over-all natural frequency of the aggregate.

As the authors have described, it was found that the governors did not produce or maintain surges. It was also found that the governors possessed a surprising amount of damping—so much so that it was quite difficult to produce sufficient oscillation to determine the frequency with any precision. The motion was almost aperiodic. This unusual damping is due to the Coriolis component,—the forces produced under the principle of the conservation of angular momentum. In the present case, such damping operates in our favor.

The authors are to be commended for their initiative and courage in staging such an important and serious test on their system in the endeavor to find the answer to surge phenomena.

**C. A. Powel:** Messrs. Purcell and Hayward present to the Institute for the first time, tests showing the true nature of a disturbance variously described as instability, hunting, and surging. It seems, however, that a distinction should be made between them.

Instability is mostly an electrical disturbance in which the angle between two synchronous machines tied together through an impedance exceeds a critical value so that the machines pull apart. Hunting is usually an electromechanical phenomenon in which periodic pulses in the system input or output produce continuous oscillations of which the amplitude is determined by the damping properties present. Surging is a peculiar disturbance differing from the other two just mentioned, and which is well described by Mr. Hayward in the pole-slipping tests. If a generator pulls out of synchronism due to overload or the loss of field, the governor may be sufficiently sensitive and rapid to reduce the generator input so that it pulls into step again. The primary cause of the trouble, however, being still present, the generator again pulls out of synchronism. Thus, surging may continue for a long period of time.

**R. D. Evans:** Messrs. Purcell and Hayward give the results of tests on operating characteristics of governors, particularly in respect to their capacity to initiate or suppress a system disturbance. This naturally suggests a review of the performance of current and ideal forms of governors.

Considering first the steady load conditions, hunting phenomena may arise if the natural period of governor response corresponds with the electromechanical period of the system or with the period of pulsation of load or prime mover input. Under these conditions, the governor, while performing its normal function to control prime mover input, may, unless properly adjusted, constitute a liability to system operation.

Under changes in system loads, the increments of prime mover input are supplied by the units with sensitive governors of little "droop" and not in response to the distribution of the load increments. Consequently, automatic governors may cause the flow of large amounts of power over interconnections or over lines between various parts of a single system. This condition may not be harmful in itself but may lead to instability on the occurrence of faults. Hence, the present automatic governor control, even when modified for time-keeping purposes, leaves something to be desired from a system stability point of view. This suggests the control of prime mover input to limit the transfer of load between tie lines for normal operation and under fault conditions. The pole slipping tests described by Messrs. Purcell and Hayward are of interest in this connection. It has been suggested previously that on long transmission lines the prime mover input at the sending end should be reduced on the occurrence of faults so that greater loads could be carried without instability resulting from a system disturbance. Similarly, the prime mover input at the receiver end of transmission lines could be increased by special control to accomplish the same end.

Consider next the operation of the system in case synchronism has been lost. With respect to the machine, it is, of course, necessary to prevent excessive overspeed, which may be accomplished by special overspeed trips or by governor action in the conventional way; or overspeed may be limited by special prime mover input control, in which the input would be balanced against the output or operate on a sudden change in output. An alternative means would be to use an "out of synchronism" relay which would operate when a difference occurs between the frequency applied to the armature and the frequency corresponding to the rotation of the rotor.

Having prevented excessive overspeed, attention may then be directed to the problem of resynchronizing. Governor operation in the usual way will limit overspeed and eventually reduce the input to give the normal no-load frequency. At this time, however, there may be a considerable difference in frequency of rotation of the machines to be synchronized, which may make it impossible to develop sufficient synchronizing torque. Hence, it may be necessary manually or automatically to reduce the prime mover input until resynchronization takes place. It may be observed that, in general, the conditions for resynchronization will be obtained more rapidly by leaving the machines connected to the system, than by splitting the system and resynchronizing through breakers in the conventional way. Of course, such a process places exceedingly severe strains on all the electrical apparatus, and from this standpoint is objectionable. It may be noted that, in general, the special prime mover input control for improving stability will also operate to facilitate the resynchronizing of machines in case pullout actually takes place.

**A. P. Hayward:** In reply to the discussion of Mr. Dryer, I might state a similar series of tests covering the performance of the turbo-generators running free was conducted at Colfax during 1924 and 1925. Following these tests, the governors were revamped to include practically all of the features suggested. Oil accumulators were added to insure an adequate supply of oil to the governor valve operating cylinders. Oil ports were enlarged and oil relays were added to assist the flyballs during a movement of the governor linkage.

As originally installed, there was one oil relay between the flyballs and the primary valve. This allowed the flyballs to expend part of their force directly on the primary valve system. After the change, all of the force from the flyballs is available at a small oil relay, which in turn actuates an oil engine connected to the valve linkage. In this manner the oil pressure is used to move the linkage and valves, permitting the flyballs to respond to speed changes without dragging the valve linkage with them.

As a result of these modifications, the sensitivity of the governors

was increased, without changing the speed regulation. This increased sensitivity was thought to be a contributing cause of the system surges. The tests were devised to check this point.

The governor action of a turbo-generator when running free, as after a load dump, and the governor action of the same machine running with a system whose inertia is probably at least five to six times the inertia of the turbo-generator, which represents 10 to 15 per cent of the entire system capacity, is not to be compared. In one case, the speed changes are relatively large giving favorable governor action, in the other case the system does not allow rapid or wide changes in speed.

It has been shown in the tests that severe surges can exist on a generator without the change in speed during these surges affecting the governor system.

# Cathode Energy of the Iron Arc*

BY GILBERT E. DOAN†

Non-Member

*Synopsis.—The available energy at the cathode of the iron arc for welding in air, and the disbursement of this available energy to the cathode processes, are set up in balance-sheet form for purposes of study. Since many of the constants involved are not accurately known the results obtained are approximate only and indicate the probable order of magnitude of the quantities involved rather than the exact quantities themselves. The paper thus represents a preliminary survey.*

*The energy as heat at the cathode includes that from: (1) Ionic bombardment, (2) Ohmic resistance of cathode tip, (3) Radiation from the anode, (4) Combustion. The sum of the first three items should approximate one-half of the total energy input to the arc, (since the division of total arc energy between anode and cathode is nearly an equal one).*

*Item (1) is by far the largest heat source. But using values of $f = 0.825$ (fraction of current at cathode which is carried by electrons) as determined by Compton and by Günther-Schulze, and taking the cathode voltage drop $V_c = 9.0$ volts which is higher than $V_1$ the ionizing potential, ( = 7.83 volts, Mohler) this quantity, together with the smaller items (2), (3), and (4), is still too small to account for the observed rate of melting of the cathode. Possibly $\phi_+$, the heat of condensation of incoming ions, is not zero for this arc as Compton has shown for the tungsten arc.*

*Item (4), the heat developed by combustion of iron vapor is large, perhaps 77 calories, but the fraction of this heat returned to the cathode is small.*

*Heat Disbursement at Cathode: The principal consumption of heat at the cathode is by (5) melting of cathode, (6) evaporation of atoms at cathode, (7) evaporation of electrons at cathode, (8) dissociation of arc vapors, (9) radiation to anode and to air. Of the total heat disbursed by the arc more than half is consumed, as shown by measurement, by the melting of the electrode. The heat consumption for this melting is greater than the calculated value of total heat received at the cathode. The latter value is, therefore, not correct but need be revised using higher values of $V_c$ or $\phi_+$ or both. Some heat is consumed in vaporizing cathode metal, but not enough energy is available to vaporize all of it. Theories requiring the transfer of cathode material entirely in the vapor form are therefore untenable. No heat is lost from the arc by conduction through the cathode, because the rate of melting of the cathode outstrips the rate of heat conduction through the cathode.*

*On the other hand the calculated total energy consumption at the cathode corresponds closely to one-half the measured total electrical input to the arc and is, therefore, approximately correct, whereas the calculated input of energy to the cathode, using the present constants for $V_c$, $\phi_+$, $f$, etc., is about half what it should be. These values, therefore, seem to need revision before they are suited for this arc.*

THE iron arc in air, as used for electric welding, has been studied recently by P. Alexander, Weber, Eschholz, Green, and others because of its growing use commercially. Other arcs, such as the mercury arc and the carbon arc, are interesting from the point of view of the classical physicist and present an important field for the study of the electron and atom. In this field Langmuir, K. T. Compton, Richardson, and J. J. Thomson have contributed to the English literature, while Hagenbach, Seeliger, Schottky, and Günther-Schulze are among the recent contributors to the German literature. Most of the studies of the commercial arc have dealt, however, with the changes of the *materials* of electrode and of the welded article during the progress of the welding, and with the changes in chemical and physical properties of these materials by the welding process. The present paper deals with the changes in *energy* which accompany the operation of the commercial welding arc.

The basis chosen for this study is that of the energy supplied and disbursed at the cathode. The conservation of energy is assumed as a guiding principle. The method followed is one that has yielded fruits in the study of many other processes, physical and physicochemical, namely that of quantitative energy analysis. The present study consists primarily in an attempt at casting up the energy balance at the cathode of the arc, showing the sources of heat, as compared with the measured and calculated disbursements of this heat by the processes involved. The intimate understanding of the arc phenomena thus gained should indicate means for improvement in the welding process. Such a quantitative study seems absolutely essential to the further development of the industrial art here concerned. Obviously, the arcs drawn in flash welding and at the opening of electrical circuits by switches, etc., will also exhibit similar phenomena.

The present study is necessarily of a preliminary nature because of the lack of exact data for many of the calculations involved. It was undertaken in order to survey the cathode process as a whole, to discover the order of magnitude of each part of the process, and to decide just where experimental work is most needed. It has revealed several phases which need closer study, and such study has since been begun.

## Energy Conditions at the Cathode

The cathode conditions have been chosen for first study for several reasons. In the first place it has recently been recognized that the processes at the cathode are highly important in determining the choice of the electrode or welding wire to be used in commercial welding, and therefore, when the cathode processes are better understood, much of the present confusion in selecting commercial welding wire will, it is hoped, be eliminated. Also, it has been shown[1] that the conditions

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†Lehigh University, Bethlehem, Pa.

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1. For references see Bibliography

at the cathode of the arc are considerably less complicated and less variable than those at the anode, and are therefore more readily subject to study.

Fig. 1 shows the arc in outline with the polarity most commonly used for mild steel. Current flows through the cathode, across the arc-gap, and through the anode plate being welded. The tip of the cathode melts and the cathode globules thus formed fall into the anode puddle or crater. The freezing of this molten crater in the wake of the advancing arc constitutes the welding process. Some metal deposition in the crater probably also takes place as vapor in addition to the rain of globules. The total electrical energy supplied to the arc is, of course, the product of the total arc voltage and the current flowing. In the commercial arc this quantity is commonly 18 volts times 150 amperes or 2700 watts or 645 calories per second. Of this total arc energy that available at the *cathode* tip may be due to:

1. Heat developed at the cathode spot of the arc by ionic bonbardment.
2. Heat generated by ohmic resistance in the growing molten cathode globule and in the adjacent electrode wire.
3. Heat radiated to the growing globule from the anode crater.
4. Thermo-chemical heat of oxidation at and near the surface of the cathode globule in air, and from other minor sources.

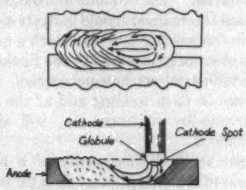


Fig. 1—Welding Arc

The discussion and calculation of each of these cathode heat sources will be taken up separately.

On the other hand the consumption of this energy at the cathode takes place chiefly by:

5. Melting of cathode, including latent heat of fusion and sensible heats of the solid and liquid metal melted.
6. Evaporation of atoms.
7. Evaporation of electrons from the cathode spot.
8. Dissociation of iron vapor and of $N_2$ and $O_2$ gas in the arc stream.
9. Radiation from the cathode crater.
10. Conduction of heat away from the globule through the cathode shank.
11. Gaseous convection and conduction.

These eleven items comprehend the origin and the disbursement of the chief energy quantites involved in the cathode process. Since the arc quickly reaches thermal equilibrium the sum of items (1) to (4) must equal the sum of items (5) to (11) and a thermal balance sheet may be drawn up. This equilibrium is the basis of the present study. Some of these quantities can be measured, at least approximately, such as the rate of melting of the cathode, the ohmic resistance of the globule, and the rate of conduction of heat from the cathode tip. Others may be calculated from known laws of electrical resistance, of thermo-chemical reaction and of heat radiation, using extrapolations of the physical constants for the extremely high temperatures involved, when necessary. The results of a quantitative analysis of these energy relations should be significant in two principal respects: (1) They should indicate the magnitude of the energy involved in each feature of the cathode processes and thus reveal more clearly their nature; (2) They should test in a rough manner the universality of the conclusions reached by Compton and others in their studies of the mercury arc and carbon arc. With these goals in view, we are ready to consider individually each of the four heat sources mentioned above.

## Heat Sources—Part I

*Item (1). Energy Developed at Cathode Spot of the Arc by Ionic Bombardment.* According to Compton[5] the heating of the cathode accompanying the maintenance of an arc is equal to:

$$(1 - f)\,(V_c + \phi_+) + F\,[f\,V_c - (1 - f)\,V_i]$$

where $(1 - f)$ is the fraction of the current at the cathode which is carried by incoming ions.

$f$ = the fraction of the current carried by electrons evaporated or pulled out from the cathode.

$V_c$ = the cathode fall of potential.

$\phi_+$ = the latent heat of neutralization of positive ions at the surface of the cathode.

$V_i$ = the ionizing potential of the gas in the arc.

$F$ = the fraction of the electron energy which is returned to the cathode by radiation after neutralization of the emitted electron by an ion.

Or, expressed in words, "The heating at the cathode is the sum of the heating due to bombardment of the cathode by incoming ions plus that heat due to the fraction of outgoing electrons which are returned to the cathode." The best values available for each of these items will be chosen. Since both Günther-Schulze[4] and Compton find $f$ between 0.55 and 0.70 as a maximum, considering both the mercury arc and the carbon arc, we shall adopt a mean figure $f = 0.625$ for the iron arc. Values of $V_c$ determined by the sounding method have been shown by Langmuir and Mott-Smith[6] to be incorrect and probably several volts too low. Recent direct measurements[7] of the cathode fall in a mercury arc corroborate this doubt and indicate, surprisingly enough, that the true cathode fall $V_c$ for the mercury arc is higher by several volts than the ionizing potential of mercury ($V_i = 10.4$ volts). By analogy

$V_c$ for iron may also be higher by one or two volts than $V_i$, the ionizing potential of iron, which is given variously as 5.3, 6.5, and 7.83[8] volts. The cathode fall $V_c$ for iron may, therefore, be as high as 9.0 volts. This value would seem more nearly to explain the observed rate of energy liberation in welding and will be adopted in these calculations: The third factor $\phi_+$ has recently been shown by Compton and Voorhis[6] to be very small and probably zero. Thus:

$$0.375 \times 9.0 = \frac{3.375 \text{ watts} \times 150 \text{ amperes}}{4.18} = 121$$

calories per second.

The presence of air ($V_i$ = about 16 volts) mixed with the iron vapor would tend to raise the cathode fall, and therefore, raise further the value of $V_c$ for the commercial arc. Even this figure, 121 calories per second, is rather small since this item probably is the largest single heat source at the cathode. Possibly $V_c$ will be shown later to be even higher than 9.0 volts. Perhaps also in the iron arc in air $\phi_+$, the heat of condensation of the incoming ions reaching the cathode is not zero, as Compton has shown it to be for the tungsten arc and applied to the mercury arc. The density of the ion stream certainly is very great in the iron arc and more of the incoming ions may reach the cathode un-neutralized and there give up their heat directly to the cathode. This heat of condensation might be a considerable heat source at the cathode.

If $N_2$ and $O_2$ are the principal conductors, then $V_c$ may be as high as 16 or 18 volts ($V_i$ for $N_2$ = 16 volts) and our value for (1) becomes $\frac{0.375 \times 16}{4.18} = 143$ $\times$ 150 amperes = 215 calories per second, which is rather high, as will be seen later. Furthermore the total arc voltage is only 18 volts, of which the anode fall is generally thought to be no small part. It would thus appear that the vapor which supports the discharge is not air but probably is iron vapor. This is in agreement with the theory of Cravens.[9] On the other hand it is conceivable that the anode fall be negative instead of positive. In this case it would be possible for $V_c$ to account for as much as 16 volts or more of the total 18 volts of the arc. The most trustworthy evidence indicates, however, that the anode fall in this arc is a small positive value, leaving considerably less than 16 volts for $V_c$. The value 9.0 volts, slightly above $V_i$ for iron, will be adopted in the absence of better data for these calculations.

The second member of the equation, containing $F$, cannot be large. This item is expressed by Compton as $F\,[f\,V_c - (1-f)\,V_i]$ where $f\,V_c$ is the energy gained by the electrons in the cathode fall space; $(1-f)\,V_i$ is the energy of these electrons which is consumed in ionizing the gas whose ionizing potential is $V_i$; and $F$ is the fraction of the remaining energy which is returned to the cathode by radiation, etc. "No determination of this fraction $F$ has been made, but it cannot be more than 0.5 and is probably much nearer 0.0, especially in the case of a rapidly vaporizing cathode, where a blast of atoms vaporized from the cathode would tend to carry away any high-speed atoms which might have been indirectly accelerated by the electrons. Radiation of this residual energy from the gas back to the cathode would be a small positive factor." (Compton.) Since no determination of this factor $F$ has been made, however, and since it cannot be calculated it will be necessary to omit from the calculations this item, probably a small one, until experimental data are available.

Examination of the remaining heat sources, items (2), (3), and (4) at the cathode will show presently that they are relatively small parts of the total energy supplied to the arc electrically, as compared with those just considered.

*Item 2. Heat Developed by Ohmic Resistance of the Globule and the Adjacent Hot Electrode Shank.* In addition to the ionic bombardment just considered the cathode globule is heated by the current flowing through it. The heat supplied by ohmic resistance of the globule itself might be rather high, because of the known high electrical resistivity of molten steel as compared with

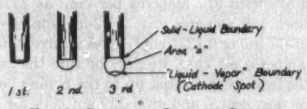


FIG. 2—STAGES OF GLOBULE GROWTH

that of solid steel, and will be considered first. In order to calculate this quantity we need to know the average length and sectional area of the globule, its mean temperature, and the specific electrical resistivity of the metal composing it.

## GLOBULE SIZE

An idealized sketch showing three stages in the growth of a globule is given in Fig. 2. The length of the path of the current through the globule increases gradually, therefore, from zero just at the moment after a globule has detached itself, up to length $L$ just before the globule separates. About 2 globules are formed and detached per second. The mean length of the liquid conductor, assuming a uniform rate of growth (it probably grows rapidly at first and much more slowly in the later states), is therefore $\frac{L}{2}$. Of course, when a very short arc is maintained, the globule, if undisturbed, will touch the anode before it detaches itself from the cathode, thus momentarily short circuiting the arc, and the globule diameter thus never exceeds the arc length, say 4 mm. Thus the average length would be 2 mm.

This length, 4 mm., assumes that the globule grows until it touches the anode and then is drawn over to it

by surface tension. But transfer does not necessarily take place in this way. The explosion of gas included in the molten globule may blow the globule off the end of the electrode before it has grown to the full length of 4 mm. The approximate figure, 2 mm., will be used, however, for the present.

### Globule Temperature and Resistivity

The specific electrical resistivity[10] of iron at 0 deg. cent. is 9.57; at 1000 deg. cent. it is 122.4. The mean temperature of the globule may be considered, for the present purpose, as the mean of the temperature at the solid-liquid boundary of the globule where it joints the electrode wire, *i. e.*, 1535 deg. cent. (the melting point of iron), and that at the liquid-vapor boundary of the globule where it joints the arc proper, *i. e.*, 2450 deg. cent. (Hagenbach and Langbein[11] give 2150 deg. cent.) the boiling point of iron. This mean temperature would be 1992 deg. cent. Due, however, to active circulation and convection currents in the globule, it is probably somewhat higher than this linear average.

For comparison with these figures it may be noted that the temperature at the cathode spot for the carbon arc with a current density of 127 amperes per cm.$^2$ is given by Compton, (1. c) as 3230 deg. cent.; for the tungsten arc with 977 amperes per cm.$^2$ as 3370 deg. cent. Since 150 amperes in a 5/32-in. iron electrode (area 0.01917 in.$^2$ or 0.1236 cm.$^2$) gives a current density of 1215 amperes per cm.$^2$, we may be sure the cathode spot in the iron arc is at least up to the boiling point of iron (2450 deg. cent.), and probably not very far above it, due to rapid vaporization of iron. The mean temperature of the entire globule is, therefore, between 1530 deg. cent. and 2450 deg. cent., with a mathematical average of 1992 deg. cent. Extrapolation of the electrical resistivity data for iron as given by Guertler shows at 1992 deg. cent. a resistivity of 225 ohms, nearly 25 times its resistivity at room temperature, and it is probably even higher due to a discontinuous increase in resistivity upon change of state.

### Area of Cathode Spot

If $k$, the specific resistivity of iron = 225, and $L$ the length of path $= \frac{1\,L}{2} = 0.2$ cm., then $S$, the mean sectional area of the globular conductor might be calculated, but, as will be evident later, an estimation will be entirely adequate for this purpose. Current enters the globule through the end of the cathode, sectional area 0.1236 cm$^2$. It leaves through the cathode spot. The area of the cathode spot for the carbon arc[12] is directly proportional to the current, that is the current density in the cathode spot is constant, *provided* the cathode is far enough removed from the anode. Otherwise heat radiation from the anode increases the area of the cathode spot. This latter condition obtains to a marked degree with the commercial iron arc using 150 amperes at an average arc length of about 4 mm. Its normal area, based on Günther-Schulze's experiments for the iron arc in air, would be $\frac{150 \text{ ampere}}{7200 \text{ cm.}^2}$ or 0.021 cm.$^2$, with widely separated electrodes. Accurate measurements of the area of the cathode spot for commerical "short arc" conditions have not been made. The arc length, 4 mm., is much shorter than the one used by Schottky and, undoubtedly, the area would be increased above the normal value 0.021 cm.$^2$ by radiation from the closely opposed anode. Measurements of the area of cathode spots can be taken, in spite of the rapid movement of the cathode spot, by the use of a revolving mirror and a camera. Such measurements for the iron arc would be valuable to the development of the science but have not yet been made. The area of a hemispherical globule of 3/16 in. diameter is 0.36 cm.$^2$ Visual observation of the cathode spot (5/32 in.) electrode (150 amperes) indicates that it covers only part of the lower half of the globule, but is approximately the size of the sectional area of the electrode 0.1236 cm$^2$. Green's photographs of the arc substantiate this observation fairly well. The figure 0.1236 cm$^2$. will therefore be used, although it is only a first approximation. If, therefore, a straight path of current through the globule of mean sectional area 0.1236 cm$^2$. and mean length $\frac{L}{2} = 0.2$ cm. is taken, we have

$$H = R\,I^2 = \frac{225}{10^6} \times \frac{0.2}{0.1236} \times 150 \times 150 = 8.20$$

watts or 1.96 calories per second, which is a rather small figure compared with 121 calories heat derived in Item (1) from the arc proper. Of course the globule probably becomes contaminated by oxides very rapidly and suffers an increase in electrical resistance from this cause, but since it is so rapidly detached (about two globules per second), the contamination has not time enough to be complete, and this source seems to remain a small contributor of heat to the cathode. If the cathode spot were twice as large and some collateral conduction through the globule were considered, we then would have even less heat from this source. It therefore becomes evident that the large bulk of the cathode heat is developed by ionic bombardment and only a fraction, say at the most 2 per cent, comes from the ohmic resistance of the globule to current flow. Changing the specific resistance of the material in the globule would, therefore, not be expected to improve appreciably the melting rate of the electrode.

The metal of the cathode is pre-heated before it enters the arc. This is done by the current flowing in the electrode shank and amounts to about 1.24 calories per second. (See under (9) "Conduction of Heat through the Electrode".) At the same time, the electrode shank would seem to extract some heat from the cathode globule by conduction. Both of these

conditions are considered together under Item 10.

*Items (3) and (9). The Heat Radiated to and from the Cathode.* Energy is radiated from a hot body to a cooler one in proportion to the fourth power of their absolute temperatures. Thus if the cathode and anode spots were both at the same temperature and were intimately opposed to each other the net loss from each would be nearly zero.

Actually, it has been shown experimentally[13] that the anode of the iron arc in air, if the iron contains less than 1 per cent carbon, melts at about the same rate as the cathode. Thus, if the temperatures and areas at anode and cathode are assumed equal, it is evident that the heat radiated by the anode crater to the cathode globule would be less than that lost from the globule only by the small amount of radiation from the upper and cooler hemisphere of the globule marked *a* in Fig. II, and from this upper hemisphere must be excluded the area of contact of globule to un-melted electrode.

The rate of radiation from a globule at temperature 1992 deg. cent. to surrounding air at 20 deg. cent. assuming an emissivity coefficient of unity, is, according to the Stefan-Boltzmann law, 36.4 calories per second per cm$^2$. of surface. The intensely hot cathode and anode *spots* would, of course, radiate much faster, but they are so intimately opposed to each other in the arc that little heat can escape as radiant energy. By considering the area of the cathode spot and the area of the junction of globule to wire separately we can compute the radiation from the remaining surface of the globule.

The area of a globule 3/16 in. in diameter is 0.715 cm.$^2$ The area of a half globule is, of course, 0.36 cm.$^2$ The rate of radiation from the cathode spot proper, itself of area approximately 0.123 cm.$^2$ at 2450 deg. cent. to air at 20 deg. cent. would be $55.2 \times 1.41 \times 0.123 = 9.65$ calories per second, but most of this radiation is received by the anode which, it is assumed, returns an equal amount to the cathode.

Now if we subtract from the total area of a full-sized globule, the area of the cathode spot 0.1236 cm.$^2$ and also the area of the contact of globule to cathode wire, 0.123 cm.$^2$ we have 0.468 cm.$^2$ left. For a half-grown globule assume the radiating surface is one-half or 0.234 cm.$^2$ Then if the rate of radiation at 1992 deg. cent. is 36.4 calories per second per cm.$^2$, we have $0.234 \times 36.4$ or 8.55 calories per second radiated from a globule of mean area to the air. The total radiation to air and to anode would be 8.55 plus 9.65 or 18.20 calories per second. The total radiation received by the lower hemisphere of the cathode from the anode will be taken as equal to that radiated from cathode to anode, *i. e.*, 9.65 calories. The net loss by radiation from the cathode is thus of the order of 8.55 calories per second or one per cent of the total arc energy and 3 per cent of the heat disbursed at the cathode, and is again rather small as compared with item (1).

*Item (4). Thermo-chemical Heat.* According to Spragen 13 per cent of the weight of cathode melted is lost in welding. The presumption is that it is lost by globule spattering and as vapor and mist. Iron in this finely divided condition and at this high temperature ignites spontaneously[14] in air. It probably forms a burning envelope just outside of the arc proper and the burning of this envelope will aid in heating the globule by radiating back to the globule some of the thermo-chemical heat produced in the envelope.

If all of this metal loss to air is considered to be in the form of vapor and mist then each second 0.0443 grams (see item 6) will burn and generate

$$\frac{0.0443 \times 195{,}600}{112} = 77.3 \text{ calories, according to the}$$

equation: $4\,Fe + 3O_2 = 2\,Fe_2O_3 + {}^3(195{,}600)$ calories, which thus appears to be one of the largest heat sources in the entire process. Not all of this heat is returned to the cathode, however, because the oxidation takes place not only at the cathode and in the arc stream itself, but also at the anode, most of it, perhaps, in the latter two places. Only a small fraction of this heat is carried to the cathode. If three-fourths of it burns in the arc stream and at the anode, and one-fourth at the cathode, then perhaps one-eighth of this thermo-chemical heat is absorbed by the cathode globule. It seems very unlikely that more is absorbed. This would give 9.7 calories per second delivered to the cathode from the burning of iron vapor and mist.

Furthermore, if this envelope of burning iron does not completely protect the molten globule from like oxidation, then a film of $Fe_3O_4$ would be expected to form on the globule itself, and be churned into the molten metal of the globule. The reaction probably is:

$3\,Fe + 2O_2 = Fe_3O_4 + 270{,}000$ calories and this reaction also contributes heat to the globule. Just how much oxidation goes on in the globule is not known but it is known that the nitrogen content increases considerably. The nitrogen content of arc-fused metal after deposition is known to be as high as 0.13 per cent as compared with 0.003 per cent in the cathode before fusion.[15] Evidently the metal is strongly acted upon by air during deposition.

This burning envelope which encompasses the entire arc zone is very probably the principal source of the light and heat which the casual observer notices in observing the arc. The actual cathode and anode spots are rather completely hidden from view. The effect of this hot envelope upon the weld is probably to diminish somewhat the very high temperature gradient at the anode, as well as to protect, partially at least, the depositing metal from rapid oxidation.

## Energy Balance at the Cathode

Heat received at the cathode (calories per second) with 150 amperes:

| | |
|---|---|
| (1) By ionic bombardment, etc. | 121.0 |
| (2) By ohmic resistance in the molten globule 1.96 and adjacent 1.24 electrode | 3.20 |
| (3) By radiation from the anode | 9.65 |
| (4) By oxidation of iron vapor and mist | 9.70 |
| | 143.55 |

Heat disbursed at the cathode (calories per second) with 150 amperes flowing:

| | |
|---|---|
| (5) By melting of electrode (including sensible heat) | 161 |
| (6) By evaporation of atoms | 12.6 |
| (7) By evaporation of electrons | 95.5 |
| (8) By dissociation of iron vapor and air | .. |
| (9) By radiation to anode 9.65 and to surrounding air 8.55 | 18.20 |
| (10) By conduction through the electrode shank | 0.00 |
| (11) By gaseous convection and conduction | .. |
| | 287.3 |

## Discussion of Heat Sources

The sources of heat at the cathode just considered indicate broadly, as the Balance Sheet shows, that we have some 143 calories per second available at this point. Of this total, 80 per cent or more is generated in the cathode itself by ionic bombardment and relatively little heat is received from outside sources such as radiation, burning of iron, or ohmic resistance. This discovery seems to limit any considerable increase in rate of melting to an increase in welding current or in cathode fall.

The calculation of item (1) is of course dependent upon values for $V_e$, $\phi_+$ etc., which are as yet not accurately known even for the mercury and carbon arcs upon which so much study has been expended. It is useful, however, to know the *order* of magnitude of this item for the iron arc and its relative part in the arc process. Refinement of the calculation can be made when more exact data are available.

Perhaps the chief source of heating other than ionic bombardment is that of radiation from the anode, which increases so markedly the area of the cathode spot over the isolation value of 0.021 cm.$^2$ given by Günther-Schulze. This would seem to indicate that the use of a very short arc would produce a lowering of the current density in the cathode spot. How much this affects the character of metal deposition is not known.

The heat generated by arc oxidation is a surprisingly large quantity. It is apparently equal to more than 10 per cent of the electrical input to the arc. It deserves careful study. If burned in the theoretical amount of air without losses, this envelope of burning iron would reach a temperature of 1965 deg. cent. Just how this envelope functions in blanketing the arc chemically and thermally, and the diffusion of heat from it, would be an interesting study.

## Heat Disbursement—Part II

*Item (6). Melting and Vaporization of Electrode.* The primary function of the cathode process in welding is to melt and vaporize electrode material and to deposit this metal in the anode crater. Both the rate of melting electrode and the loss of metal to the air during melting can be measured. These measurements will indicate the speed of welding which can be maintained and are therefore of practical importance. Also they will show how much of the cathode energy will be required in melting electrode and in vaporizing a part of it. These measurements were made in the Welding Laboratory of Lehigh University. They show, among other things, that the grade of electrode used has a large effect upon the speed of welding.

Under standard conditions as adopted in this study (5/32 in. electrode of mild steel, 150 amperes, 18-volt arc), No. 1 electrode melted at the rate of 0.39 grams per second. The loss to the air during melting was 10.6 per cent of the weight of electrode melted. Another type of electrode melted at the rate of 0.34 gram per second, with a loss of 10.2 per cent. These rates are for hand welding. The G. E. automatic welder gave values not much different from these. The value given by Viall in "Electric Welding" is 0.315 gram per second, while Spraragen gives 0.284 gram per second. This last value is, however, on an hourly basis and includes time for changing electrodes.

The heat required to raise 1 gram of iron from room temperature to its melting point, to melt it, and to superheat the molten iron to 1992 deg. cent. is 413.4 calories (Richards, "Metallurgical Calculations"). Thus for 0.39 gram there are needed $0.39 \times 413.4 = 161$ calories per second or for electrode No. 2, $34 \times 413.4 = 141$ calories per second. At once it is evident that the observed rate of melting calls for quite a large amount of heat at the cathode, and also it is apparent that the thermal efficiency of the arc in melting metal is good. It indicates clearly that more energy is present at the cathode than that shown by the calculations in Part I above. It corroborates the belief that $V_e$ for the iron arc in air is higher than the ionization potential of iron, as Compton has proposed. Since this rate of melting requires more heat than the calculations have shown to be available at the cathode, it is obvious that the calculations must be revised. The value for $V_e$ may be much higher than 9.0 volts. If it were as high as 16 volts, assuming that air is the ionizing gas, then 215 calories per second are produced by ion impact. This would supply the needed amount of heat. In the second place $\phi_+$ the latent heat of condensation of ions upon the cathode may be appreciable. Until these data are available no accurate correction can be made. The qualities of the electrode which influence strongly this rate of melting, such as coating of electrode, freedom from gases, etc., will not be considered here, but will be the subject of a separate paper.

A further consumption of cathode energy is required by the vaporization of part of the melted metal. This metal must be heated from 1992 deg. cent. up to the boiling point (2450 deg. cent.) and then vaporized This action would occur at the hottest part of the glo

bule, namely the cathode spot itself. The latent heat of vaporization of iron calculated by Trouton's Rule, is 1224 calories per gram. But not the entire 10.6 per cent of it occurs at the cathode. Probably at least half of it occurs at the anode and in the arc stream leaving only

$$\frac{0.106 \times 0.39}{2} = 0.0207 \text{ gram per second from the}$$

cathode. Of this total loss, 0.0207 gram, part is mist and part is spray, neither of which carries the latent heat of evaporation. If this mist and spray constitutes one-half of the total cathode loss then 0.0103 grams per second are actually vaporized, requiring $0.0103 \times 1224 = 12.6$ calories for the true evaporation of atoms at the cathode.

If it is considered that all the metal deposited by the arc is transferred as vapor, according to the hypothesis of Professor Slocum,[16] then at least $165 + 1224 \times 0.39 = 643$ calories per second would be necessary at the cathode. This figure is just about equal to the total energy input to the arc (18 volts $\times$ 150 amperes = 2700 watts = 645 calories per second), and the hypothesis is therefore very improbable. Some small part of the metal deposited at the anode is, however, unquestionably transferred through the arc as vapor, condensing upon the anode. We are unable to calculate the energy required at the cathode for the vaporization, only that fraction of the material which escapes to air and does not condense having been weighed. If the average globule size could be measured and the rate of globule deposition counted by an oscillograph, then the product of these two quantities would give the weight of metal transferred as globules. Subtracting this from the total weight of cathode melted would leave that which formed mist and vapor. Another method using a rapidly moving anode of polished surface has been suggested by Dr. Samuel Hoyt of the General Electric Company. This method is, however, still in process of development.

The efficiency of the process in melting cathode wire

is thus about $\frac{165}{645} \times 100$ or 25 per cent of the total

energy input. The rate of melting of anode is nearly the same, giving a total melting efficiency in the arc of 50 per cent. These rather high efficiencies are due to the concentration of heat at the desired point which is one of the distinct advantages of electrical heating in general.

*Item (7). Evaporation of Electrons at the Cathode.* The current at the cathode is carried partly by ions which impinge upon the cathode and partly by electrons which are evaporated from the cathode. The latent heat of evaporation of electrons $\phi_-$ is estimated by Thomas[17] at 5 volts. Compton[18] believes that this value is too high and that it should lie between 4 or 4.5 volts. This gives us for the value

$$f\,\phi_- = 0.625 \times 4.25 \text{ or } 2.66 \text{ volts}$$

$$\text{at 150 amperes } \frac{150 \times 2.66}{4.18} = 95.5 \frac{\text{calories}}{\text{second}}$$

The magnitude of this item, 95.5 calories per second, indicates again that, except for the melting action at anode and cathode, the fundamental processes of the arc and not the attendant ones are most important in accounting for its energy distribution.

*Item (8). Dissociation of Iron Vapor.* The atomic hydrogen arc as developed by the General Electric Company depends for its operation upon the dissociation of molecular hydrogen gas into atomic hydrogen at arc temperatures in the arc stream. Iron vapor is, however, already in the dissociated or non-atomic[19] state and, therefore, does not absorb any heat for this purpose. It seems quite probable from the low value of item (1) that either $N_2$ or $O_2$ is present at the cathode. If so, they would dissociate at these temperatures almost completely into the atomic state. The heat of dissociation of these gases is not known. As the atoms diffuse away from the hot zone, they re-combine and liberate this heat, part of it being returned to the cathode by radiation. Since the amount of these gases dissociated is not known and since the atoms re-combine a very short distance away from the cathode (due to their very high temperature of dissociation), thus returning a rather large part of the heat extracted,—this quantity will not be included in the heat balance.

*Item (10). Conduction of Heat through the Electrode and $I^2 R$ Heat Generated in it.* The cooler electrode shank near the globule extracts some heat from the cathode globule by conduction. This raises the temperature of the shank within a half centimeter of the globule to a visible red. If the room be dark, this red portion can be observed by removing the protective glasses from the eye immediately after the arc is broken. If this portion of the electrode be sectioned longitudinally after cooling, it shows a definite zone in which the heat has caused re-crystallization of the wire, and a measurement of the length of this zone (0.23 cm.) gives the temperature gradient in the wire from the globule contact at 1530 deg. cent., (the melting point), back to the re-crystallization boundary at about 1000 deg. cent. To calculate the rate of heat flow or loss by conduction under these conditions would be a simple problem, provided thermal equilibrium were permitted to establish itself. Actually, the melting back of the electrode is constantly causing this re-crystallization zone to advance into the cold shank of the electrode. Experience with continuous welding shows that the rate of advance of the wire by melting is faster than the rate of heat conduction through the wire, and that at a distance of say 2 ft. from the tip, no rise in temperature of the wire is perceptible. Therefore, no heat is lost from the

cathode by conduction, (if we except that small amount carried away by air convection). The process is simply that the metal of the shank near the arc is pre-heated by conduction from the globule and a moment later itself re-enters the globule and returns the pre-heat to it. Of course, if the rate of melting is slow enough, the re-crystallization zone becomes wider and under these conditions the rate of heat conduction may outstrip that of melting. But we shall consider the actual operating conditions only.

While extracting heat from the cathode by conduction from the arc, the electrode shank receives heat uniformly along its length, by its ohmic resistance to the flow of current, and delivers this heat as pre-heated metal to the arc. Near and in the re-crystallization zone the amount of this $R\,I^2$ heat is increased due to rise in temperature of the wire and accompanying rises in specific resistivity and may be considerable in amount. This condition also serves to pre-heat the shank just before it enters the globule. At room temperature 0.393 calories per second are generated in each centimeter along a 5/32 in. wire of mild steel carrying 150 amperes. In the half centimeter next to the globule, the mean temperature is near 765 deg. cent. $\left(\frac{1530-0}{2}\right)$, the mean specific resistivity is much greater (about 9 times) and as much as 1.24 calories per second may be generated in this section. This heat is a substantial contribution to the heat sources at the cathode and since this voltage drop occurs outside the arc an addition must be made for this amount. Added to the $I^2\,R$ heat from the globule proper, we have $1.96 + 1.24 = 3.20$ calories per second heat added to the globule from these sources.

*Item.* (11). *Heat Loss by Gaseous Convection and Conduction.* The loss of heat by gaseous convection and conduction from an arc maintained in still air is very small (Langmuir, *General Elec. Rev.*, March 1926) unless the arc be cooled by blowing it. The loss from the cathode may be negative and would be so if the surrounding gas were hotter than the cathode itself, which probably is the case in the iron arc. For these reasons this small item will be neglected in the present calculations.

## Discussion of the Balance Sheet

The outstanding result of the attempt to balance the energy account at the cathode is the appearance of a deficit of energy of about 156 calories. This makes the cathode account show only 45 per cent of the energy which must be present there during welding, as demanded by the measured rate of melting, etc. In attempting to find the source of error item (1) offers the best possibilities. Either $V_c$ or $\phi_+$ may be larger or $f$ may be smaller than is now supposed. It is hoped that more of these data will become available.

The total energy consumption at the cathode is 288 calories. This seems logical and is probably nearly correct. The total arc energy (150 amperes $\times$ 18 volts) is 645 calories per second. Of this total 10 per cent may be expended in the arc stream, (see Hart, "Welding" p. 37, also Compton[3]), leaving 580 calories at the two electrodes. Half of this at the cathode would give 290 calories which checks rather well with the 288 calories obtained by adding the items calculated in Part II. That just about half of the total energy will be at each pole has been shown by the practically equal rates of melting of anode and cathode. There seems to be little question, therefore, that on the one hand item (1) must be larger than that calculated, and on the other hand the sum of items (5) to (11), the total cathode energy consumption as calculated in this study, is very nearly correct.

There is great need for more careful measurement of several of the other quantities involved, and this will be accomplished gradually, both in this and in other laboratories. The "loss to air" could be collected, weighed, and analyzed. The area of the cathode spot with short arc conditions should be measured. The exact nature of transfer of metal, and the size of the globules would well reward close study since upon it depends an important step in the process.

## General Conclusions

The following conceptions of the cathode processes seem indicated by the present study:

1. That the energy consumption at the cathode, as here calculated, agrees closely with the total energy input to the arc and with the equal division 90 per cent of this energy between anode and cathode.

2. That the energy available at the cathode as here calculated is sufficient to account for only about half of the known rate of energy consumption.

3. That the principal heat quantities at the cathode are due to the arc phenomena proper, such as ionic bombardment and electron evaporation, with two exceptions, (1) the heat consumed in melting electrode metal, and (2) the heat contributed by combustion of iron.

4. That the transfer of metal from cathode to anode takes place chiefly as liquid iron, the energy available there being insufficient to vaporize it.

Incidentally the following conceptions result:

1. That the amount of radiation from the anode and cathode spots to the neighboring atmosphere is small. Most of the radiation observed comes not from the arc proper, but from the burning envelope about the arc.

2. That the current density in the cathode spot of a "short arc" as used in welding is much lower than the normal value of 7200 amperes per cm.$^2$

3. That practically no heat is extracted from the arc by conduction through the cathode wire. The rate of melting outstrips the rate of heat conduction. This applies to "bare" wire electrodes.

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## Discussion

**J. W. Barker:** Dr. Doan has treated a topic which is of growing importance in the development of electric welding. In order that we may attack intelligently the problems involved in increasing speed of welding or of improving the quality of the weld, we must know the factors which control the generation and consumption of heat energy in the arc, particularly at the cathode.

It seems to me the weakest spot is his assumption of 62.5 per cent of the current in the arc being carried by the electrons (p. 2. Item (1)). In Compton's paper on *The Electric Arc*, TRANS. A. I. E. E. Vol. XLVI, p. 876, in discussing Günther-schulze's work on the mercury arc, we find $f$ the fraction of the current carried by electrons to be from 25 per cent to 16 per cent. This is also confirmed by Slepian in his discussion of Compton's paper TRANS. A. I. E. E. Vol. XLVI, p. 879.

In the paper by Slepian on the *Extinction of a Long A-C. Arc*, presented at this convention, he again brings up this point that the fraction of the current carried by the electrons probably is very small indeed and he goes to Compton's compilation. We have no positive evidence for the iron arc as to the value of this factor $f$ the percentage of the arc current carried by electrons. We are forced to guess as Dr. Doan did, yet this one factor alone controls the major portion of the computation of heat energy generated at the cathode.

In the computations of heat energy made by Dr. Doan and summarized on page 728, we find that items (2), (3), and (4) are very small and even 100 per cent error in computing them will not affect greatly the total heat generated. They, however, are relatively more precise than item (1). On the other side of the balance sheet, item (5), that is, the sensible heat at the melting electrode, is relatively quite accurate, item (6) is not so precise nor is item (9), yet they are both small. Item (7), the heat disbursed by the evaporation of electrons, depends again on this value of $f$. Therefore the largest uncertainties occur in just those items involving $f$, one on each side of the balance sheet.

If all the factors of heat generation and consumption have been listed or at least the important ones, then can we not find $f$ by balancing the sheet, and either prove or disprove the thermal ionization theory by recomputing $f$. I have done that in a very casual way by assuming the fraction of the current carried by the electron is 0.3.

An assumption of $f = 0.30$ gives

| | | | |
|---|---|---|---|
| item (1) | 226 cal/sec. | item (5) | 161 |
| (2) | 3 | (6) | 13 |
| (3) | 9 | (7) | 46 |
| (4) | 10 | (8) | 18 |
| | 248 cal/sec. | | 238 cal/sec. |

This makes the energy balance fairly good. This again checks with Alexander's computation.

What physical reasons would influence this value of $f$?

A computation of the true thermionic emission from the cathode hot-spot using Dushman's modification of Richardson's equation

$$i = A\,T^2\,E^{-\frac{\phi e}{kT}}$$

and assuming $A = 60$ amperes/sq. cm./deg.$^2$, $T = 2700\ K$ (Doan gives temp. of hot spot as 2450 deg. cent. boiling point of iron) and $\phi$ as 4.2 5 eq. volts (Doan uses this value on page 729 in computing item (7) evaporation of electrons) and calling the area 0.1236 sq. cm. (given by Doan on page 726) we find about 0.5 ampere as the thermionic saturation current. Since the arc is carrying 150 amperes, this is about 0.3 per cent and almost negligible. This indicates to me at least that, in spite of the fact that we know it is very hot, we cannot have a very large thermionic current.

We must hence fall back on "pulling electrons" out of the cathode by an intense potential gradient. Now the positive iron ion is not as heavy as the mercury ion and is somewhat more mobile. It is far heavier than the carbon positive ion and far less mobile. Therefore we might expect that the potential gradient would be less steep than the gradient near the mercury cathode and steeper than that near the carbon cathode and in both of those arcs we know the condition somewhat better than in the case of the iron arc.

Furthermore the carbon cathode is much hotter than the iron cathode and hence would have greater pure thermionic emission per unit area. All this reasoning points to a value of $f$ for the iron arc between Günther-Schulze's 0.25 (computed by Compton & Slepian) for the mercury arc and Compton's 0.55 for the carbon arc and, therefore, my assumption at least of 0.30 is not unreasonable from a philosophical standpoint.

That we should be using a value of $f$ less than 0.5 can be justified also from the standpoint that the cathode drop $V_c$ does exceed the ionizing potential and hence Compton's argument on page 876 of his paper drops out.

I believe we will have the greatest difficulty in determining $f$ by any direct measurements but possibly a refinement of Dr. Doan's work will allow us to compute backward for it.

**J. C. Lincoln:** Dr. Doan's paper is based to a considerable extent on the assumption that the metal goes across the arc in globules.

If you will look at the oscillogram in Mr. Alexander's paper you will see that the oscillogram shows the voltage, dropping practically to zero every 10 to 30 cycles. The short circuit lasts for one or two cycles, indicating that at these times the arc is actually short-circuited by a globule of metal between the arc and the work.

We have been doing some work on electrodes in Cleveland and we found that when the arc is heavily covered no short circuits appear in the oscillograph reducing the voltage, indicating that with electrodes of this sort the metal goes across the arc either as a vapor or as very small particles, particles which are small enough so that no short circuit in the arc occurs. This demonstrates that in some types of electrodes no short circuit of

the arc ever occurs. It seems to me likely that in the regular bare wire electrode in which short-circuiting does occur a considerable portion of the metal goes across the arc either in the shape of vapor or in the shape of very small particles too small to short-circuit the arc.

If all metal went across the arc in the form of globules the periods of short circuit as indicated by the oscillogram would be approximately constant. For example, a short circuit should occur every 5 or 10 cycles and this period should be approximately constant because, as is well known, the rate of feed of the electrode in the arc is approximately constant. The oscillogram of Mr. Alexander's paper shows that sometimes the arc is short-circuited rather frequently and at other times 20 to nearly 30 cycles will occur between short circuits, indicating, it would seem to me, that during the time when no short circuit occurs the metal goes across the arc either in the form of vapor or very small particles which do not short-circuit the arc. Therefore, conclusions which are based on the assumption that all metal goes across the arc in the form of globules would have to be revised.

**William Spraragen:** I was very much interested in one of Dr. Doan's assumptions. He stated that there are about two globules that go across the arc per second.

This summer when I was in Germany I saw a film of the study of the arc made at very high speed; about 3600 pictures per second were made and with this high-speed motion picture film they were able to study the transfer of metal in the iron arc better than it had been done before. They found that the transference of metal takes place at a very rapid pace and, sometimes, the globule would cross the arc in 0.16 to 0.002 seconds and I think that on the average you might say that 20 to 30 globules went across the arc per second. However, I do not think that this matter seriously affects Dr. Doan's calculations. Those who are interested will find it very much to their advantage to study this paper and perhaps through experimentation or calculation arrive at more definite values for some of the assumptions that Dr. Doan makes in this paper.

**R. C. Mason:** It seems to me hardly reasonable to take $f = 0.625$ arbitrarily, as Dr. Doan does, without examining the sources from which the values of $f$ come. The methods employed in this paper have been applied to the carbon and the mercury arcs by Compton and by Gunther-Schulze. For the carbon arc, where thermionic emission can account for all the current carried by electrons, Compton did find $f = 0.63$. In the calculations, though, the value of the cathode fall was taken as 9 volts. Recently Nottingham (*J. F. I.* 206, 43, 1928) has found the cathode fall to be 5 volts. If this value had been used in Compton's calculations, $f$ would have come out 0.47. For the mercury arc Gunther-Schulze obtained $f = 0.55$ only by assuming $\varphi_+ = 7.1$, a value probably much too high, as later work of Compton and Van Voorhis shows that $\varphi_+$ is likely close to zero. Compton, using practically the same data as Gunther-Schulze, but setting $\varphi_+ = 0$, found $f = 0.16$ to 0.25. Only by assuming that no heat was lost by evaporation or radiation, and that electrons were pulled out by high fields so that $\varphi_- = 0$, could $f$ become as high as 0.70. It is not at all certain that the first assumption is justified, and if it is neglected, $f = 0.23$ to 0.36. Even if the cathode fall were as high as 12 volts, $f = 0.45$ to 0.54. So there is no basis for saying that $f = 0.625$ for the iron arc.

For arcs in which there can be no considerable thermionic emission, two theories have been developed to explain the way in which current is carried to the cathode: (1) The first, suggested by Langmuir, assumes the cathode fall to be concentrated in so small a distance as to give a gradient of millions of volts per cm.; such a high field may pull out electrons from even cold metals. (2) The second, due to Slepian, suggests that the current is carried to the cathode perhaps entirely by positive ions, arising from intense thermal ionization just in front of the cathode. An accurate knowledge of $f$, then, is of great importance in differentiating between these two theories; so, it is more to the point to take the data given by Dr. Doan and calculate a value for $f$.

In Dr. Doan's energy balance sheet, item (7), the heat lost by evaporating electrons, should be neglected. The value given would be correct only if the fraction $f$ of electrons escape by ordinary thermionic emission. By either theory of the arc, $f\,\varphi_-$ will be equal to zero, or at any rate will be very small, for by the first theory, $\varphi_-$ approaches zero, and by the second, $f$ approaches zero.

Incidentally, the latest values of the boiling point and the latent heat of vaporization of iron, as given by the International Critical Tables, Vol. 1, are somewhat higher than those used by Dr. Doan. If the new values are used, and the same methods of calculating employed as in the paper, the total heat in the molten iron and the heat lost by evaporation and by radiation are increased by about 10 per cent.

Putting $+\varphi_- = 0$, $\varphi_+ = 0$, and making the changes mentioned above, we have for the revised energy balance sheet:

$$\text{Heat received by cathode } \frac{(1-f)\,V_c\,i}{4.187} + 32.5$$

$$\text{Heat lost by cathode } \quad 225.85$$

By equating the two, we can solve for $f$. Thus

$$f = 1 - \frac{193.35 \times 4.187}{i\,V_c} = 1 - \frac{5.38}{V_c}$$

What value shall be taken for $V_c$? Nottingham has measured the cathode fall of a number of arcs at atmospheric pressure, and has found that the cathode fall is ordinarily the first ionization potential of the active vapor—usually the vapor of the cathode material—but in the normal copper arc, the cathode fall was the same as the second ionization potential of copper. Russell (*Astrophys. Jour.* 66, 250, 1927) gives as the most probable values of the first and second ionization potentials of iron, 7.83, and 16.5 respectively. We might not be surprised to find either of these as the cathode fall.

We can also get an idea of $V_a$ by calculating the anode fall by the energy balanced method. Dr. Doan believes that about half the total arc energy goes into the anode, as evidenced by equal rates of melting of the cathode and anode. At the anode though, considerable heat may be lost by conduction. As an upper limit, the energy lost at the anode may be found from the cathode energy calculated above, for total energy = (energy lost in arc stream + energy lost at cathode) + energy lost at anode.

Then, the anode energy lies between 290 and 354 calories.

All the current at the anode is carried by electrons, so almost all the energy input $= i\,(\varphi_- + V_a)$. Making minor corrections for heat inputs analogous to items (3) and (4), we have $i\,(\varphi_- + V_a) = 261$ or 325. Let $\varphi_- = 4$, then $V_a = 3.3$ or 5.1 volts. The voltage fall in the arc stream is about 2 volts. Thus, the upper limit for the cathode fall, as calculated in this way, lies between 12.7 and 10.9 volts. The cathode fall cannot correspond to the second ionization potential of iron, nor to the first ionization potential of oxygen or nitrogen.

Putting in these different values of $V_c$, we have for $f$,

| | |
|---|---|
| If $V_c = 7.83$ | $f = 0.31$ |
| $V_c = 9.0$ | $f = 0.40$ |
| $V_c = 10.9$ | $f = 0.51$ |
| $V_c = 12.7$ | $f = 0.576$ |

It seems very probable that $f$ is less than 0.5; so if we accept Langmuir's theory of the arc, some of the $1 - f$ positive ions must be created by means other than direct impact of the $f$ electrons coming out from the cathode. If $f = 0$, as by Slepian's theory, $V_c$ must equal 5.38; or else, if $V_c$ is larger than 5.38, then not all of the positive ions possess the full energy $V_c$ when they reach the cathode.

The chief experimental contribution of Dr. Doan's paper lies in the data for energy lost at the cathode. When we have an accurate value of the cathode fall of the iron arc, these data will

be of great assistance in finding an explanation of the mechanism at the cathode.

**K. T. Compton:** I agree with the men who have previously discussed this paper that the greatest value of Dr. Doan's work is in enabling us to estimate some of these unknown quantities which without careful work of this sort would have to be guessed at rather blindly.

Since my name has been attached to some of these theories, I feel a bit like a father with two children, because there are two theories involved, and I must say that I feel like a father with two children one of whom is only about half right. I hope I may be able to clarify the matter somewhat if we distinguish these two theories.

First was a theory I proposed in 1923 to the effect that the current was carried at the cathode by thermionic emission. About the same time Langmuir proposed a theory that the current at the cathode was due primarily to electrons which were pulled out by the very large electric fields existing at the cathode.

The difference in the heat balance is simply that on the thermionic theory every electron which comes out cools the cathode and on the other theory the electrons which come out do not cool the cathode, but are pulled out by an external agency; consequently, the theory as to the mechanism of the electric arc is involved in the present discussion of the heat balance only in the question as to how to evaluate one of the terms which enters into the balance equation.

The second theory, that of the heat balance at the cathode, is nothing less than the theory of conservation of energy. It must be right if we take all the facts into consideration and properly evaluate them.

If we assume, not as Dr. Doan did, that the electrons are evaporated, but assume that they are pulled out as seems to be the case in metallic arcs, as I pointed out in a paper of 1927 which has been referred to, then item 7 of Dr. Doan's paper which was given as 95.5 should be reduced to zero. If the electrons are only partially pulled out, the value would lie between 95.5 and zero. This correction is in a right direction to bring about a balance, but is not sufficient.

There is a second point, namely, regarding the quantity $\varphi_+$ which is the heat of neutralization of a positive ion at the cathode surface. Two or three years ago Dr. Van Voorhis and I presented experimental evidence which led us to believe that $\varphi_+$ is much less than its theoretical maximum value $V_i - \varphi_-$ and is perhaps nearly zero,—giving a reasonable qualitative reason for this. In drawing this conclusion we failed to recognize a new phenomenon which enters in and which has not yet been called to attention, and which I will now describe.

If we have a cathode surrounded by a region in which there is a cathode drop, being bombarded by positive ions that fall through the cathode drop, it has been considered in all preceding attempts that these positive ions became neutralized and at the same time gave up all their kinetic energy to the cathode. Recently we have found that is not correct, but when neutralized, ions have a tendency to go away with considerable energy. It is something which has been recognized in the cooling of hot wires by gases and described by the term "accommodation coefficient." A gas or vapor molecule that strikes a surface at a different temperature from that of the gas or vapor, does not come away necessarily in thermal equilibrium with the surface which it struck, but partially in equilibrium. In the present case they have come up with high speed and apparently they carry away some of their energy.

As far as this is concerned, this alone would make the heat balance worse, but it was this phenomenon and not the phenomenon that we thought it was that led us to the probably erroneous conclusion that $\varphi_+$ was negligible. In view of this newly discovered phenomenon, we now see that $\varphi_+$ may not be negligible but may be as high as 4.5 volts as an upper limit, so it must be somewhere between zero and 4.5. If we take this into account, item 1 can be raised to a maximum possible value of 169.

If we make these two corrections, the heat balance checks out 191 against 192. This apparent exact check is purely by accident, for I don't think it means anything as nice as that because the fraction $f$ of the current carried by electrons is the big unknown factor and I agree with the previous speaker that the great value of work of this sort at present is that it has given us some additional very carefully obtained data whose greatest use will be to aid in determining that particular quantity $f$.

**C. A. Adams:** Although theoretical analysis of the phenomena of the metallic arc is at the present time rather crude and subject to question from the quantitative standpoint, and although it may seem rather useless to the practical man, it is certain that the more we know about the reason why of these phenomena, the more likely we are to be able to solve the many troublesome problems of arc welding.

Dr. Doan assumed the resistivity of molten steel at 225 microhm-centimeters. After searching the literature very thoroughly, I failed to find any authentic experimental data on this subject, but as this resistivity was very important in connection with some high-frequency induction furnace work, I used the indirect method and adopted a value which checked with the test results on a considerable range of furnace sizes. This value was 166 microhm-centimeters. I do not claim that this is exact because of the approximations involved in the method of calculating the furnace constants. I do wish to point out that apparently no direct test has ever been made.

Mr. Lincoln spoke of our ideas in regard to the properties of cast steel as compared with forged or wrought steel. The facts seem to be that if you can get cast steel which is pure, that is, free from non-metallic inclusions and from excessive gas inclusions, there is no reason why it should not have the same properties as forged steel, assuming of course the same heat treatment. As a matter of fact, it has been found that large gun barrels made of centrifugal castings are superior to any forged guns.

Our problem in arc welding, therefore, consists in so depositing the metal (assuming it to have the proper composition) that it will be clean, that is, free from non-metallic inclusions and also from occluded gases and porosity. Owing to the conditions surrounding the arc welding process, it is not likely that we can reach perfection in this matter, but we are in fact approaching it close enough to produce welds substantially equal in properties to the parent or base metal. The use of the short arc, of fluxed electrodes, of the shielded arc, of the atomic hydrogen torch, are all for the same purpose, namely, to protect the metal in passing through the arc from contamination by the surrounding atmosphere.

**J. C. Lincoln:** Dr. Doan has given some very valuable theoretical considerations of what goes on in the arc. Two or three years ago Professor Compton had a paper before the Institute on the subject of what happened in the arc and as a discussion to Professor Compton's paper, I called attention to the fact that when a carbon is used as the negative terminal and a hollow water cooled copper electrode is used as a positive, a strange phenomenon results which we have called the electric torch. A long, very hot flame is projected through the hole in the hollow positive electrode and most of the heat of the arc is found in this flame. It is my belief that a further investigation of this phenomenon would lead to further knowledge of the mechanics of the arc and I hope that some one else besides myself will talk about this phenomenon in the near future.

**J. M. Weed:** The papers and discussions to which we have listened have illustrated the very small extent of our knowledge of the welding arc. For instance, in Dr. Doan's paper, we have Professor Compton's formula for calculating the energy of ionic bombardment for the general arc applied to the welding arc. If this formula is applicable to the welding arc its usefulness depends upon the possession of correct values of the various

constants which appear in the formula. Not one of these constants is known within wide limits. It is not strange, therefore, that the calculation for heat received by the cathode is only one-half of that calculated for disbursement.

Dr. Doan's calculation for heat disbursed from the cathode is based upon the assumption that practically all of the electrode metal is transferred to the work in liquid condition. I am sure that a large amount of it is so transferred, but I am equally convinced that a considerable portion is transferred in the form of vapor. This vapor forms at the electrode tip and condenses in the crater on the work. This phenomenon is the same whether the electrode is negative and the work positive as assumed in the paper or the polarity reversed. It is caused by the great thermal capacity of the work which results in a lower temperature in the crater than on the electrode tip. The continuous formation of vapor at the electrode tip results in an elevated vapor pressure at this end of the arc, while the condensation in the crater lowers the pressure here. The resulting pressure difference causes the vapor to flow from the electrode to the work, forming a draught which is sufficient to carry globules of the unvaporized molten metal with it even against the action of gravity in the case of overhead welding.

This conception of the way metal is transferred across the arc is practically forced on one who carefully observes and studies its action under various conditions. If this view be accepted, Item 6 of Dr. Doan's thermal balance becomes important and the discrepancy in the calculations will become considerably greater than that shown in the paper.

The conception of a practically equal distribution of heat between anode and cathode supported in Mr. Alexander's paper on the strength of experiments which bear no close relation to the welding arc and advanced in Dr. Doan's paper on the strength of data not given in the paper is one which I think may be seriously questioned. From one point of view the total heat of the arc, with exception of losses incurred, is delivered to the work. The condensation of metallic vapor from the electrode delivers its latent heat to the work, and a very important contribution is made by the superheated metal deposited from the electrode. From this point of view portions of the heat may be utilized over and over again as part of it is radiated back to the electrode tip and again delivered to the work. The importance of radiation is demonstrated by large differences in the melting rates of the electrode when welding on cold and hot plates.

If we consider the distribution of the heat in its initial generation, I have no doubt that this varies greatly with conditions, such as the composition of the electrode and the coating material used, the composition and the temperature of the work, the rate of travel along the work, the amount of welding current used and the length of the arc. It would certainly be dangerous to make a general assumption regarding the distribution of heat between the cathode and anode. Moreover, I have no doubt that all of the variables here mentioned, and some besides, will affect the values of the constants appearing in Compton's formula and most of the items appearing in Dr. Doan's calculations.

It is unfortunate that we have made so little progress in the investigation of the fundamentals of arc welding. These papers indicate some lines of attack, and will inspire renewed efforts along these lines.

**F. Creedy:** One of the speakers referred to the very high speed film that has been taken of the arc. I should like to ask whether that didn't show some high-frequency oscillations? For instance, in all papers we see this high-frequency vibration in arc voltage and it seems to me it hasn't received sufficient attention. In some of my oscillograms the frequency is about 20 cycles per second, far higher than the frequency with which drops pass. It is closely connected with the transmission of the iron vapor across the arc in the form of mist or spray and any further light that could be thrown on the subject by means of a film would be extremely valuable.

**G. E. Doan:** Professor Barker's suggestion that $f$ be calculated from the heat balance instead of using Professor Compton's value and from this calculating the iron arc heat balance, is interesting. This is exactly what Professor Compton did in reference No. 3, using the mercury arc and the carbon arc, and his conclusion about $f$ was used as a basis for the newer study of the iron arc. The suggestion is a logical one and, in view of the later work of Compton, the results of the calculation seem well substantiated. As presented, the heat balance forms a trial of the generality of the laws established for the other arcs, and shows the need of modification. I think the lower value of $f$ chosen by Professor Barker is quite probably much nearer the true value, as is indicated by the better agreement of the heat balance.

Mr. Lincoln assumes that the smaller fluctuations on the oscillogram of arc voltage are due to detachment of spray, the larger ones being due to detachment of larger globules. This may very well be the case. They might be caused, however, by other means such as Professor Creedy suggests, *i. e.*, by rotation of the arc stream about the globule.

To assume that all of the metal is transferred as vapor, even during the intervals between detachment of globules, would entail a drastic cooling of the electrode tip by the evaporation of iron. This would cool the tip and thus prevent globule growth and subsequent detachment of globules. Again I must say that insufficient energy is available at the cathode for continued evaporation of iron at the normal rate of deposit. It may, however, pass as mist or spray without this drastic cooling of the electrode tip.

Mr. Spraragen's remarks pointing out that rapid motion pictures reveal 7 or 8 globules passing per second would modify the calculations of "mean globule size." They would not affect the larger items such as rate of melting, rate of evaporation, etc. The study of the arc by motion picture records may, it is hoped, shortly reveal a better picture of the mechanism of transfer of metal.

Mr. Mason suggests using the heat balance of the iron arc as a basis from which to compute $f$, just as does Professor Barker. The results at which he arrives are clearly stated. If $V_c$ for the iron arc were known, the equation could be satisfactorily completed.

The light of recent investigations which Professor Compton brings to the problem, especially in the matter of the accommodation coefficient of gas or vapor molecules in the neighborhood of hot surfaces is most welcome. In this case $\phi_4$ need not be considered as equal to zero. With the corrections thus made possible a better balance is brought about. The work of Professor Compton and his school does in this instance, clearly illustrate the value of purely scientific measurements as the basis for engineering work.

The author had the same difficulties in finding a value for the resistivity of molten iron as has Professor Adams. The value finally used, 225, was obtained by linear extrapolation from the temperature coefficient for solid iron. Recently published data[1] for pure iron at 1550 deg. cent give 133, which is nearer to Professor Adams' figure of 166. This correction would change the total by only 1 or 2 per cent.

It does not seem logical to expect iron vapor (atoms) to evaporate at the electrode and condense at the member being welded. As Mr. Weed suggests, both are at a very high temperature. Mr. Alexander has shown in his paper that blasts originate in both poles and oppose each other. This might merely indicate, as one would expect, that the mid-section of the arc column was a region of lower pressure, rather than the member being welded. It would be interesting to explore the column with a pressure measuring device similar to a manometer.

1. Sauerwald, "Lehrbuch der Metallkunde," Berlin, 1929, p. 8.

# Electric Welding by the Carbon Arc

BY J. C. LINCOLN[1]

Member, A. I. E. E.

*Synopsis.—This paper discusses the butt welding of steel sheets by the carbon arc process. It explains first that autogenous welding is divided into two main classes, viz., gas and electric; that electric arc welding is divided into two classes, viz., metallic and carbon arc.*

*Gas and metallic arc welding in general require beveling of plates for butt welds while carbon arc welding does not. The controlling variables in carbon arc welding are (1) amperes in the arc, (2) voltage across the arc, (3) magnetic field about the arc, (4) atmosphere about the arc, (5) speed of feed, and (6) filling-in material.*

*Discussion is given of the effect of each of these variables of the resulting weld with special reference to the action of a magnetic field parallel to the direction of the arc upon the current in the arc and the effect of the atmosphere about the arc on the ductility of the resulting weld.*

WITHIN the last few years, the fusion welding method of joining steel sheets has come into increasing importance. In some cases it has replaced the riveting method. In fact those vessels which carry fluid under the highest pressure and highest temperature *can be made only by the welding method.* For instance, it is impossible to make the large stills for cracking petroleum products into gasoline by the riveting method. In these stills the temperatures are of the order of 1000 deg. fahr. and the pressure of about 1000 lb. per sq. in. A large number of these stills has been welded and has been in satisfactory operation for years and a representative of one of the largest boiler-making concerns in the country stated recently that it would be impossible to make such a vessel by riveting.

There are three fairly distinct processes of welding steel sheets to each other, (1) the acetylene gas process, (2) the metallic arc process, and (3) the carbon arc process. In the acetylene gas process the edges of the sheets are melted by the oxy-acetylene flame and additional weld metal is melted between the sheets, thereby joining or welding them together. In the metallic-arc process an arc is drawn between a piece of wire and the surface of the sheets to be joined. The arc heats the surface of the sheets to a melting temperature and at the same time melts off a portion of the metallic electrode. This molten metal fuses with the surface of the sheets and thereby makes a weld. In both of these processes it is necessary in most cases to bevel the edges of the sheets so that the heating flame can fuse the surfaces at the bottom of the sheets. Fig. 1 shows a sketch of sheets ready to be joined and shows the beveling of the sheets which allows the gas flame or the metallic arc to fuse the bottom portions, thereby making possible a weld clear through the sheet.

The third process is the carbon arc process which is the subject of this paper. The use of this process does not require beveling the edges of the sheets which are to be joined.

The carbon arc process has the advantage of being able to melt clear through a sheet ¼ or ⅜ in. thick without previous beveling. This is due to the fact that most of the heat in the carbon arc is developed on the positive terminal which in this case is the surface of the sheets to be joined. This excess of heat on the positive terminal produces a crater which is deep enough to penetrate through the sheets.

Fig. 2 is a sketch showing the cross section of the essential parts of the mechanism necessary to the use of the carbon arc. The lower sketch, Fig. 2, is a cross section of two plates butt-welded by the carbon arc process. The carbon arc process has the important advantage that the resulting weld is *more ductile* than the ordinary metallic arc weld.

Fig. 3 is a view of the welding head, the carbon electrode, the string reel, feeding mechanism, and general assembly. Fig. 4 is a view of the whole machine.

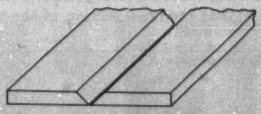

FIG. 1—SHOWING BEVEL REQUIRED FOR ACETYLENE OR METAL ARC WELDING

As seen in Fig. 2 the work is held in the machine by clamps on each side of the weld which are operated by compressed air. When it is desired to make a weld, the metal is rolled into the form of a tube, introduced into the machine with the seam midway between the clamps and when the seam is properly located, the clamps are dropped on to the metal to hold it rigidly in place.

The bottom of each clamp is formed of copper fingers which firmly grip the cylinder. Copper is used for the fingers on account of its high heat conductivity, so that while the weld is being made the intense heat of the arc will not fuse the fingers.

The operation is very simple. The arc is struck at one end of the seam to be welded. The welding head is moved along the seam by automatically controlled means and when properly adjusted the weld is made clear through the thickness of the sheets to be joined. When the head has arrived at the other end of the seam, the weld is completed.

1. The Lincoln Electric Company, Cleveland, Ohio.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

At this time, the two clamps are raised by pneumatic or hydraulic means and the welded cylinder, which may be pipe or part of a range boiler, or part of an unfired pressure vessel of any sort, is removed from the machine and the operation is repeated.

There is a number of variables which have to be adjusted to each other and to the work to be done in order to get the best results. The controlling variables may be mentioned as: (1) the amperes in the arc, (2)

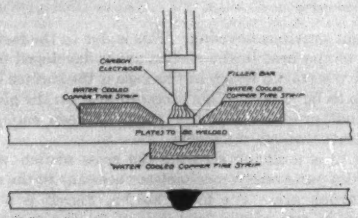


FIG. 2—DRAWING OF ESSENTIAL PARTS USED IN CARBON ARC WELDING

the voltage across the arc, (3) the magnetic field in the space occupied by the arc, (4) the atmosphere about the arc, (5) speed of feed, and (6) the material which may be laid along the seam to be joined to furnish added weld metal so that the cross section of the weld will be

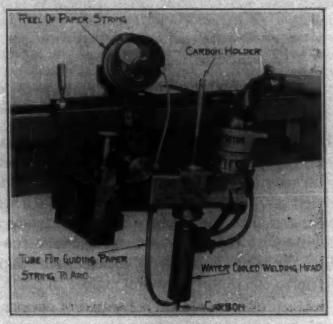


FIG. 3—CARBON ARC WELDING HEAD

somewhat greater than the cross section of the original sheets which are being joined.

The variables which occur in the resulting weld and which depend on the proper control of the variables mentioned above may be listed as: (1) the depth of the weld, (2) the width of the weld, (3) the tensile strength of the weld, and (4) ductility of the weld.

The carbon arc process which I am describing is called the "Electronic Tornado" process for the reason that the metal in the molten state is revolved by magnetic action. There is provided in the movable head a winding which produces a magnetic field whose lines are substantially parallel to the direction of the arc. This field accomplishes two purposes: (1) It produces a rotation of the material which is being melted by the

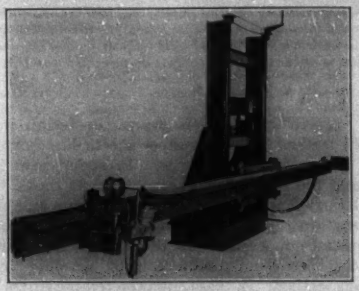

FIG. 4—COMPLETE MACHINE FOR CARBON ARC WELDING

arc, thereby mixing it more thoroughly, and (2) It provides a magnetic field which is in such a direction as to "stiffen" the arc and render it thereby less liable to trouble from parasitic magnetic fields.

Those who have had experience in arc welding know that the presence of parasitic magnetic fields causes a blow of the arc, especially at the end of a weld, which makes welding much more difficult than it otherwise would be, and by rendering the work more difficult is likely to interfere with its quality.

The reason why the magnetic field produces the

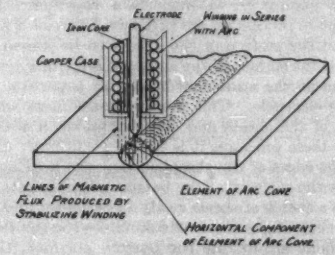


FIG. 5—DIAGRAM SHOWING WINDING FOR PRODUCING MAGNETIC FIELD

rotation of the melted material can be seen from Fig. 5. It is a fact that in any carbon arc the cross section of the arc is smaller at the carbon electrode than it is at the work, or in other words, the arc is cone-shaped, the small end of the cone being at the carbon electrode. With a cone-shaped arc there is a component of current at right angles to the axis of the arc. This component of current is acted on by a magnetic flux parallel to the axis of the arc which produces rotation. Experience

shows that this rotation causes a more perfect mixing of the material which is being melted from the edges of the sheets which are being joined.

The action of the controlling variables on the resulting weld will be commented on below in the order in which they were given.

*Current.* The amperes in the arc in general determine the depth of the weld. This is what would be expected on account of the fact that the heat developed at the positive terminal of the carbon arc is equal to what is called the "anode drop," multiplied by current in amperes. This "anode drop" can be taken as about 12 or 13 volts and this multiplied by the amperes in the arc gives the watts and therefore, the heat developed at the immediate surface of the sheets which are being welded. The so-called "anode drop" is practically independent of the current; therefore, the heat developed and consequently the amount of metal melted will depend substantially on the amount of current used. Table I gives thickness of metal, amperes required, volts across the arc, and speed for butt welds.

TABLE I

CURRENT, VOLTAGE, AND SPEED IN BUTT WITH THE CARBON ARC

| Thickness | Current amperes | Voltage across arc | Speed ft. per hr. |
|---|---|---|---|
| No. 14 0.078 in. | 350 | 25 | 150 |
| No. 12 0.109 in. | 425 | 30 | 110 |
| No. 10 0.140 in. | 425 | 30 | 95 |
| 3/16 in. | 450 | 32 | 75 |
| 1/4 in. | 450 | 32 | 60 |
| 3/8 in. | 550 | 35 | 40 |

*Voltage across the Arc.* The feed of the carbon electrode is controlled automatically by a magnetic

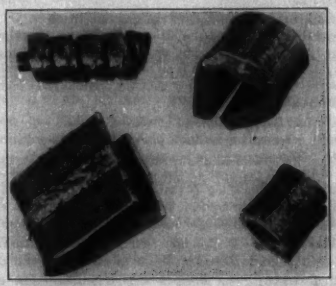

Fig. 6—Samples of Steel Welded and Deformed without Failure of Weld

clutch and the carbon is continually rotated in order to preserve a symmetrical point on the carbon. The magnetic clutch operates when the voltage across the arc is greater or less than the predetermined amount and the feeding mechanism is thus brought into action. By this means the voltage across the arc is automatically maintained. When the voltage across the arc is high, the arc is long and the width of the weld is greater than it is with a short arc. Another effect which exists is that with a long arc the total heat developed in the arc is greater than it is with a shorter arc and consequently there is some additional heat supplied to the surfaces which are being melted, though from a practical standpoint increasing the length of the arc does not greatly increase the effective heat.

*Field Strength.* The stabilizing magnetic field is produced by the winding shown in Fig. 5. The welding

Fig. 7—Weld Metal Twisted without Failure

current passes through this winding and the field is proportional to the current. About seven turns are ordinarily used. With 400 amperes this gives 2800 ampere-turns.

*The Atmosphere around the Arc.* The atmosphere around the arc is of controlling importance in determining the ductility of the resulting weld metal. Experience has determined that the oxidizing action of the

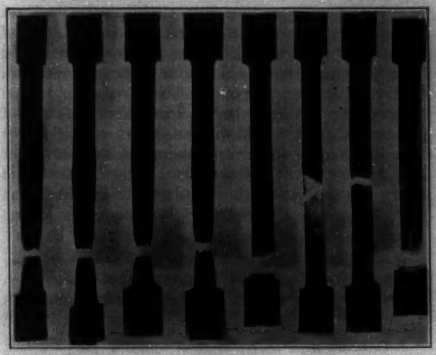

Fig. 8—Welded Strips which Failed under Tension Outside of the Welds

atmosphere is the cause of the lack of ductility in the ordinary metallic arc weld and in the carbon arc weld without means of controlling the atmosphere. In the particular head which is being described, a means is provided for controlling the atmosphere about the arc which consists in feeding paper string continuously into the arc. This string burns as it approaches the arc and produces an atmosphere having $CO^2$, possibly CO and some hydro carbons.

*Speed of Feed.* The speed of feed of the head or of

the arc along the seam to be welded is controlled and varies from 6 in. to 3 ft. a minute depending upon the thickness of the weld to be made and the amount of current used, etc. As would be expected a high speed produces a shallow weld with a given current. A lower speed produces a deeper weld. The speed of feed and the current and the thickness of the weld have to be so adjusted in reference to each other that the weld will penetrate to the desired depth. See Table I.

*Feed-In Material.* It is possible in general to make a weld which is stronger than the parent metal. In order to produce this result usually additional fill-in material is placed along the seam which is being welded so that after the weld is completed, its cross section will be about 20 per cent greater than the cross section of the parent metal. If desired special alloy fill-in material, such as nickel steel, may be used to increase the strength of the weld.

It is likely that the art will grow toward the decrease of the amount of added metal because the only reason for adding 20 per cent to the thickness of the weld as compared to the parent sheet is to be certain that the strength of the weld is greater than the strength of the parent sheet. Probably five years from now 5 per cent added material will be considered sufficient to insure greater strength in the weld than in the parent metal.

The welds made by this carbon-arc process are very ductile and strong. Figs. 6, 7, and 8 show test pieces which demonstrate these points. Fig. 6 shows three pieces of ½ in. steel butt-welded with the addition of 20 per cent of soft steel. These pieces were bent cold after welding as shown. No failure of the weld occurred. In the upper left corner of Fig. 6 is a strip of weld metal twisted around a pipe. In Fig. 7 are shown two strips of weld metal twisted cold without failure. Fig. 8 shows a number of sample strips of steel which were welded at their center. They were broken by tension and in every case the break occurred outside of the weld.

## Discussion

**B. L. Barns:** Fig. 2 of Mr. Lincoln's paper shows cooling shields but the slides which he has shown of apparatus set up on actual work do not, I believe, show the cooling shields in use. I wish to ask whether the cooling shields are used in the commercial use of the apparatus he describes.

**J. C. Lincoln:** Fig. 2 is more of a diagram than anything else. All of the mechanism is not shown there, except the means of mechanically holding the plates. If you look at Fig. 5, you will see more nearly the actual apparatus. In Fig. 5 you will see the copper case which holds the cooling water and the iron core which carries the flux and the winding which carries the magnetic field.

**Morris Stone:** What were the physical properties of the weld that you made up according to the carbon arc welding process, particularly the ductility figures, if you have them, elongation and reduction of area on the weld metal?

**J. C. Lincoln:** Our methods of measuring ductility are very crude. What we do is to make a weld and put it in a vise and then bend it double. If it breaks before it bends double, we don't think it is as ductile as if it bends before it breaks. From a scientific standpoint, that is not a very exact measure. From a practical standpoint, it is quite valuable because if we can get a weld that will bend double, we have a considerable degree of ductility. I can't answer the question by giving the exact degree, but we have made some progress, as you can see from the samples.

**S. Martin, Jr.:** What is the comparative ultimate strength of the plate and weld? If the ultimate strength of the plate is 45,000 lb. per sq. in. and the plate 60,000 to 65,000 lb. per sq. in., several holes could be drilled through the weld without causing the break to occur in it. The yield point in the above case would be comparatively low for the plate and high for the weld and this would cause the plate to break first.

I should also like to comment on the matter of the globule going across the arc and shorting it. In metallic welding with a bare steel electrode the arc is usually short. The short arc permits the globules passing across the gap between the electrode and the plate to short circuit the arc, thereby giving the dips in voltage on the oscillogram. On the other hand, the coated or heavily fluxed electrode uses a long arc which perhaps is too large a gap to be closed by a globule and, therefore, give the dip in voltage. This may assist in the analysis of the oscillograms.

**W. E. Crawford:** What is the relationship between the yield point in the plate and in the weld metal? Is it not true that, probably due to the raising of the ultimate strength, you have also raised the yield point and thereby caused the plate to start elongating before the ultimate strength has been reached and thus reduced the ultimate strength and section of the sample being tested?

**J. C. Lincoln:** To answer the question specifically, I would say that the plate is welded a little over half way through on one side and then a little over half way through on the other side so the welds intersect. There is no alloy steel used or anything of that sort. All we do is simply melt the original plate metal and that forms a weld metal.

It is a fact that when metal is treated in that way, for some reason or other which we don't know, the tensile strength is increased. The approximate increase in tensile strength is in the order of 10 or 15 per cent in the samples which I have shown, but the remarkable thing is that the original plate metal when melted and passed through the arc is stronger than the plate metal was before it was melted, as demonstrated by these samples.

**S. Martin, Jr.:** Do you use a straight metal in cutting up the strip or higher grade of steel on the outside and inside of it?

**J. C. Lincoln:** The filling-in strip is ordinary low carbon steel.

# Behavior of Dielectrics

## A Study of the Anomalous Charging Current and the Variation of Dielectric Energy Loss and Capacitance with Frequency in Solid Dielectrics

BY R. R. BENEDICT*

Associate, A. I. E. E.

*Synopsis.—The paper describes a research undertaken with the object of throwing light on the relations between the electrical properties of dielectrics or insulating materials, especially on the relation between the "anomalous charging current" under a direct voltage test and the dielectric energy loss for an impressed alternating voltage.*

*After a review of the theory of this relationship, the methods developed in this study for observing the anomalous charging current in condensers in the time range from 0.0007 to 0.100 seconds after impressing a steady potential are described. The methods used in observing the "normal leakage current" and the alternating energy loss and capacitance in the frequency range from 200 to 4000 cycles per second are also described.*

*The results of measurements by these methods on mica, glass, varnished cloth, and paraffin paper condensers are given. These measurements include a series giving the effect of varying temperatures on the properties of the glass and varnished cloth condensers.*

*Finally, the comparisons between the dielectric energy loss and capacitance variation with frequency predicted on the basis of the d-c. anomalous charging current tests and the variations which were actually observed are given. These comparisons show that a fair agreement exists between the predicted and observed curves.*

* * * * *

### I. Introduction

1. A STUDY of the energy losses which occur in dielectrics in alternating fields is of importance because of the effect of these losses in increasing the attenuation constant of telephone and telegraph cables, because of the reduction which the losses occasion in the current-carrying capacity of power cables, because of the role which the losses may play in the breakdown of dielectrics (according to the theories of breakdown due to thermal instability developed by Wagner,[1] and Dreyfuss,[2] and others), and finally because of the light which a study of the losses may throw on atomic and molecular structure.

2. The loss which occurs in a dielectric subjected to an alternating field was first observed in 1864 by Siemens,[3] who noted a striking rise in the temperature of a glass plate condenser after it was charged and discharged in an oscillatory manner for a short time.

Since that time the losses in dielectrics have been the subject of a great number of investigations.† The loss per cubic centimeter which occurs in many solid dielectrics in a field which alternates between given peak electric intensities may be a thousand times as great as the loss which occurs in the same dielectric in an unvarying electric field in which the intensity is kept constantly at the peak value attained in the alternating field. Many theories have been advanced which attempt to account for this excess loss.‡ The postulated properties of the dielectric upon which these explanations are based include, (1) the non-homogeneity of the material (Maxwell), (2) the presence of molecules which act as damped resonators, (3) the presence of free ions within the body of the dielectric, and (4) the presence of dipolar molecules in the dielectric.

A close relation has been observed between the anomalous effects in a dielectric for alternating voltages (excess loss in dielectric) and for direct voltages (residual voltages, residual currents). Von Schweidler[4] has deduced the dielectric loss which should be observed in an alternating field in a dielectric which is characterized by a given anomalous charging current curve in a steady field. The anomalous charging current curve of a condenser having a solid dielectric may be defined to be the curve which shows the differences between the instantaneous values of the charging current which actually flows under a steady charging e. m. f. and the corresponding values of current as computed by the classical theory assuming a constant value of resistance, inductance, capacitance, and leakage conductance.

F. Tank[5] experimentally determined the form of the anomalous charging current curve in the range of time from 0.0008 to 0.185 sec. after applying the steady voltage. He then calculated the alternating loss for a frequency of 50 cycles per second on the basis of this function by the method of von Schweidler and measured the losses at the same frequency. The measured losses were in good agreement with those calculated (differences from 0.4 to 23 per cent). The results of MacLeod[6] on solid dielectrics show a loss that varies with frequency in the range from 500 to 1,000,000 cycles per second in a manner which is in accord with the equations developed by von Schweidler and used by Tank. This result suggests the possibility of calculating the losses in solid dielectrics over a wide range of frequency from

*Instructor in Electrical Engineering, University of Wisconsin, Madison, Wis.

1. For references see Bibliography.

†See extended bibliographies of E. von Schweidler,[4] E. H. Raynor,[5] D. M. Simons,[6] J. B. Whitehead.[7]

‡See the thorough discussion of these theories by J. B. Whitehead.[7]

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the knowledge of the form of the anomalous charging current function.

3. The objects of this investigation were, therefore, (a) to study experimentally the anomalous charging current in solid dielectrics and to compare the loss calculated on the basis of this current with that measured over a range of frequency; (b) to determine the relative effect of the normal leakage current of the condensers tested on the total dielectric loss; (c) to try to arrive at conclusions as to the nature of the losses from the comparison of computed and measured loss; and (d) to try to obtain a physical explanation for the anomalous charging current.

## II. Theoretical Development

*The anomalous charging current of a condenser.*

4. Suppose that a condenser (having a solid dielectric, such as glass, paraffin, rubber, or impregnated paper) is connected by a circuit of low resistance and inductance to a source of constant voltage $E$. A "normal charge" will then flow into the condenser, giving rise to the transient *normal charging current* which rapidly approaches zero. If the condenser has a solid dielectric, an additional current is superimposed on the normal charging current. This additional current is considered to have two components, the *normal conduction current* and the *anomalous charging current*. The final leakage current of the condenser after a sufficient time has elapsed so that this current has reached a steady value has been called the *normal conduction current*. The difference obtained by subtracting the sum of the normal conduction current and the normal charging current from the total observed current gives a component of current in the circuit which may be called the *anomalous charging current*. The anomalous charging current is closely associated with the anomalous effects observed in solid dielectrics, such as the residual voltage of condensers, the excess losses in alternating fields, and the variation of capacitance of condensers with varying frequency of the alternating field. The anomalous charging current has been the subject of a large number of experimental and theoretical studies.* The theoretical considerations given here will be limited to a brief development of the formulas used in the interpretation of the experimental results.

5. The forms of the anomalous charging current curve for solid dielectrics have received much study, and empirically determined equations for the curves have been obtained by J. Hopkinson[10] and J. Curie.[11] The investigations have resulted in the formulation of two laws to which the curves in general conform.[9] The first law is to the effect that the ordinates of the anomalous charging current curve of a given insulating substance at a given temperature are directly proportional to the steady voltage impressed on the condenser and to the capacitance of the condenser, thus

$$i_a = E\,C_o\,\phi\,(t) \tag{1}$$

in which $i_a$ is the anomalous charging current at the time $t$, $E$ is the applied voltage, and $\phi\,(t)$ is the anomalous charging current function which characterizes the given substance. The capacitance $C_o$ is the capacitance for a very short time of charge on direct voltage or for very high-frequency on alternating voltage, and has been called the *geometrical capacitance* by Curtis.[12]

The second law governing the form of the anomalous charging current curves is the *principle of superposition*, which may be stated as follows: the anomalous charging current curve associated with a given increment in the impressed voltage is independent of the preceding values of the impressed voltage. For example, if the voltage $E$ is impressed on the condenser at zero time, and at the time $\delta$ the voltage changes by the amount $\Delta\,e$, the total current at the time $t$ is given by the undisturbed variation of the original current plus the current which the increment in voltage would produce if acting alone, that is

$$i_a = E\,C_o\,\phi\,(t) + \Delta\,e\,C_o\,\phi\,(t-\delta) \tag{2}$$

The experimental laws as enunciated above have been generalized to give an expression which makes possible the calculation of the anomalous charging current at any time $t$ after the application of a voltage which is an arbitrary function of the time $E\,(\tau)$. This is

$$i_a = C_o \int_{-\infty}^{t} \frac{d\,E\,(\tau)}{d\,\tau}\,\phi\,(t-\tau)\,d\,\tau, \tag{3}$$

where the $\phi$ function is the same as that in Equation (1). If $(t-\tau)$ is replaced by $u$, Equation (3) may be written

$$i_a = -\,C_o \int_{0}^{\infty} \frac{d\,E\,(t-u)}{d\,u}\,\phi\,(u)\,d\,u, \tag{4}$$

where $u$ may be looked on as the elapsed time from the increment in voltage $\dfrac{d\,E\,(t-u)}{d\,u}$ to the fixed time $t$.

This formula makes possible the calculation of the dielectric loss accompanying an impressed alternating voltage.

*Calculation of the dielectric loss and capacitance on alternating voltage.*

6. Let the condenser be connected to a source of alternating voltage $e = E_m \sin \omega\,t$. It will be assumed that there will be a normal current given by

$$i_e = \omega\,C_o\,E_m \cos \omega\,t + G_e\,E_m \sin \omega\,t \tag{5}$$

where $G_e$ is the normal leakage conductance based on the measured normal conduction current defined in Section 4.

In addition to the normal current, there will be the anomalous charging current of the condenser. This

*See bibliographies *loc. cit.*

component of current will be calculated by means of Equation (4). Since the applied voltage is

$$E_m \sin \omega t,$$

the function $E(t-u)$ in Equation (4) becomes $E_m \sin \omega (t-u)$. Introducing this in (4) and expanding the sine function and differentiating with respect to $u$ there results

$$i_a = \omega C_o E_m \left[ \cos \omega t \int_0^\infty \phi(u) \cos \omega u \, d u + \sin \omega t \int_0^\infty \phi(u) \sin \omega u \, d u \right]. \quad (6)$$

Since the integrals in this equation do not contain $t$ they may be looked upon as constants at a given frequency, and the anomalous charging current becomes a sinusoidal function of fundamental frequency. If we let the integrals be represented by

$$\left.\begin{aligned} A &= \int_0^\infty \phi(u) \cos \omega u \, d u \\ B &= \int_0^\infty \phi(u) \sin \omega u \, d u \end{aligned}\right\} \quad (7)$$

we can, by Equations (5) and (6), write the total alternating current in the form

$$i = i_o + i_a = \omega C_o E_m (1 + A) \cos \omega t + E_m (G_o + \omega B C_o) \sin \omega t. \quad (8)$$

This equation shows that the anomalous charging current has the effect of increasing the apparent capacitance of the condenser and of contributing a loss of energy. The apparent equivalent shunt capacitance $C$ is given by

$$C = C_o (1 + A). \quad (9)$$

The tangent of the angle of phase difference $\phi$ for the condenser as computed from (8) becomes

$$\tan \phi = \frac{G_o + \omega B C_o}{\omega C_o (1 + A)} = \frac{G_o}{\omega C_o (1 + A)} + \frac{B}{1 + A} \quad (10)$$

The first term of the right side of Equation (10) gives the effect of the normal leakage conductance on the phase difference and the second part gives the effect of the anomalous charging current. For phase angles $\phi$ up to seven degrees the expression (10) also gives the power-factor of the condenser to an accuracy of one per cent, since in this range $\tan \phi \approx \cos \theta$, where $\theta$ is the power-factor angle.

7. The effect of the anomalous charging current on the capacitance and power-factor of the condenser can be computed from Equations (7), (9), and (10) provided the anomalous charging current function $\phi(u)$ in Equation (7) is determined from theoretical considerations or empirically determined from experiment. Several observers* have been able to represent their results by the empirical function

$$\phi(u) = \beta u^{-n}. \quad (11)$$

*Hopkinson,[10] J. Curie,[11] von Schweidler,[4] Ashton,[13] Jordan,[14] Tank.[5]

The integrals in Equation (7) have been evaluated by von Schweidler[4] for the function of Equations (11) for the values of $n$ lying between 0 and 1, and the results are

$$\left.\begin{aligned} A &= \frac{\beta \Gamma (1-n) \cos (1-n) \pi/2}{\omega^{(1-n)}} \\ B &= \frac{\beta \pi}{\omega^{(1-n)} \, 2 \, \Gamma (n) \cos (1-n) \pi/2} \end{aligned}\right\} \quad (12)$$

Where $\Gamma$ is the Gamma function.† On substituting these values in Equations (9) and (10) we obtain

$$C = C_o \left[ 1 + \frac{\beta \Gamma (1-n) \cos (1-n) \pi/2}{\omega^{(1-n)}} \right] \quad (13)$$

and

$$\tan \phi = \frac{G_o}{\omega C} + \frac{\beta \pi}{\left[ \omega^{(1-n)} \, 2 \, \Gamma (n) \cos (1-n) \frac{\pi}{2} \right] \frac{C}{C_o}} \quad (14)$$

Equations (13) and (14) may be employed in the calculation of the capacitance and power factor of a condenser for different frequencies, provided the anomalous charging current function in Equation (11) is a good approximation to the actual current-time function over a wide range of time.

8. By Equations (1) and (11) the anomalous charging current variation with time for a steady impressed voltage is given by

$$i_a = E C_o \beta t^{-n} \quad (15)$$

where $\beta$ and $n$ may be looked upon as constants of the material of the condenser at the given temperature. These constants may be determined from a test of the anomalous charging current with a steady voltage impressed on the condenser. After these constants have been determined, the capacitance and power factor of the condenser can be calculated by Equations (13) and (14). This is the method followed in this study, and the predicted capacitance and power factor are compared with the measured values over a range of frequency.

## III. Description of Methods

*Method of measuring anomalous charging currents of condensers at short time intervals after applying a steady potential.*

9. The determination of the anomalous charging current curves for short time intervals after the application of a steady potential requires the measurement of rapidly varying currents of small magnitude. By means of the circuit and switching arrangement shown in Fig. 1, the trace of the anomalous charging current of the condenser $C$ upon connecting it to the battery

†See Pierce, B. O. "A Short Table of Integrals," p. 140.

$E$ is photographically recorded by the oscillograph vibrator $V$. In this circuit, the two switches $S_2$ and $S_3$ are opened by a bullet fired from the gun $M$. The switches $S_2$ and $S_3$ are small phosphor bronze strips about 0.2 cm. wide, 0.038 cm. thick, and 5 cm. long which are destroyed by the bullet. Initially the switch $S_1$ is open and the switches $S_2$ and $S_3$ are closed. The sequence of switching operations in obtaining the oscillograms showing the anomalous charging current of the condenser $C$ under the continuous e. m. f. of the battery is charted in Fig. 2. This sequence is as follows:

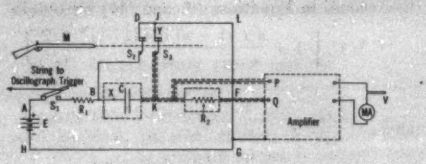


FIG. 1—CIRCUIT FOR MEASURING ANOMALOUS CHARGING CURRENT OF CONDENSERS

*First Switching Operation.* At the instant $A$ (Fig. 2) the switch $S_1$ is closed and at the same time the string attached to the switch pulls the trigger of the "oscillograph worm contactor."

Upon the closure of the switch $S_1$, current builds up in the circuit $A\,S_1\,B\,D\,L\,F\,G\,H\,A$. This circuit contains a battery whose e. m. f. is, say, 100 volts; the circuit has a resistance of 2000 ohms and an inductance of 5 microhenries. Hence, the time constant of the circuit is $2.5 \times 10^{-9}$ sec. The current in the above circuit builds up to within $10^{-16}$ amperes of its steady-state value in less than a millionth of a second and continues to approach the steady-state value of 0.050 ampere until the circuit is disturbed by the opening of the switch $S_2$ in the manner described below.

*Second Switching Operation.* The pulling of the trigger of the oscillograph worm contactor at the instant $A$ drops a contactor in the groove of the worm on the shaft of the oscillograph drum. At the instant $B$, after from 0.3 to 1.3 revolutions of the drum, the contactor makes contact with the wire in the bottom of the groove, causing the shutter magnet to open the oscillograph shutter at the instant $D$, 3 cm. (9 mil. sec.) before the joint in the photographic film passes the light slit. The contactor remains in contact with this wire for one revolution of the drum and holds the shutter open for one revolution (100 mil. sec.).

*Third Switching Operation.* The oscillograph shutter has a small mercury-contact switch mounted on its shaft which opens at the instant $C$ when the shutter is three-quarters open. This closed switch is in the "oscillograph shutter-opening circuit" and when it opens it causes the "shutter opening current" (which it had previously diverted) to flow through the tripping relay which pulls the trigger of the gun $M$ at the instant $E$.

*Fourth Switching Operation.* The tripping relay which pulls the trigger of the gun $M$ is so adjusted that it allows the zero lines to be traced on the film for 3 cm. (9 mil sec.) before and about 14 cm. after the joint in the film passes the light slit before the bullet from the gun opens the switch $S_2$.

The bullet from the gun $M$ opens the switch $S_2$ (that is, it destroys the contact strip $S_2$) at the instant $F$, thus removing the shunt $B\,D\,J\,K$ from the condenser $C$ which is under test. When the switch $S_2$ opens, the condenser $C$, of a capacitance of say 0.002 $\mu$f. is thrown in series with the resistance, inductance, and source of e. m. f. described above. This circuit is aperiodically damped; it has an undamped period of $6.3 \times 10^{-4}$ mil-sec., and a time constant $(C\,R)$ of $4 \times 10^{-3}$ mil-sec. Accordingly the current of 0.050 ampere is diverted into the condenser and if the condenser is free of leakage currents and anomalous effects the voltage of the condenser will attain the voltage of the battery to within $2 \times 10^{-7}$ volts and the normal charging current will be less than $10^{-10}$ amperes in 0.08 mil-sec.

*Fifth Switching Operation.* The bullet from the 0.22 caliber gun has a muzzle velocity of 30,000 cm. per sec. (1000 ft. per sec.) and at the instant $G$, 0.08 mil-sec. after opening the switch $S_2$, it opens the switch $S_3$, which is located 2.4 cm. beyond $S_2$. When the switch $S_3$ is opened, it removes the shunt $K\,J\,L\,F$ from the resistance $R_2$ and the anomalous charging current and leakage current of the condenser must flow through this resistance $R_2$, thereby setting up a difference of potential between the terminals $K$ and $F$ of the resistance. This difference of potential is at every instant propor-

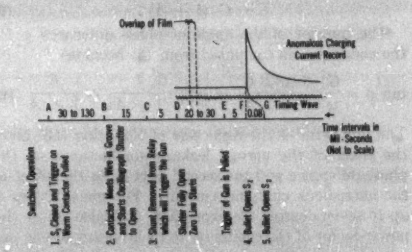


FIG. 2—CHART SHOWING SEQUENCE OF SWITCHING OPERATIONS

tional to the instantaneous value of the current. This difference of potential is impressed on the amplifier terminals $P\,Q$. The output current of the amplifier is recorded by the oscillograph vibrator $V$, thus giving the record of the anomalous charging current plus the leakage current as shown in Fig. 2. A typical oscillogram showing two tests on a condenser is shown in Fig. 5.

The system of shielding used in the anomalous charging current tests is shown by the dotted lines in Fig. 1. The battery supplying the voltage $E$ was a

storage battery having a 2.5 ampere-hour capacity. The distance from the muzzle of the gun $M$ to the switch $S_2$ was 120 cm. A baffle was placed between the muzzle of the gun and the switch $S_2$. Its object was to reduce the amount of burned powder which reaches the region of the switches $S_2$ and $S_1$.

10. The magnitude of the difference of potential obtainable across the resistance $R_2$ with which to operate the amplifier is limited by the fact that the resistance $R_2$ must be kept sufficiently small. If the resistance $R_2$ is too large, the time constant of the circuit becomes too great and the current in the circuit will not give the true anomalous charging current. In these experiments, $R_2$ was limited to 100,000 ohms, so that the maximum time constant of the circuit after the shunt $K\ J\ E\ F$ is removed from $R_2$ is 0.2 mil-sec.

11. The amplifier which was used is shown in Fig. 3. This is a so-called "d-c. amplifier." The amplifier comprises two stages of voltage amplification using four element tubes and an output stage consisting of two tubes in parallel. When the amplifier is properly adjusted the grids of all the tubes are at negative potentials with respect to their respective filaments. The potential of the grid of the second tube may be changed by means of the potential dividing resistance $B$. Such a change will change the output current. The steady plate current of the two output tubes is continually present in the oscillograph vibrator $V$, thus giving rise to a deflection of the vibrator. This deflection may be looked on as a sort of false zero. This false zero deflection has a tendency to drift slightly in this type of amplifier. The adjustment $B$ is needed to keep the false zero deflection at a preassigned value. Now an increment in the voltage applied to the input terminals of the amplifier causes a corresponding increase in the output current and in the deflection of the vibrator. A curve showing the relation between the increments in voltage applied to the input terminals and the corresponding increments in the output current will be called a calibration curve of the amplifier. This calibration curve formed the basis for the derivation of the values of the anomalous charging current from the oscillographic record. The following section describes an experimental check of the reliability of this method. The calibrating circuit is shown at the left in Fig. 3. While the calibration curve of the amplifier changes only slightly from time to time, either the whole calibration curve was taken after each anomalous charging current test, or one point on the curve was obtained as a check on a previous calibration. The sensitivity of the amplifier was such that a 20-millivolt increment in the grid voltage gave an increment in plate current of about 30 milliamperes. With the sensitive oscillograph vibrator that was used (sensitivity of 10 millamperes per cm.) and using the maximum value of $R_2$ of 100,000 ohms, the over-all sensitivity was such as to give a 30-mm. deflection of the vibrator for a test circuit current of $20 \times 10^{-8}$ amperes.

12. Since an attempt was being made to measure the values of the transient current accurately for short time intervals after the start of the current, it is naturally important to consider the problem of the determination of the shortest time at which reliable readings may be obtained from the oscillograms. Tests were made of the response of the oscillograph vibrator when constant alternating voltages of different frequencies were applied to the input terminals of the amplifier. The influence of the temperature of the damping fluid of the oscillograph vibrator on the resulting frequency-response curves was determined. These curves gave an indication of the optimum damping fluid temperature for the tests of the transient current.

The shortest time for the first reliable reading on the oscillogram was tested by impressing a transient voltage of calculable time variation on the input of the amplifier. Then a comparison was made of the calculated current curve and that derived from the oscillogram for the test. The calculable transient current was obtained by charging an air condenser to a constant voltage through a high resistance. The circuit of Fig. 1 was modified to give the required test circuit. A con-

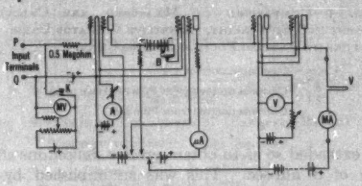


Fig. 3—Circuit Diagram of Amplifier

denser $C$ of $1.10 \times 10^{-9}$ farads capacitance was charged to a voltage of 124.0 volts through a resistance of $2.04 \times 10^{6}$ ohms. The comparison between the calculated current and that derived from the oscillograms is shown in Fig. 4. The results of the tests show that the initial current reading may be taken from the oscillogram at a time 0.7 mil-sec. after the start of the transient. This test may also be considered to be a check of the method of deriving the currents in the test circuit from the oscillograms. The slope and amplitude of the calculated curve are fairly well reproduced by the points obtained from the oscillograms.

13. A further test of the reliability of the apparatus consisted in a test for the anomalous charging current of an air condenser. The air condenser was placed at $C$ in Fig. 1 and the test was carried out as described in section 9. After the disturbances which affected the record were reduced to a minimum, records were obtained which showed only a slight deflection using the maximum amplification. These tests showed that the anomalous charging current of the air condenser was less than five per cent of the currents observed in the later tests of the condensers having solid dielectrics.

*Modification of the method of observing anomalous charging currents for time intervals from 8 to 100 mil-sec.*

14. It can be seen from Fig. 5 that the anomalous charging current drops so rapidly with time that a deflection of 40 mm. on a record at 0.7 mil-sec. may drop to 4 mm. at 8 mil-sec. The range of measurement

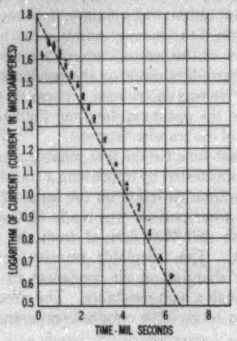


Fig. 4—Comparison of Measured and Calculated Current in Test Circuit. Sensitive Vibrator Used. Temperature of Damping Fluid = 36 Deg. Cent.

- - - - Calculated current
x } Currents derived from Film 244 (two tests)
o } Currents derived from Film 245

was extended so as to obtain greater deflections after a time of 8 mil-sec. This was accomplished by two modifications of the method described in Section 9. One change consisted in arranging switches $S_2$ and $S_3$ in Fig. 1 so that they could be opened by a spring

Fig. 5—Tests of Condenser 36 (Treated Cloth)

Film 302 $E$ = 97.0 volts $R_2$ = 6000 ohms
Condenser temperature = 60.0 deg. cent.
Damping fluid temperature = 42 deg. cent.
Frequency of timing wave = 1000 cycles per second

operated lever. The time between the opening of $S_2$ and of $S_3$ was adjusted to 8 mil-sec. The other change consisted in inserting a resistance in the circuit of Fig. 1 at the point $Y$ so that the time of opening switch $S_2$ would be recorded on the oscillogram. A record taken by the modified method is shown in Fig. 6.

## Description of Test Condensers

15. The condensers designated 35, 36, and 37 were constructed according to the same plan. A parallel plate condenser was made in the following manner. An even number of sheets of the dielectric were fitted with lead foil electrodes. These sheets were then placed between 7.5-by 9.5-by 0.6-cm. bakelite end pieces. The whole was then clamped together, using small steel angles outside the bakelite end piece to insure rigidity. Having used an even number of layers of dielectric in parallel it follows that the two outermost lead foil electrodes are connected to the same terminal of the condenser. This terminal was designated the "ground" terminal of the condenser. Each of these condensers was placed in a shallow metal pan having dimensions of 11 by 11 by 4.5 cm. Condensers 35 and 36 were covered with melted petrolatum, and condenser 37 was covered with melted paraffin.

Condenser 35 contains six 7- by 7-cm. sheets of soda-lime glass having an average thickness of 0.125 cm. Thickness measurements were made by means of a micrometer. The lead foil electrodes were applied to both sides of each sheet of glass with a thin layer of petrolatum between the lead foil and the glass. The

Fig. 6—Test of Condenser 35 (Glass)

Film 277
$E$ = 98.5 volts $R_2$ = 80,000 ohms
Condenser temperature = 30.3 deg. cent.
Damping fluid temperature = 45 deg. cent.

lead foil electrodes had the shape of a 5 by 5 cm. square with a tongue 1.5 cm. wide attached to one corner. These tongues were soldered to a copper wire which formed one terminal of the condenser.

Condenser 36 contains four 3.7- by 7-cm. strips of treated cloth taken from a "varnished cambric" cable. The cloth had been treated with black varnish. The average thickness of the treated cloth was 0.0307 cm. The electrodes were effectively 2 by 5 cm.

Condenser 37 contains two 7- by 7-cm. sheets of paraffin paper. The electrodes have dimensions of 5 by 5 cm. White bond paper having an average thickness of 0.0106 cm. was treated in paraffin under atmospheric pressure at a temperature of 112-118 deg. cent. for 60 min. The paraffin had a softening point of about 53 deg. cent. The electrodes were applied to the sheets of paper before the paraffin solidified.

Condenser 39 was a commercial mica condenser which is molded into a bakelite case. Its nominal capacitance was 0.001 $\mu$f. This condenser was taken apart for

examination after the tests were concluded. It contained three effective sheets of clear mica having an average thickness of 0.0056 cm. The dimensions of the effective part of the electrodes were 1.55 cm. by 2.03 cm. The mica sheets were 0.5 cm. wider than the tinfoil electrodes.

TABLE I
RESULTS OF NORMAL CONDUCTANCE MEASUREMENTS

| Condenser | Material | Temperature deg. cent. | Leakage conductance $G_0$ $10^{-10}$ mhos | Conductivity $10^{-14}$ mho-cm. units |
|---|---|---|---|---|
| 37 | Paraffin paper | 30 | 0.185 | 0.38 |
| 39 | Mica | 30 | 0.086 | 0.43 |
| 35 | Glass | 30 | 0.32 | 2.6 |
| | | 40 | 1.4 | 11.4 |
| | | 50 | 4.0 | 32.5 |
| | | 60 | 11.6 | 94. |
| | | 70 | 26.3 | 214. |
| 36 | Treated cloth | 30 | 0.24 | 1.8 |
| | | 40 | 1.7 | 12.8 |
| | | 50 | 5.0 | 37.5 |
| | | 60 | 14.5 | 109. |
| | | 70 | 36.0 | 270. |

*Arrangement of condensers for test.*

16. The large variation of the properties of dielectrics with variations in temperature is well known. In order to conduct experiments at a constant temperature, the condensers were installed in a metal box which was equipped with automatic temperature controlling apparatus. The temperatures of the condensers were read by thermometers placed adjacent to the condenser proper, and in the material used to cover the condenser. The observed temperatures have not been reported in the results, but instead the standard temperatures of 30, 40, 50, 60, and 70 deg. cent. have been given. The observed temperatures for individual tests were not

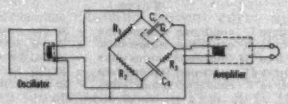


FIG. 7—CIRCUIT FOR BRIDGE MEASUREMENTS ON CONDENSERS

more than 0.5 deg. cent. different from the standard temperatures.

The metallic heating box served as the shield shown around the condenser $C$ in Fig. 1. The "ground" terminal of the condenser was connected in each case to the point marked $K$ in Fig. 1. This connection minimizes the effect of the stray capacitance of the ground electrodes with respect to the shield system.

*Measurement of normal leakage current.*

17. The normal leakage current of the condensers was measured by the galvanometer method. The galvanometer had a sensitivity of $7 \times 10^{-10}$ amperes per mm. scale deflection. The voltage applied was 147 volts for the tests at 30 deg. cent. and 44 volts for the tests at the higher temperatures. The leakage current was practically constant after a time of 5 minutes had elapsed, and the normal leakage conductance was computed on the basis of the current observed at this time. The results of these measurements are tabulated in Table I. It may be noted that the conductivities given in Table I may not be strictly accurate on account of the possibility of leakage over the surface of the sheets of dielectrics. This is especially true of the mica

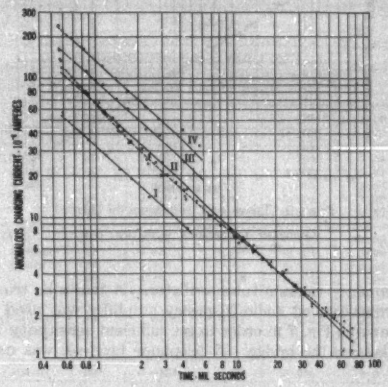


FIG. 8—TESTS OF CONDENSER 37 (PARAFFIN PAPER)

Condenser temperature = 30 deg. cent.
Curve I $E$ = 50 volts
Curve II $E$ = 99 volts
Curve III $E$ = 147.5 volts
Curve IV $E$ = 197.5 volts

condenser 39 in which the leakage path over the edge of the mica sheets is short.

*Method used in the measurement of alternating loss and capacitance.*

18. A bridge method of measuring the loss and capacitance of the condensers was used. The circuit arrangement is shown in Fig. 7. The bridge is a modified Wien bridge. The resistances $R_1$ and $R_2$ were equal and had a resistance of 500 ohms. Then under balanced conditions the equivalent series capacitance of the test condenser $C$ is equal to the capacitance of the standard condenser $C_s$, and the equivalent series resistance of the condenser $C$ is equal to the resistance $R_3$. Then the tangent of the angle of phase difference of condenser $C$ will be

$$\tan \phi = R_3 \, \omega \, C_s$$

if it is assumed that the standard air condenser $C_s$ has a negligible phase difference or dielectric loss. The measurements of Giebe and Zickner[15] show that for technical air condensers this assumption may introduce errors as high as one minute in the phase difference. However, since no better air condenser was available

and since the phase difference of the air condenser that was used could not readily be determined, the assumption that the air condenser had negligible losses was used as a basis for the computation of the measured power-factor of the condensers.

The source of voltage for the bridge was a variable-

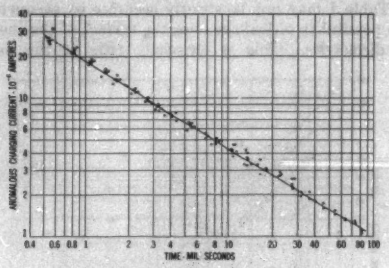


FIG. 9—TESTS OF CONDENSER 39 (MICA)

Condenser temperature = 30 deg. cent.
$E$ = 99 volts

frequency vacuum tube oscillator. A two-tube transformer-coupled audio-frequency amplifier was used as shown in Fig. 7 in order to get sufficient sensitivity for balancing the bridge. A telephone head-set was used

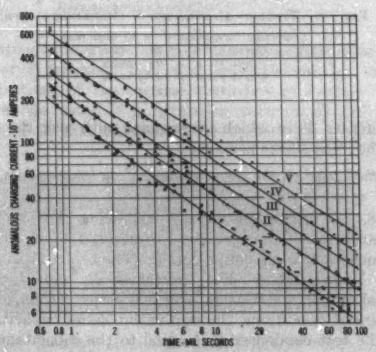


FIG. 10—TESTS OF CONDENSER 35 (GLASS) $E$ = 99 VOLTS

Curve I condenser temperature = 30 deg. cent.
Curve II condenser temperature = 40 deg. cent.
Curve III condenser temperature = 50 deg. cent.
Curve IV condenser temperature = 60 deg. cent.
Curve V condenser temperature = 70 deg. cent.

as a detector for frequencies from 200 to 4000 cycles per second. A set of observations was taken at a frequency of 100 cycles per second. The detector was a string galvanometer which was tuned to be resonant at this frequency.

## IV. RESULTS OF TESTS

*Results of tests of anomalous charging current.*

19. The methods used in determining the anomalous charging current curve for condensers have been discussed above (sections 9 to 14 inclusive). Sample records are shown in Figs. 5 and 6. The anomalous charging current curves were obtained by subtracting the ultimate leakage current from the currents derived from the oscillograph records. These curves are plotted to double logarithmic coordinates in Figs. 8, 9, 10, and 11. In these figures the points obtained by the two methods of test have been marked differently, the result of the "short-time" tests being indicated by circles or open figures and the results of the auxiliary method by dots or closed figures. From two to five records were usually taken for each condenser at each temperature

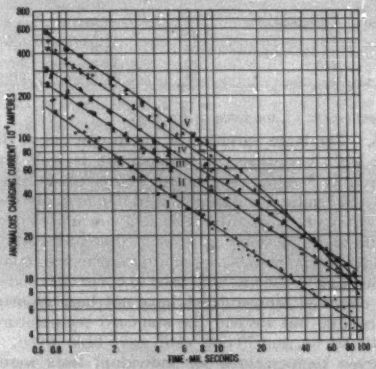


FIG. 11—TESTS OF CONDENSER 36 (TREATED CLOTH) $E$ = 99 VOLTS

Curve I condenser temperature = 30 deg. cent.
Curve II condenser temperature = 40 deg. cent.
Curve III condenser temperature = 50 deg. cent.
Curve IV condenser temperature = 60 deg. cent.
Curve V condenser temperature = 70 deg. cent.

by both methods of test. The results of all the tests were superposed on the graphs. No attempt has been made to distinguish one individual test from another. All the tests were considered in drawing the straight lines through the observed points.

The straight lines which have been drawn in these graphs are represented by the formula $i_a = K\,t^{-n}$. In nearly all cases, the observations fall along these straight lines, and, therefore, the anomalous charging current may be represented by the formula

$$i_a = E\,C_o\,\beta\,t^{-n}. \tag{15}$$

The instances in which the observations deviate from the straight line relations are shown in Curve II in Fig. 8, and in Curves *IV* and *V* in Fig. 11. The dotted curve in Fig. 8 would represent the observed points a

little more accurately than the straight line. However, the deviation from the straight line relation is not large compared to the possible experimental error. The deviations from the straight line relation in Fig. 11 are for the longer times and for the higher temperatures. Under these conditions, the final leakage current is from 30 to 85 per cent of the total observed current. It appears that when this is true the anomalous charging current cannot be accurately represented by Equation (15).

The dependence of the anomalous charging current on the applied voltage $E$ was tested for the paraffin paper condenser 37. The current-time curves for the various voltages used are shown in Fig. 8. Fig. 12 shows the dependence of the anomalous charging current on the voltage for different time intervals after application of the voltage. This figure shows that within the accuracy of the experiments the ordinates

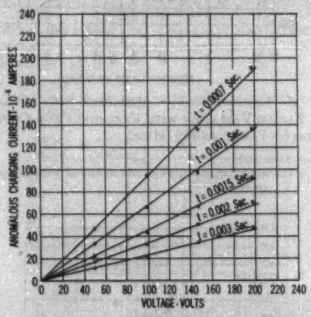


FIG. 12—ANOMALOUS CHARGING CURRENT VARIATION WITH APPLIED VOLTAGE FOR CONDENSER 37 (PARAFFIN PAPER)

of the anomalous charging current curve are directly proportional to the applied voltage, as indicated by Equation (15).

The constants $\beta$ and $n$ in Equation (15) were determined from the straight lines in Figs. 8, 9, 10, and 11. In order to determine the value of $n$ it is merely necessary to measure the slope of the straight line. In order to find $\beta$, however, it is necessary to know the geometric capacitance $C_o$. For a first approximation, the measured capacitance of the condenser at a frequency of 4000 cycles per second was used as $C_o$ in Equation (15), and by inserting measured values of $i_a$, $E$, $n$, and $t$ in Equation (15), an approximate value of $\beta$ was computed. Using this approximate value for $\beta$ and the value of $n$ obtained above, the ratio of the apparent capacitance at a frequency of 4000 cycles per second to the geometric capacitance ($C/C_o$) that would be expected on the basis of the theory was computed by means of Equation (13) (Section 7). A second approximation to $C_o$ was then obtained by the division of the measured value of $C$ at 4000 cycles per second by this computed ratio $C/C_o$. Then a second approximation to the value of $\beta$ was obtained by using this value of $C_o$ in Equation (15). The process could be repeated to obtain better approximations for $C_o$ and $\beta$, but the second approximation was sufficiently accurate in all cases. The values of the constants $\beta$, $n$, and $C_o$ for the condensers tested are given in Table II. The relative permittivities corresponding to the geometric capacitances have also been tabulated in Table II. The results for the relative

TABLE II

RESULTS FOR CONSTANTS IN THE ANOMALOUS CHARGING CURRENT FORMULA, EQUATION (15)

| Condenser | Temp. deg. cent. | Constants in the anomalous charging current formula, Equation (15) | | | Relative permittivity |
|---|---|---|---|---|---|
| | | $\beta$ | $n$ | $C_o - 10^{-9}$ farads | $p_r$ |
| 35-(Soda-lime glass) | 30 | 0.113 | 0.75 | 0.789 | 7.15 |
| | 40 | 0.211 | 0.70 | 0.800 | 7.25 |
| | 50 | 0.317 | 0.67 | 0.810 | 7.35 |
| | 60 | 0.396 | 0.69 | 0.804 | 7.29 |
| | 70 | 0.531 | 0.69 | 0.806 | 7.31 |
| 36 (Varnished cloth) | 30 | 0.165 | 0.75 | 0.448 | 3.82 |
| | 40 | 0.367 | 0.69 | 0.464 | 3.96 |
| | 50 | 0.456 | 0.69 | 0.475 | 4.05 |
| | 60 | 0.486 | 0.73 | 0.471 | 4.02 |
| | 70 | 0.588 | 0.74 | 0.471 | 4.02 |
| 37 (Paraffin paper) | 30 | 0.00765 | 0.92 | 1.510 | 3.6 |
| 39 (Mica) | 30 | 0.0255 | 0.63 | 0.945 | 6.3 |

permittivities of condensers 36 and 37 are somewhat uncertain because of a probable change of the thickness of the dielectric after the condenser was clamped together.

The thickness of the treated cloth for condenser 36 was measured by a micrometer before assembling the condenser. The thickness of the paper before treatment was used as the thickness of the sheets of paraffin paper in condenser 37. The actual thickness of the dielectric after clamping may be less than the measured thickness and therefore the values of relative permittivity may be too high.

*Results of measurements with alternating current.*

20. The results of the measurement of power factor and capacitance of the test condensers at various frequencies are shown by the solid curves in Figs. 13 to 18 inclusive. It may be seen that the measured power factor may either decrease (Fig. 13, Fig. 14, and curve for condenser 39 in Fig. 15) or increase (curve for condenser 37 in Fig. 15) as the frequency increases. The curves between the tangent of the phase difference angle ($\tan \phi$) and the frequency are practically straight lines for glass condenser 35 and paraffin paper condenser 37, and approximately so for mica condenser 39 and treated cloth condenser 36 at the lower temperatures. This shows that the relation between $\tan \phi$ and the

frequency may be represented by an equation of the form

$$\tan \phi = \frac{K}{f^{(1-n)}} \tag{16}$$

in the frequency range studied. This type of variation was found by MacLeod[9] and is approximately the type

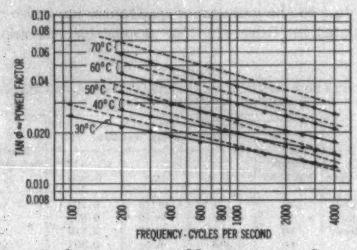


FIG. 13—COMPARISON OF MEASURED AND CALCULATED POWER FACTOR VARIATION WITH FREQUENCY FOR CONDENSER 35 (GLASS)

——o—— Measured
- - - - - Calculated on the basis of the measured anomalous charging current

of variation given by Equation (14); which is, neglecting the leakage conductance,

$$\tan \phi = \frac{\beta \pi}{\left[ \omega^{(1-n)} 2 \Gamma (n) \cos \frac{(1-n)\pi}{2} \right] \frac{C}{C_o}}$$

Since $C/C_o$ is practically equal to unity for good dielec-

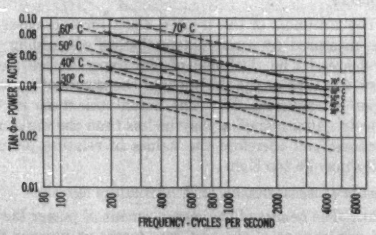


FIG. 14—COMPARISON OF MEASURED AND CALCULATED POWER FACTOR VARIATION WITH FREQUENCY FOR CONDENSER 36 (TREATED CLOTH)

——o—— Measured
- - - - - Calculated on the basis of the measured anomalous charging current

trics, the equation above gives the same type of variation of tan $\phi$ with frequency as is given in Equation (16). Therefore, the observed variation of power factor with frequency follows the law predicted by the theory.

The curves in Figs. 16, 17, and 18 show that the observed capacitance of the condensers decreases with increasing frequency.

*Comparison of loss caused by leakage conductance with total dielectric loss.*

21. The contribution of the normal leakage conductance to tan $\phi$, as given by the first term in the right side of Equation (14), namely $G_o/\omega C$, was computed for a frequency of 200 cycles per second. The normal

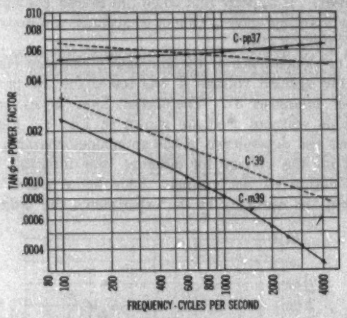


FIG. 15—COMPARISON OF MEASURED AND CALCULATED POWER FACTOR VARIATION WITH FREQUENCY FOR CONDENSERS 37 (PARAFFIN PAPER) AND 39 (MICA)

——o—— Measured
- - - - - Calculated on the basis of the measured anomalous charging current

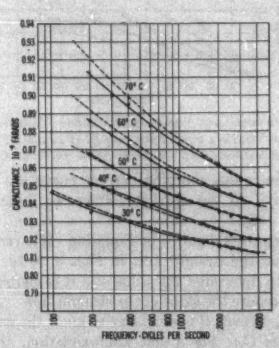


FIG. 16—COMPARISON OF MEASURED AND CALCULATED CAPACITANCE VARIATION WITH FREQUENCY FOR CONDENSER 35 (GLASS)

——o—— Measured
- - - - - Calculated on the basis of the measured anomalous charging current

leakage conductances are tabulated in Table I. The values of $G_o/\omega C$ are compared to the measured power factor of the condensers in Table III. This table shows that the loss contributed by the normal leakage current at 200 cycles per second at ordinary temperatures is from 0.0015 to 0.07 of the total dielectric loss.

At the higher temperatures and at lower frequencies the leakage loss may become an important part of the total dielectric loss. For the commercial frequency of 60 cycles per second it is estimated that the ratios of leakage loss to total loss would be about two to three times the values given in Table III. At frequencies higher than 200 cycles per second this ratio becomes smaller.

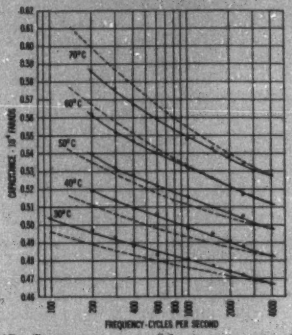


FIG. 17—COMPARISON OF MEASURED AND CALCULATED CAPACITANCE VARIATION WITH FREQUENCY FOR CONDENSER 36 (TREATED CLOTH)

———o— Measured
- - - - - Calculated on the basis of the measured anomalous charging current

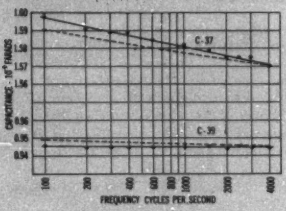


FIG. 18—COMPARISON OF THE MEASURED AND CALCULATED CAPACITANCE VARIATION WITH FREQUENCY FOR CONDENSERS 37 (PARAFFIN PAPER) AND 39 (MICA)

———o—Measured
- - - - - Calculated on the basis of the measured anomalous charging current

TABLE III
COMPARISON OF TOTAL DIELECTRIC LOSS TO LEAKAGE CONDUCTANCE LOSS

| Condenser | Temperature deg. cent. | Contribution of leakage conductance to $\tan\phi$, $G_0/\omega C$ Freq. = 200 cycles per sec. | Measured power-factor $\tan\phi$ | Ratio $\frac{G_0/\omega C}{\tan\phi}$ |
|---|---|---|---|---|
| 35 (Soda-lime glass) | 30 | 0.000033 | 0.0215 | 0.0015 |
| | 40 | 0.000139 | 0.0272 | 0.051 |
| | 50 | 0.00039 | 0.035 | 0.011 |
| | 60 | 0.00115 | 0.045 | 0.026 |
| | 70 | 0.0026 | 0.059 | 0.044 |
| 36 (Varnished cloth) | 30 | 0.000039 | 0.0355 | 0.0011 |
| | 40 | 0.00029 | 0.042 | 0.0069 |
| | 50 | 0.0083 | 0.051 | 0.016 |
| | 60 | 0.0025 | 0.064 | 0.039 |
| | 70 | 0.0060 | 0.081 | 0.074 |
| 37 Paraffin paper | 30 | 0.0000097 | 0.0053 | 0.0018 |
| 39 Mica | 30 | 0.0000072 | 0.00177 | 0.0041 |

*Comparison of the measured power-factor and capacitance with that calculated on the basis of the measured anomalous charging current.*

22. The determinations of the anomalous charging current curves for the condensers make possible the calculation of the behavior of the condenser under alternating electromotive force. The results for the constants $\beta$ and $n$ as determined from the anomalous charging current tests and as given in Table II were used to calculate the power factor and capacitance at different frequencies. Equations (13) and (14) were used for these computations. Comparisons between the calculated and measured power factors and capacitances are shown in Figs. 13 to 18 inclusive. In these figures, the measured values are spotted and are represented by the full curves, while the calculated values are represented by the dashed curves.

The calculated power-factor curves are, in general, in fair agreement with the observed curves. The better agreement is found in the lower end of the frequency range. This could be expected from a consideration of the time intervals during which the anomalous charging currents were measured. The anomalous charging current measured with direct voltage applied during a range of time equivalent to, say, from one-tenth to five periods of a particular alternating wave is most important for the prediction of the loss at that particular frequency. If Equation (15) for the anomalous charging current were valid for all times, it would suffice to determine the constants $\beta$ and $n$ during any time range, say by galvanometer measurements from 30 to 300 sec. after voltage is applied. However, Equation (15) is only an approximation formula and it is necessary to determine the constants in Equation (15) for short times of the order indicated above if the losses for a given frequency of applied alternating voltage are to be predicted.

The capacitance variation predicted on the basis of the measured anomalous charging current curves is, in general, in good agreement with the observed variation. The measured value of the capacitance at 4000 cycles per second was used as a basis for computing the geometric capacitance $C_o$, and therefore was also the basis for the predicted curves in Figs. 16, 17, and 18. It may be seen that the glass condenser 35, which shows the closest agreement between measured and computed power factor, also shows the closest agreement between computed and measured capacitance.

## V. CONCLUSIONS ON THE BEHAVIOR OF THE ANOMALOUS CHARGING CURRENT

23. These experiments show that for the dielectrics studied the empirical equation

$$i_a = E\,C_o\,\beta\,t^{-n}$$

is a good approximation for the anomalous charging current in a condenser in the time range studied; namely, for the interval from 0.7 to 100 mil-sec. after impressing the charging electromotive force. In this formula the constants $\beta$ and $n$ are constants of the dielectric which depend, however, on its temperature, moisture content, impurities, and previous preparation. The tests at elevated temperatures showed that the constant $n$ remains nearly constant as the temperature is increased while the constant $\beta$ increases rapidly for glass and varnished cloth.

The alternating anomalous charging current as computed from the $\beta t^{-n}$ anomalous charging current function derived from the d-c. measurements is sufficient to account for the major portion of the losses at low frequency in the solid dielectrics studied. For these dielectrics, the computed loss based on the normal leakage current varied from less than one-half of one per cent of the total measured loss at a frequency of 200 cycles per second and at a temperature of 30 deg. cent. to a maximum of about eight per cent at the same frequency and at 70 deg. cent.

The capacitance variation with frequency as computed on the basis of the measured anomalous charging current is in fair agreement with the measured variation in the frequency range studied.

The data obtained are insufficient to allow a choice among the theories of the underlying physical nature of solid dielectrics having losses. The explanations which seem most plausible at the present time are those based on the anomalies of conduction (accumulation of ions at the electrodes, movement of ions in submicroscopic cleavages or in limited paths)[16] or on the properties of dipolar molecules.[17,18] The observations in favor of the first explanation are those on the intimate relation between the anomalous charging current and the final conduction current, and the identification of the conduction current in dielectrics with the movement of ions within the material. It may be noted that in order that a substance made up of dipolar molecules may give an anomalous charging current function as found in these experiments $[\phi(t) = \beta t^{-n}]$ it would be necessary that the different dipoles or complexes of dipoles have widely different "relaxation times." That is, a single kind of dipole would not be sufficient to account for the observed curves. The wide distribution of relaxation times necessary might be accounted for on the basis of the association of the molecular dipoles into aggregates. The impurities having molecules of a distinctly dipolar character (water, for example) might have a great effect on the behavior of the dielectric.

ACKNOWLEDGMENT

I wish to acknowledge my indebtedness to Professor Edward Bennett for valuable suggestions and counsel, and to the Wisconsin Utilities Association and the Regents of the University of Wisconsin for financial aid for this work.

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## Discussion

**W. B. Kouwenhoven:** Professor Benedict's paper is a very interesting one and there are two points upon which I wish that he would furnish additional data, namely:

1. In Fig. 7 of the paper is shown the simple diagram of a Wien bridge. I should like to know if the author used this bridge without shields or guards? I have used this bridge in a "Study of the Phase Defect Angle of Air Capacitors." I found that unless the most careful guarding and shielding was provided, and their potentials properly adjusted, the results obtained were in error.

2. The author reports a good agreement between his direct and alternating current loss measurements. I should like to ask him if he used the same value of voltage in both tests.

In our tests at Johns Hopkins University we have found in a number of cases a good agreement between the a-c. and d-c. results when both were made under the same effective stress. Dr. Whitehead reported in a Franklin Institute paper entitled "Dielectric Absorption and Dielectric Loss," Vol. 208, Oct. 1929, a good agreement for specimens of impregnated paper in which the loss was due to absorption. I have made some measurements on a good grade of insulating compound in which conduction

accounts for all of the dielectric loss. In the table below are given some results obtained at 70 deg. cent.

| Voltage gradient volts per mil | A-c. 60 cycle loss micro-watts | D-c. conduction loss micro-watts |
|---|---|---|
| 8.3 | 161 | 167 |
| 16.7 | 575 | 680 |
| 25.0 | 1590 | 1600 |

The continuous current records were obtained from oscillograms using a method similar in principle to that of Professor Benedict's. The comparisons in Dr. Whitehead's and my tests were made at the same effective a-c. and d-c. voltages.

**V. Karapetoff:** There is a feature of research in dielectrics which may be of interest to those present, and that is the connection between this research and the progress in pure physics, chemistry, and mathematics. We have a distinct group of dielectricians among electrical engineers who are working either separately or on one or two committees, among others the Committee on Electrical Insulation of the National Research Council. At the same time we have separate groups of pure physicists, chemists, and mathematicians mostly working on problems of great importance to us and yet not being aware of their importance nor there being much connection between the two.

The Committee on Electrical Insulation, realizing the existence of such a gap, formed two subcommittees, one on physics and one on chemistry, in an endeavor to bridge the gap. While many useful results are being obtained by the work of dielectricians by themselves, yet the experience in the progress of other branches of electrical engineering unmistakably points out that we must draw from the recent advances of the pure sciences.

This is a more difficult undertaking than may appear on the surface because of the absence of a common ground or of a definite bridge or channels for a free flow of this information. A person could go over our papers on dielectrics and extract all the special terms used therein, such as ionization, critical potential, absorption, and so forth. With these terms one can obtain only a definite number of combinations and permutations. So that no matter what you say, it is only a new combination of these old terms. In order to bring about a distinct progress it is of importance to enrich our vocabulary with new terms, new concepts, and new combinations of ideas.

What would you say of a group of engineers who in their chemical difficulties were using the chemistry of the latter part of the eighteenth century, on the plea that what has occurred after that is too complicated and theoretical? In the same way, if you look over our old papers on dielectrics you will often find the theory based on fictitious condensers and resistances in parallel. Then, grudgingly, and against the opposition of older men, the term "ionization" was introduced and the idea of discontinuity in the structure of gases. Since then the progress has been more rapid. Yet there are a great many recent terms in pure physics and chemistry that are yet to be introduced into our profession. Ultimately their introduction is inevitable. Looking forward some twenty or thirty years I know that they will be used. Why wait, then? Why not make a determined effort to establish more channels between the two branches of science, pure and applied, right now?

**Bela Gati:** Three decades ago a big cable factory wanted to sue me because I had written in one of my articles that the insulation of its telephone cable measured with direct current and found to be 2000 megohms, had not even one megohm insulation measured by telephone frequency current. I think everybody is convinced today, that there is in reality a difference between the values when measured with direct current one minute electrification, and when measured with high-frequency or telephone frequency current. I appreciate the University men who for the most part have made this fact clear and understandable for the general knowledge.

I should like to ask Mr. Benedict about the formula between the molecular structure of the dielectric material and the dielectric capacity of same, furthermore whether he has found any connection between the molecular structure and the dielectric loss of the dielectric material. I want to take only one very simple example. Plain water has the chemical structure of $H_2O$. This compound is in reality $H_{2n}O_n$. It is only steam which has two hydrogens and one oxygen. The liquid water has probably more than three molecules. Taking the human blood, for instance, the haemoglobin has a molecular structure of about 17,000 molecules. I cannot imagine that the blood liquid has only 2 parts hydrogen and one part oxygen in its compound; a verification is necessary for this. I imagine that measuring the dielectric loss and the dielectric capacity of the blood liquid with various frequencies, perhaps we could find out what our blood is in reality, what cyclic compounds exist in it, what at present we do not know. The blood is the most miraculous liquid.

From another point of view, in case any one takes too much alcohol, then the latent oxygen of the tissues is decreased. We can counteract this detrimental effect, if we know the exact condition of the tissues. Of course it is very difficult to make experiments, but if we can measure, for instance, the dielectric loss and the dielectric capacity of the whole body, perhaps we can reach some result. We can counteract the loss of the latent oxygen in the tissues; we can fight with success against the alcoholic habit.

**J. B. Whitehead:** The question of the cause of the energy losses in dielectrics and insulation subjected to alternating stress has been an unsolved riddle to both engineers and physicists, ever since the importance of this loss was first recognized by Siemens in his observations on condensers in 1864. For a time it was assumed that these losses were similar in character to those due to hysteresis in iron. Many experimental facts, however, show that this assumption is untenable, and the many investigators who have attacked this question have had to look elsewhere for an explanation of dielectric loss and other anomalies of dielectric behavior. No completely satisfactory theory of the nature of dielectric loss has yet been proposed, but it has been found possible to connect both theoretically and experimentally two of the most important anomalous properties of dielectrics. Mr. Benedict's paper does not attempt to throw any new light on the nature of dielectric loss, but does present many interesting and important evidences of the relationship between dielectric loss and that other conspicuous dielectric anomaly, dielectric absorption.

This paper is especially interesting to me because, with my colleagues at Johns Hopkins, I have carried out experiments of a similar nature with an almost identical method. The first results of this work were published in the *Journal of the Franklin Institute* for November 1929. We worked with a carefully prepared impregnated paper condenser at 60 cycles, within the range 500 to 1500 volts and at one temperature. We found an exceedingly close agreement between the measured loss and that computed in terms of dielectric absorption. The summary of our results is given in the attached table:

TABLE I

COMPARISON OF COMPUTED AND MEASURED VALUES OF LOSS

| | $\varphi(t) = B \cdot C \cdot t^{-n}$ | | | $\varphi(t) = m \cdot C \cdot e^{-\alpha t}$ | | | |
|---|---|---|---|---|---|---|---|
| Volts | $n$ | $\frac{B}{E}$ | Loss watts comp. | $\alpha$ | $\frac{m}{E}$ | Loss watts comp. | Loss watts obs. |
| 500 | 1.06 | 2.65 | .00042 | 578 | 6.03 | .00032 | .00033 |
| 1000 | 1.06 | 2.52 | .0017 | 578 | 5.66 | .00131 | .00132 |
| 1500 | 1.06 | 2.57 | .00377 | 578 | 5.75 | .00295 | .00297 |
| Average | 1.06 | 2.58 | | 578 | 5.82 | | |

Mr. Benedict has extended the same type of study over a considerable range of temperature and a wider range of frequency, and it is a pleasure to find that his observations show general agreement between computed and measured values under the wide variation of conditions mentioned.

However, the agreement between computation and measurements in Mr. Benedict's results is not all that could be desired, in the matter of the variation of loss or power factor with frequency, as indicated, particularly in the cases of the treated cloth and mica condensers, in Figs. 14 and 15.

I wish to make the following suggestions as possible causes of some of the discrepancies in his results:

1. The question of the presence of an irreversible absorption component in the charging current of the condenser. I think it probable that this component of current was present in all condensers, with the possible exception of that of mica. The unusually high values of leakage current would appear to confirm this. In our own work we found it important to take discharge as well as charge curves for information as to the presence or absence of this component. Its presence in any considerable amount might have an important effect on the values of the computed loss, which might or might not have a corresponding influence on the measured loss. I should think that this might well account for a considerable part of the increased measured losses over those computed at high frequencies, in the case of treated cloth especially.

(2) Several questions arise in connection with the methods of assembly and measurement. For example, apparently none of the condensers, including the air condenser of the bridge, was equipped with guard rings. If this is true, it might well lead to variable leakage in the condensers, and particularly to errors in measured values over a range of frequency. There is also the question of the actual temperature within the condensers. At the high values of power factor shown in Table III, it is probable that the losses as measured pertain to higher values of temperature than those indicated by external thermometers. This also would have the effect of lifting the curves in Fig. 14. No statement is made as to the voltages at which corresponding continuous and alternating measurements were made. The check with theory requires that they should have the same effective value. The linear relationship between charging current and voltage, as shown in Fig. 12, is by no means universal as among various dielectric materials.

3. The question of the relationship between the period of the alternating circuit and that of the charging current or absorption curve is an important one and is mentioned by the author as a possible cause of the discrepancies between computed and measured values. I agree in general with this, and think the charging current curve should be read and its equation computed for a time interval beginning less than one-half period after closing the circuit and lasting not much longer than one period.

4. The author uses the negative power of the time for the decay of the charging current under continuous potential, as indicated in formula (11). Moreover, the curves of Fig. 8 seem to warrant this choice. It is an interesting fact that the results of many other observers seem to indicate this relationship. Yet it is obviously not the correct form for the decaying function of the time, inasmuch as it indicates infinite current at zero time. Consequently as we observe these charging curves nearer and nearer to their beginnings, it is evident that the actual values must fall below those computed from the relation of Equations (1) and (11). An error of this kind would tend to throw the computed values of loss higher than the measured values, as indicated especially in Figs. 13 and 15. I should like to ask the author whether he has examined his observations for short intervals of time, from the standpoint of a negative exponential relation with time for the charging curve. In our own work, referred to above, we find a much better, and in fact an extremely close agreement between computed and measured values, in using the negative exponential relation.

In formula (16) the author suggests that the power factor is definitely related to the frequency by an inverse power of the latter. This is indicated by the straight lines of Fig. 16 but is not a fixed relation. However, experimental curves over a wide range of frequency show that the power factor passes through a maximum at a definite frequency. This question has been examined analytically by Bouasse and Lahousse from the standpoint of absorption, and the variation mentioned is definitely accounted for. Presumably if the author had extended his studies in the direction of still lower frequencies this maximum might have been reached. An approach to it is suggested by the lower curve of Fig. 15.

As regards the correct explanation of dielectric loss, it is my opinion that it is entirely due to electric conduction, *i. e.*, that the losses arise in the electric resistance of the material. It must be understood, however, that the conduction is highly anomalous in character and may have different origins and follow different laws for a variation of materials and conditions. The decreasing charging current may readily be explained in terms of the motion of ions, their withdrawal, and their accumulation as space charges, as set forth in the paper by Dr. Marvin and myself in today's program. As regards the suggestion that the oscillation of polar molecules may account for dielectric loss, I think this may be true in part for frequencies say above 100,000. But for the range of commercial frequencies, from the nature of the theory of polar molecules, and our knowledge of their behavior in other phenomena, a loss due to this cause is entirely negligible.

**S. K. Waldorf:** As you have been told, we at Johns Hopkins are working along similar lines, so a comparison of methods should be of interest. In his oscillographic studies, Mr. Benedict used a rather unique method for obtaining very short periods of low sensitivity, down to about eight hundredths of a millisecond in duration. He used a small rifle which was discharged, the bullet cutting very small strips of metal, and in that way operating the circuit very rapidly. We have employed a quick acting spring operated switch in which a small rocker arm, released by the oscillograph shutter circuit, applies the high voltage to the specimen. An instant later, this instant being adjustable from about a tenth of a millisecond to about ten milliseconds, the sensitivity of the amplifier-oscillograph is changed from the very low value used to by-pass the geometric charge to a very high value for recording the residual current. The circuit is also arranged to take care of discharge as well as charge currents.

We also are using a higher film speed for the most part, running it at about 18 feet per second, to obtain greater accuracy in our measurements of time. I think, if I am correct, that his film speeds are about eight feet per second. For very special work, as in oils, we slow it down to as low as about two and a half inches per second.

Another interesting point is that we have used the high sensitivity oscillograph vibrator, as Mr. Benedict has done, because it uses relatively very little current. Unfortunately, to get this high current sensitivity, the vibrator is lacking in frequency response. For our high-speed work on dielectrics, as most of it is, we use a so-called standard vibrator because it gives a little better frequency response and consequently will more faithfully reproduce the actual current of charge or discharge.

There are a few questions that come to mind because, as I say, we in this work are very anxious to get improved methods if we can. I believe from the data given in the paper, Mr. Benedict used d-c. voltages only up to 200. I should like to know if any higher voltages were used, as we are using up to 1500 volts d-c. at the present time and this high voltage has caused a great deal of troublesome transients in the measuring circuits. We think we now have them eliminated by careful shielding and grounding, so it would be interesting to hear if Mr. Benedict met with similar difficulties.

There are a few questions about this amplifier I should like

him to answer in his closing. I believe the four-element tubes he has there are the UX-222 of the Radio Corporation. I should like to know authoritatively what the type is. I should also like to know the type of tube used in the output circuit, its manufacturer, and the plate voltage used there. As Mr. Benedict has said, the oscillograph vibrator has a steady current passing through it all the time. I should very much like to know the approximate value of this current, and the change in the current through a given vibrator for a given deflection.

**C. L. Dawes:** (communicated after adjournment) In the paper by Mr. Benedict an interesting comparison is made between the values of power factor computed from current-time curves by means of the von Schweidler function and values determined experimentally with a Wien bridge. The results are given in Figs. 13, 14, and 15. The agreement between computed and experimental values is, I believe, as close as may be expected. The measured values may, however, be in error, unless shielding not shown in Fig. 7 is used. For example, the junction of $R_2$ and $C_4$ is above ground potential by the voltage drop in $R_3$. Hence there is capacitance current from the plate of $C_s$ which is connected to $R_3$, to ground. This current has the effect of making the power factor of the test condenser $C$ less than it actually is. This effect increases with frequency and tends to make the power factor of the test specimen lower with increase in frequency. This effect is not borne out by the curves in Figs. 13, 14, and 15, but nevertheless I believe that it should be investigated by the author.

The direct-current measurements were made at 100 volts and the alternating-current measurements were made apparently at low voltage. It probably would have been more rational were the a-c. measurements made at approximately the same voltage as the d-c. measurements.

Table III shows that leakage conductance contributes little to the power factor. This has been our experience. On the other hand, Dr. Whitehead on page 7 of his paper states that the apparent resistance computed from the charging-current curves are of the correct order of magnitude to account for the alternating-current loss. May I ask the authors if they can reconcile these two statements?

Moreover, it would have been interesting if Mr. Benedict could have computed losses down to very low frequencies. For example, we have found that between frequencies of 25 and 75 cycles per second the power loss in oils, compounds, and glass is a linear function of the frequency. (*Elec. Wld.*, Vol. 91, 1928, p. 1331.) Were the graphs extrapolated to zero frequency the corresponding loss is of much higher order of magnitude than the measured d-c. loss. Apparently it is not known whether this is due to a variation in the power-frequency function at the lowest frequencies or to an abrupt discontinuity in the function near zero frequency.

**R. R. Benedict:** Several questions have arisen concerning the bridge method of measuring power loss in condensers which was used in obtaining the data presented in my paper. The variable air condenser which was taken as the standard of comparison and which was assumed to have zero losses was a General Radio Co. condenser Type 246L, and this condenser will be referred to as No. 720. It had a capacitance range from about $55 \times 10^{-12}$ to $1550 \times 10^{-12}$ farads. This condenser was used as $C_s$ in Fig. 7 of the paper in all of the tests except that of condenser 37. For this test a General Radio Co. air condenser Type 246M, to be designated by No. 792, was used as $C_s$. This condenser had a capacitance range from about $80 \times 10^{-12}$ to $3030 \times 10^{-12}$ farads.

At the time of the measurements the behavior of the bridge was tested in the following manner. The air condenser No. 792 was placed at $C$ in Fig. 7 and a series of balances was obtained with condenser No. 720 as $C_s$. The apparent power-factor differences between the two air condensers as observed in this test are given in Table I.

TABLE I

| Frequency cycles per sec. | Capacitance $10^{-9}$ farads | Power-factor difference |
|---|---|---|
| 600 | 0.906 | 0.00001 |
| 1000 | 0.906 | 0.00002 |
| 4000 | 0.906 | 0.00007 |

The apparent power-factor differences given in the table may have been caused by disturbing factors in the bridge rather than by real differences in the losses in the air condensers.

An attempt was made recently to get a comparison of the losses in these two condensers, and also a comparison of the losses in these condensers with those in a third air condenser. This third air condenser was a so-called "low-loss" condenser designed for use in radio receiving sets. The electrodes of this condenser were insulated by two strips of clear bakelite arranged so that the losses in the insulation would be a minimum. The procedure in the tests was as follows. With one air condenser at $C_s$ in Fig. 7 the "low-loss" condenser and the remaining air condenser were placed in succession at $C$ in the bridge and a balance was obtained for each. The difference in the apparent power factor for the two cases was taken as an indication of the difference in the power factors of the two condensers which had been placed in the $C$ arm of the bridge. The results obtained in these tests are given in Table II.

TABLE II

| Frequency cycles per sec. | Power-factor differences | |
|---|---|---|
| | No. 792—"low-loss" | No. 720—"low-loss" |
| 300 | 0.00011 | 0.00007 |
| 600 | 0.00011 | 0.00007 |
| 1000 | 0.00009 | 0.00006 |
| 2000 | 0.00008 | 0.00006 |
| 3000 | 0.00006 | 0.00006 |
| 4000 | 0.00004 | 0.00006 |

The capacitance was adjusted to $0.45 \times 10^{-9}$ farads in eard case. This test shows that the power factors of the standach condensers are apparently somewhat higher than those of the "low-loss" condenser. If the standard condensers are assumed to have power factors which do not exceed 0.0002 it may be seen that the errors introduced from this source into the measurements are less than 4 per cent for all results (Figs. 13, 14, 15) except for the measurements of the power-factor of the mica condenser 39 (Fig. 15). For this condenser the correction would be quite a large percentage of the measured values, especially at the higher frequencies.

The selection of a one to one ratio for resistances $R_1$ and $R_2$ of the bridge circuit reduces the effects of the stray capacitances shunting these arms of the bridge. As Mr. C. L. Dawes points out, the stray capacitance shunting the resistance $R_2$ of the bridge circuit may affect the measurements. The magnitude of the errors which may have arisen from this source has been tested by the following experiment. A series arrangement of two decade resistances and an air condenser was placed in the $C$ arm of the bridge. One resistance designated $R_5$ was connected from the "top" corner of the bridge to the air condenser while the other resistance designated $R_4$ was connected from the air condenser to the "right-hand" corner of the bridge. The bridge was balanced with a given resistance setting for $R_4$ and with $R_5$ equal to zero. Then the bridge was rebalanced with the resistance $R_5$ adjusted to the same value to which $R_4$ had previously been set and with $R_4$ equal to zero. The difference in the apparent power factors for the two conditions was taken as an indication of the effect of the stray capacitance shunting $R_4$ on the observed power factor. On account of the symmetry of the

bridge, the effect of the stray capacitance shunting $R_3$ will be practically the same as that shunting $R_4$. For a given run the values of $R_4$ and $R_3$ were so chosen as to give a constant apparent power factor of the $C$ arm of the bridge. The results with condenser No. 720 at $C$ at a setting equivalent to a capacitance of $0.45 \times 10^{-6}$ farads is given in Table III.

TABLE III

| Frequency cycles per second | Power-factor difference with resistance in $C$ arm at $R_4$ and at $R_3$ Power factor of $C$ arm at head of column | | |
|---|---|---|---|
| | 0.000373 | 0.00186 | 0.0298 |
| 300 | 0.00001 | 0.00011 | 0.0013 |
| 600 | 0.00002 | 0.00011 | 0.0011 |
| 1000 | 0.00002 | 0.00004 | 0.0007 |
| 2000 | 0.00002 | 0.00004 | 0.0015 |
| 3000 | 0.00002 | 0.00004 | 0.0015 |
| 4000 | 0.00000 | 0.00002 | 0.0015 |

The measured power factor was higher in each case when the resistance was at $R_4$ in the $C$ arm. The maximum difference in power factor observed amounts to 6 per cent of the power factor of the $C$ arm. Thus the stray capacitance effects may have caused errors as high as 6 per cent in the power-factor measurements of the test condensers.

The voltage across the test condensers in the a-c. measurements was low, being of the order of 5 to 10 volts r. m. s. The following calculation shows that the temperature rise of the condenser caused by the dielectric loss in the condenser during the a-c. measurements is negligibly small. For condenser 36 under conditions of maximum power loss, that is, at a temperature of 70 deg. cent. and a frequency of 4000 cycles per second, the dielectric loss for an impressed voltage of 10 volts is $5.7 \times 10^{-5}$ watts. If all the heat generated were retained in the dielectric this loss would raise its temperature about 0.2 degree per hour.

It was not considered necessary to make the a-c. measurements at the same voltage as the d-c. measurements because of the fact that most previous studies of the losses in solid dielectrics show that at low electric stresses the dielectric loss is directly proportional to the square of the voltage. In other words, the power factor is independent of the impressed voltage.

Most of the tests of the anomalous charging currents of the condensers were carried out at one voltage. No discharge curves were obtained in the d-c. experiments on the condensers. Thus in the calculation of the losses in the condensers on the basis of the data obtained in the d-c. tests it was necessary to assume that the superposition principle was valid for the condensers tested, or in other words to assume that an "irreversible" component of the anomalous current was absent. The fact that the computed and measured losses are in fair agreement tends to show that the assumption was justified.

Dr. Whitehead questions the validity of Equation (15) for shorter and shorter times after the voltage application. Equation (15) indicates the impossible result that at zero time the anomalous charging current would become infinite. F. Tank has noted that since it is impossible to impress a steady voltage $E$ on a condenser $C$ in zero time it follows that Equation (15) contains no logical contradiction. However, it must be remembered that Equation (15) is an empirical equation which may or may not hold for wider ranges of time.

F. Tank[1] has also given a discussion of the maximum frequency at which it is permissible to predict the alternating losses in a condenser for which the anomalous charging current has been determined down to a minimum time $t_1$. He concludes that if $t_1$ is 0.0008 seconds then predictions of losses for frequencies higher than 100 cycles per second become uncertain.

The tubes used in the amplifier shown in Fig. 3 of the paper may be described as follows. The first tube from the left was a Marconi S-625 tube. The second tube was a Cunningham CX 322 tube. The third and fourth tubes were Cunningham CX 371A tubes. The potential applied to the plates of the output tubes was 150 volts, and the steady plate current in the output circuit was 10 milliamperes. The amplifier was constructed in the summer of 1928.

1. See the second article under reference 8 of the paper.

# Three Regions of Dielectric Breakdown

BY P. H. MOON[1] and A. S. NORCROSS[1]
Member, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—In a previous paper, the writers published results on the dielectric strength of various glasses and concluded that for ordinary thicknesses there were three distinct types of breakdown. The present paper emphasizes the fact that this is true not only for glass but also for fused quartz and for celluloid. By the elimination of edge-effect the following breakdown gradients were obtained: For celluloid, 2,500,000 volts/cm.; for glass, 3,100,000 to 5,000,000 volts/cm.; and for mica, 10,600,000 volts/cm. The various methods of eliminating edge-effect are discussed and compared and an attempt is made to correlate the electrical properties of the glasses with their chemical composition.*

* * * * *

ONE of the most outstanding advances in dielectric testing methods made in recent years has been the elimination of edge breakdown. In the past, uniform materials such as glass and mica failed almost invariably at or near the electrode edge, and it is only within the last few years that this trouble has been eliminated.

Edge breakdowns give data of little value for two reasons:

1. The actual breakdown gradient cannot be calculated, since it depends not only upon the exact shape of the electrode edge, but also upon the surface conductivity, the amount of corona, the properties of the immersing medium, and various other factors of unknown magnitude.

2. The gradient varies from point to point throughout the length of the breakdown path. Thus the problem, even if it were amenable to calculation, is a complicated one; and it would seem advisable to settle the question of breakdown in a uniform field before attempting the more difficult one of breakdown in a non-homogeneous field.

Thanks principally to the excellent work of Inge and Walther of Leningrad,[2] there are today several methods of forcing the punctures to occur in the uniform field under the electrode. Inge and Walther eliminated "edge-effect" by testing thin spheres blown from glass tubing. They also made use of special semi-conducting baths in testing flat specimens. By these methods they were able to increase the breakdown gradient to about ten times the usual value and thus they obtained what is apparently the true breakdown strength of the material. Their curves showed the region of thermal breakdown as well as the "disruptive" breakdown region, but failed to give conclusive evidence as to what lay between the two.

Accordingly, an investigation was begun at M. I. T. to study the matter in greater detail. Numerous breakdown tests made on hollow glass spheres during the summer of 1928 lead the writers to the belief that for ordinary thicknesses there existed *three distinct types of breakdown* rather than two. The results of these tests were presented by Dr. V. Bush before the Insulation Committee of the National Research Council in November 1928. They have also been published.[3]

Further work by the writers and by six other investigators, using different apparatus and various methods, has led to the same conclusions. The investigation has been extended to various glasses, fused quartz, celluloid, and mica. The purpose of this paper is to present a résumé of all the breakdown data recently obtained in the Electrical Research Laboratories of the Massachusetts Institute of Technology.

## Apparatus and Methods

All tests were made with direct potentials obtained either from a 100-kv. kenotron set or from a 4000-volt motor-generator set. Voltages were measured with a 100-kv. electrostatic voltmeter or with a D'Arsonval voltmeter equipped with a 20-kv. multiplier. Most of the tests on spheres were made with the apparatus previously described,[4] while tests on flat specimens were made in various semi-conducting baths or in air within an electric oven specially designed to maintain a constant temperature throughout the interior. Two sets of electrodes were used, one with sharp edges and one with edges rounded to a 3.2-mm. radius. Both had the same area in contact with the dielectric, this area being 15.9 mm. in diameter. Freezing mixtures and solid $CO_2$ were used in obtaining low temperatures. Thickness was measured with a micrometer by taking the lowest of a half-dozen readings made in the immediate vicinity of the puncture.

## Materials

The first tests were made on G-1 glass (a lead glass manufactured by the Corning Glass Works). The glass tubing was blown into the form shown in Fig. 1. Breakdowns occurred in the thinnest portions where the field was practically uniform. Similar tests were made on ordinary soda-lime glass manufactured by the

1. Both of the Massachusetts Institute of Technology, Cambridge, Mass.

2. Inge and Walther, "Durchschlag von Glas in homogenen und nichthomogenen elektrischen Feldern," *Archiv. f. El.*, 19, 1928, p. 257, *Archiv. f. El.*, 22, 1929, p. 410.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

3. Moon and Norcross, "Three Mechanisms of Breakdown Obtained on Glass by Elimination of Edge-Effect," *Franklin Inst. Jl.*, Dec. 1929.

4. Moon and Norcross, *loc. cit.*

Kimble Glass Company, and on the laboratory grade of Pyrex. Flat sheets of G-1 and German microscope cover glass were also tested. The fused quartz was "Vitreosil" which was kindly furnished by the Thermal Syndicate, Ltd. The mica was a high grade of India ruby mica having the approximate composition $H_2KAl_3(SiO_4)_3$. The celluloid was a clear transparent cellulose nitrate made by the Eastman Kodak Co. It

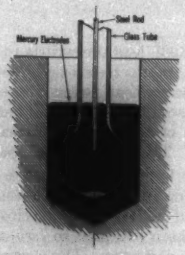



FIG. 1—FORM OF GLASS SPECIMEN USED IN BREAKDOWN TESTS

was tested as received without any baking or other treatment. The chemical compositions (approximate) of the various glasses are given in Table I.

TABLE I
COMPOSITION OF GLASSES

| | G-1 glass | Lime glass | Laboratory Pyrex | Fused quartz |
|---|---|---|---|---|
| $SiO_2$ | 66% | 69.7% | 80.8% | 99.8% + |
| $Na_2O$ | 7.5 | 15.0 | 4.1 | trace |
| $K_2O$ | 6.3 | .. | 0.1 | .. |
| CaO | .. | 6.0 | 0.3 | .. |
| $Ba_2O_3$ | .. | 1.5 | 12.0 | .. |
| Lead oxide | 20 + | .. | .. | .. |
| Alumina | trace | 2.5 | 2.2 | .. |
| Magnesia | .. | 3.8 | .. | .. |
| Boric Acid | .. | 1.0 | .. | .. |

Resistivities were measured on direct current with a D'Arsonval galvanometer, readings being taken after five or ten minutes when equilibrium conditions had apparently been reached. Electrodes and guard rings were of mercury or graphite or were chemically silvered on the glass. Table II gives the resistivity data on the materials. Here $\theta$ is the temperature at which the measurements were made, while $A$ and $B$ are the constants in Poole's equation:

$$\log \rho = A - B X$$

where $\rho$ is the resistivity in ohm-cm. and $X$ is the gradient in millions of volts per cm. It is obvious that the values of $A$ are a measure by which the relative resistivities of the various materials can be compared.

TABLE II
RESISTIVITY

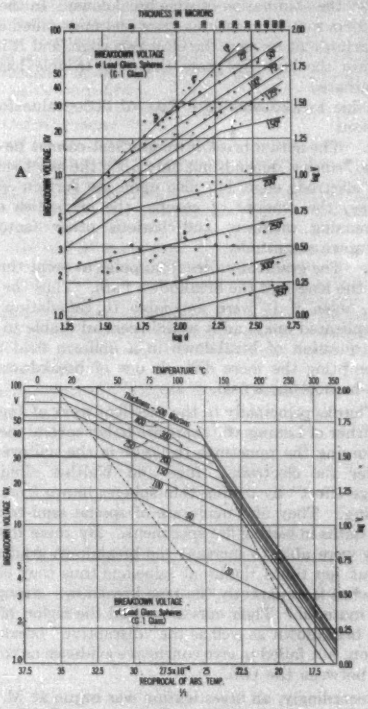
| | G-1 glass | Lime glass | Laboratory Pyrex | Cover glass | Mica |
|---|---|---|---|---|---|
| $\theta$, deg. cent. | 24.5 | 27.6 | 24.0 | 29.0 | 24.0 |
| A | 14.86 | 11.55 | 13.80 | 12.71 | 16.30 |
| B | 1.20 | 1.37 | 1.60 | 1.23 | 0.90 |

## THE THREE REGIONS—TESTS ON SPHERES

*G-1 Glass.* The results obtained on G-1 glass spheres are shown in Figs. 2A and 2B. Here the potential differences are expressed in kilovolts and the thicknesses in microns ($1\ \mu = 0.001$ mm.). In Fig. 2A the logarithm of breakdown voltage is plotted against logarithm of thickness in order to obtain straight lines. Each point represents a single breakdown measurement. It will be noted that the results seem to fall into three classes:

1. At low temperature the breakdown curve has the slope of unity. ($V = K_1 d$)

2. At higher temperatures, the points are well




FIGS. 2A, 2B—BREAKDOWN OF LEAD GLASS (G-1 GLASS) SPHERES

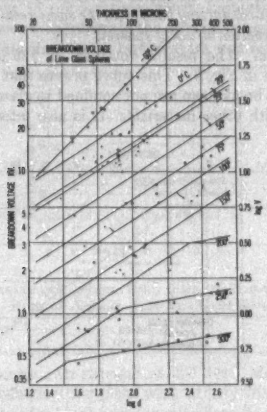
represented by a straight line with the slope 2/3 ($V = K_2 d^{2/3}$). This is shown by the 125 deg. points.

3. At the temperatures of 200 deg. and above the slope is less ($V = K_3 d^{0.35}$), which is clearly exemplified by the 250- and 300- deg. data.

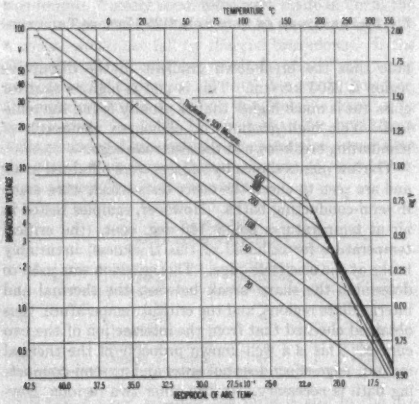
The same curves are replotted against the reciprocal of the absolute temperature in Fig. 2B. This shows the three regions of breakdown mentioned above. At low

temperatures the breakdown voltage is independent of temperature. This is usually called the "disruptive" region.

At very high temperatures the breakdown voltage varies rapidly with the temperature according to an




A




B

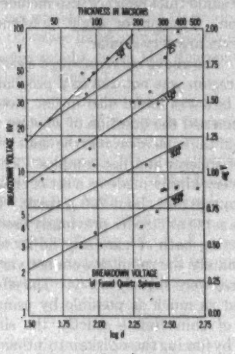
FIG. 3A, 3B—BREAKDOWN OF LIME GLASS SPHERES

exponential relationship. This has been shown[5] to be thermal breakdown.

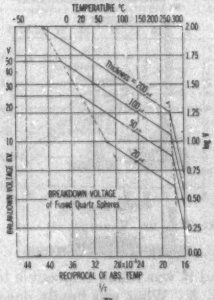
At temperatures between the other two, the voltage also appears to vary exponentially as the reciprocal of the absolute temperature, though the variation is less rapid than in the thermal region. For want of a better name, we have termed this the "intermediate region."

*Lime Glass.* Figs. 3A and 3B give similar curves for spheres of sodium-lime glass. The three regions are obtained as before, the principal difference being in the greater range of the intermediate region and the low temperatures at which the transition to disruptive breakdown occurs.

*Fused Quartz.* Fig. 4 gives the results obtained to




A




B

4A, 4B—BREAKDOWN OF FUSED QUARTZ SPHERES

date on fused quartz spheres. The samples were blown from clear transparent Vitreosil tubes by use of the oxy-hydrogen flame and were similar in size and appearance to the ones blown from glass tubing. The work on fused quartz is not yet completed, which accounts for the small number of points. However, the data seem to uphold the previous work.

## THE THREE REGIONS—FLAT SPECIMENS

*Cover Glass.* The first tests on flat samples were

5. Moon and Norcross, *loc. cit.*

made on German microscope cover glass 4 cm. square and about 200 $\mu$ thick immersed in a semi-conducting bath. The specimens were beautifully flat and uniform and gave very consistent results as shown in Fig. 5. Each point represents one breakdown. The intermediate region here appears as the long straight portion from room temperature to about 170 deg. The thermal region is also evident. No doubt the disruptive region will also be found when tests are made at lower temperatures. Curves for G-1 glass spheres and lime glass spheres of the same thickness are also included in Fig. 5 for comparison. Except for slight differences in the slopes, the curves are very similar.

*G-1 Sheets.* The above curves showed clearly that the intermediate region was not due to a peculiarity of the glass spheres but was found also in flat sheets. However, there remained the question of whether the breakdown voltage of the *same glass* was the same when tested in the form of spheres and flat samples. The Corning Glass Works very kindly made us a set of thin G-1 glass sheets 4 cm. square and about 200 $\mu$ thick. Tests were made with the same electrodes previously used and with a semi-conducting bath of carefully adjusted resistivity. Unfortunately the samples were not very uniform and the surfaces were slightly wavy. The effect of this was eliminated as much as possible by using disks of gold leaf or of thin tinfoil exactly the size of the electrodes and by forcing these disks into intimate contact with the surfaces of the sample. Despite these precautions, however, the breakdown values were not very

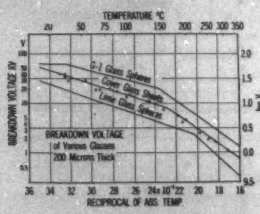



FIG. 5—BREAKDOWN OF VARIOUS GLASSES (200 MICRONS THICKNESS)

consistent, and it was found impossible to get a curve similar to Fig. 5. What was finally done was to take the average of from six to twelve readings made under the same conditions. This was done at several temperatures, and the values were compared with the results from Fig. 2 for G-1 spheres. (See Table III.)

TABLE III
BREAKDOWN OF G-1 GLASS

| $\theta$ | $d$ | Region | Flat sheets (log $V$, av. | Spheres log $V$ from Fig. 2 |
|---|---|---|---|---|
| 20.5 deg. cent. | 145$\mu$ | Disruptive | 1.72 | 1.65 |
| 23.0 | 272 | Intermediate | 1.83 | 1.87 |
| 50 | 236 | " | 1.73 | 1.69 |
| 96 | 240 | " | 1.55 | 1.52 |
| 345 | 239 | Thermal | 0.16 | 0.17 |

All tests were made in a semi-conducting bath of xylene and aniline except the last which was in air. Edge breakdown was eliminated in all cases. It will be noted that the two methods are in fairly good agreement; and since the deviations are indiscriminately plus and minus, it may be stated that *edge-effect elimination by the semi-conducting bath gives the same results as edge-effect elimination by use of spheres.*

*Celluloid.* The results obtained on 125 $\mu$ celluloid are shown in Fig. 6. This curve proves that the three regions of breakdown are not confined to glass but may appear with other materials. It is also interesting to

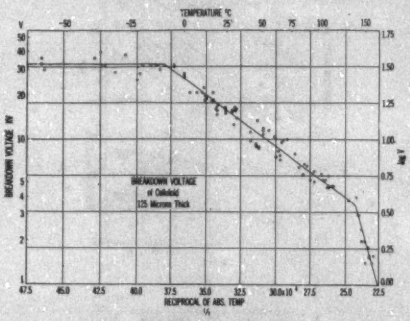



FIG. 6—BREAKDOWN OF CELLULOID (125 MICRONS THICKNESS)

note that the breakdown gradient in the disruptive region is 2500 kv./cm. This is not as high as that for glass but is much higher than is usually found for celluloid. This high gradient is, of course, the result of eliminating breakdown at the electrode edge.

The few points shown by squares were obtained in air and are seen to check the other tests which were made in semi-conducting baths. However, samples tested in air at temperatures below 140 deg. cent. (the critical temperature for celluloid of this thickness) invariably broke at the electrode edge. This criterion was used to determine the sharp break between the thermal and intermediate regions, and the critical temperature thus obtained checked that from the intersection of the two curves. This is a well-known property of the thermal region: edge-effect does not enter and no semi-conducting bath is necessary. In the other two regions, however, some effective method of eliminating edge breakdown is absolutely required.

*Mica.* An investigation was made of the breakdown of India mica at room temperature. Both sharp-edge and rounded-edge brass electrodes were used and were found to give the same results. Fig. 7 shows the final data obtained by using a bath of xylene + 20 per cent aniline and sharp-edge electrodes. It will be noted that there is a linear relationship between voltage and thickness, the average breakdown gradient being 10,600

kv./cm. This linear relationship indicates that these breakdowns are in the disruptive region. Besides the circles (room temperature) of Fig. 7, a few crosses will be noted. These represent breakdowns at 100 deg. cent. using the same electrodes and same bath. Evidently the breakdown strength has not been reduced by the increase in temperature, which supports the idea that the mica is operating in the disruptive region.

As further increase in temperature was not possible with this bath, other baths were tried in an attempt to

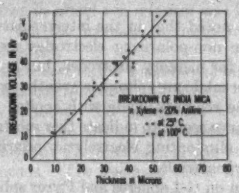



FIG. 7—BREAKDOWN OF INDIA RUBY MICA (IN SEMI-CONDUCTING BATH OF XYLENE + 20 PER CENT ANILINE)

0 = 25 deg. cent.
x = 100 deg. cent.

get the breakdown strength at 200 deg. Media which were satisfactory for glass were utterly ineffective in preventing edge breakdown on mica because of its much higher breakdown strength, and no satisfactory bath was found. Finally some tests were made in air in the oven to see if at sufficiently high temperatures the material would not fail by thermal breakdown. If the thermal region could be reached, edge-effect would automatically disappear. At 500 deg. cent., however, the mica continued to fail at the electrode edge. The results given in Table IV show that the breakdown voltage under these conditions is somewhat lower than at room temperatures, though because of edge breakdown the results are questionable.

TABLE IV
BREAKDOWN OF MICA

| θ | Medium | Edge effect eliminated | Kv./cm. |
|---|---|---|---|
| 20 deg. cent. | Air | No | 3,520 |
| 500 | Air | No | 2,520 |
| 20 | Transformer oil | No | 6,960 |
| 20 | Xylene + Aniline | Yes | 10,600 |
| 100 | Xylene + Aniline | Yes | 10,210 |

It is not evident whether the mica is still in the disruptive region at 500 deg. or has started down into the intermediate region. In any case, the superlative insulating qualities of mica are evident: the breakdown gradient remains independent of temperature to at least 100 deg. and the thermal region is apparently not reached at 500 deg.

*Criterion for Edge-Effect Elimination on Flat Sheets.* At the very beginning of the tests on flat samples, a need was felt for some means of measuring the degree of edge-effect elimination. To meet this need the following method was used:

The electrode face was considered divided into ten concentric rings of equal area. (See Fig. 8.) Now if there be absolutely no dielectric flux concentration at the electrode edge, punctures will occur presumably at random over the electrode face. Thus if a sufficiently large number of tests is made and a record kept of the position of each puncture with respect to the electrode edge, the resulting distribution curve should have an approximately flat top. That is, about the same number of failures would be expected to occur in each of the rings. On the other hand, any flux concentration at the electrode edge would cause the distribution curve to have a peak near Ring 10.

The results on mica are shown in Fig. 8. The electrodes are seen to be 15.9 mm. in diameter with sharp edges. The rings of equal area are marked from 1 to 10 from the center outward. The top distribution curve is for breakdown in air, and all of the failures will be seen to have occurred outside the electrode. The average breakdown strength was 3520 kv./cm. The next tests were made in transformer oil which gave an improved distribution, though there are still too many punctures near the electrode edge. The average breakdown

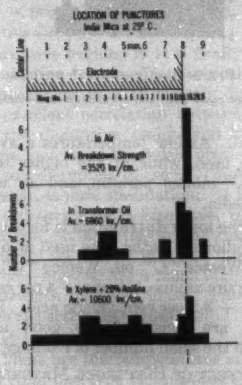



FIG. 8—LOCATION OF PUNCTURES
India mica at 25 deg. cent.

gradient was raised to 6960 kv./cm. The lowest diagram of Fig. 8 gives the distribution of all the 25 deg. data of Fig. 7. A bath of xylene and aniline was used and the breakdown gradient was found to have the high value of 10,600 kv./cm. The particular bath consisting of 20 per cent aniline was used only after considerable experimenting with different baths ranging from pure xylene (the highest resistivity bath) to xylene + 50 per cent aniline (the lowest resistivity bath). The 20 per cent bath seemed to give the best elimination of

edge-effect and was thus used in all the tests of Fig. 7. The distribution diagram (Fig. 8) seems to still indicate a slight tendency to edge breakdown. However, the writers feel sure that this tendency (if, indeed, it exists at all) causes very little error in the average breakdown gradient.

Similar distributions obtained from the cover glass tests and the celluloid tests are shown in Fig. 9. Here it will be noted that the rounded-edge electrodes were used. The cover glass results are for all the tests on

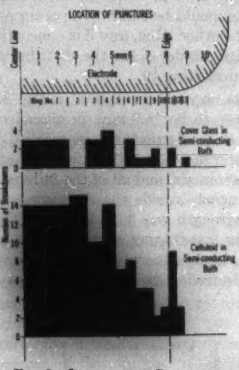



FIG. 9—LOCATION OF PUNCTURES

Microscope cover glass and celluloid in semi-conducting baths

that material. At low temperatures a xylene-acetone mixture was used, while at the higher temperatures, Mobiloil "E," molten paraffin, and air were used as immersing media.

Likewise, the lower distribution is for all the celluloid tests. The following baths were used at different temperatures: Wemco "C" oil, Wemco "C" oil + 5 per cent aniline, pure aniline, toluene + 4 per cent propionic acid, toluene + 3.5 per cent valeric acid. Both of these distributions are considered as good as could be expected with the small number of readings used.

## EFFECT OF ELECTRODE MATERIAL

The results of the above tests show no appreciable effect of ordinary changes in electrode material. Most of the tests on glass spheres were made with mercury electrodes, though a considerable number in the disruptive and intermediate regions was made with acidulated water. Absolutely no difference in breakdown voltage could be detected. In the thermal region, some tests were made with molten solder (ordinary soft solder) electrodes with very little if any difference from the values obtained with mercury electrodes.

An investigation was also made of the breakdown of glass with special electrode materials which supply the glass with sodium ions. It is generally known that the sodium ion is responsible for a large part of the conduction in ordinary glass and that the apparent resistivity of the material can be greatly lowered if electrolytic polarization is reduced. Tests were made on lime glass with electrodes of sodium amalgam, $Na_2SO_4$ solution, and molten $NaNO_3$. A set of curves like those of Fig. 2A was obtained, and these values were replotted against $1/T$ in the usual manner. One of these curves for 100 $\mu$ spheres is shown in Fig. 10. The points are the average values taken from the $log\ V - log\ d$ curves mentioned above.

It will be noted that in the intermediate region the data for the non-polarizing electrodes are practically the same as for mercury electrodes, but in the thermal region the breakdown voltage is greatly reduced. The fact that the readings made with molten $NaNO_3$ fall below the curve seems to indicate this substance is more effective in eliminating electrolytic polarization than are the other materials.

Other data on G-1 spheres and Pyrex spheres showed that in the disruptive and intermediate regions the breakdown voltage was practically unaffected by the non-polarizing electrodes while in the thermal region the breakdown voltage was considerably reduced in all cases. In this connection it should be noted that all the results on fused quartz were obtained with non-polarizing electrodes. Thus the values given for this material in the *thermal region* are probably somewhat lower than will be obtained with ordinary electrode materials.

The principal reason for the above tests was to make

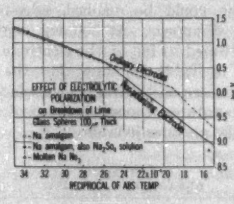



FIG. 10—EFFECT OF ELECTROLYTIC POLARIZATION ON BREAKDOWN VOLTAGE

Lime glass 100 microns thick

● = $Na_2SO_4$ solution electrodes, also Na amalgam
0 = Na amalgan electrodes
Δ = Molten Na $NO_3$ electrodes

Solid line is with non-polarizing electrodes. Dotted curve is with mercury electrodes (from Fig. 3B)

sure that the intermediate region was not caused in any way by electrolytic polarization. When polarization is present the voltage gradient is of course not uniform from one electrode to the other but tends to concentrate near the electrodes. The above results indicate that this phenomenon has no marked effect on breakdown. The reduction in puncture voltage in the thermal region is undoubtedly due to the reduced resistance of the sample and the resulting increase in heating effect. It

should be noted that if an accurate quantitative check of the Fock theory or of other thermal theories is ever made it will have to be made with non-polarizing electrodes, since a tacit assumption of all these theories is that polarization is absent.

### Effect of Time

Considerable care was exercised throughout the tests to raise the voltage slowly enough to allow approximate equilibrium conditions to obtain up to breakdown. In the thermal region, a uniform rate of voltage rise which gave breakdown in about ten minutes was found to be satisfactory. Further increase to thirty minutes had no measurable effect.

In the intermediate region a somewhat higher rate of voltage rise was used, most of the failures occurring in four or five minutes. To make sure that ordinary changes in rate had no effect, a set of tests was made on lime glass spheres at 670 volts/sec., giving breakdown in about 30 seconds. The averages check the curves of Fig. 3.

A similar run was made on G-1 glass in the disruptive region. A uniform rate of 900 volts/sec. was used and a check again obtained with the curves. Thus in the intermediate and disruptive regions the breakdown voltage was found to be independent of time within the range which could be obtained conveniently. In the thermal region, on the other hand, rate of voltage rise had a marked effect when the total time of voltage rise was less than five or ten minutes.

### Summary of Results

The data indicate that the breakdown voltage of various glasses, celluloid, and fused quartz on direct potential can be expressed by the equation:

$$V = K_i\, d^{n_i}\, (10)^{b_i/T}$$

where

$V$ = breakdown voltage in kilovolts
$d$ = thickness in cm.
$T$ = absolute temperature
$K$, $n$, and $b$ are constants determined by experiment
$i$ denotes the region considered: $i = 1$ for disruptive, $i = 2$ for intermediate, $i = 3$ for thermal.

The values of $n$ and $b$ for the three regions are tabulated below:

TABLE V

| Material | Effect of Thickness | | | | Effect of Temperature | | |
|---|---|---|---|---|---|---|---|
| | $K_1$ | $n_1$ | $n_2$ | $n_3$ | $b_1$ | $b_2$ | $b_3$ |
| Fused quartz (non-pol. elec.) | 5,000 | 1.00 | .63 | .50 | 0 | 330 | 2250 |
| Pyrex | 4.800 | 1.00 | 0.70 | .. | 0 | 715 | .. |
| Cover glass | .. | .. | .. | .. | .. | 687 | 1500 |
| G-1 glass | 3,100 | 1.00 | 0.66 | 0.25 | 0 | 470 | 1540 |
| Lime glass | 4.500 | 1.00 | 0.63 | 0.185 | 0 | 735 | 1910 |
| Lime glass (non-pol. electrodes) | 4,500 | 1.00 | 0.63 | 0.45 | 0 | 735 | 1530 |
| Celluloid | 2.500 | 1.00 | .. | .. | 0 | 705 | 2300 |
| Mica | 10.600 | 1.00 | .. | .. | 0 | .. | .. |

It will be noted that in the intermediate region $n_2$ varies between 0.63 and 0.70 for the different materials, and it seems probable that a value of $\frac{2}{3}$ is very nearly correct for all these dielectrics. Thus it may be stated that in the intermediate region the breakdown voltage varies as the $\frac{2}{3}$ power of the thickness. The values of $n_2$ vary through a wider range, but this is explicable on the basis of the Fock thermal theory[6] which allows any value from 0 to 0.50. The values of $b_2$ and $b_3$ do not differ greatly in the various materials and the values of $b_3$ check the Fock theory satisfactorily.[7]

Table VI attempts to correlate the resistivity and breakdown voltage of the various glasses with the chemical composition. With glasses of such widely different composition only a crude check can be possible at best. Nevertheless a certain correlation will be noted. If the per cent $Na_2O$, $K_2O$, and CaO is compared with the breakdown gradient in the thermal region, it will be noted that there is a perfect correlation between the two. This might be expected from the fact that thermal breakdown depends on the heating effect of the current, this effect increasing as the Na, K, and Ca ions are increased in number. A similar correlation would be expected with resistivity. This is true except for the anomaly of G-1 glass; which, despite its fairly high alkali content, has a very high resistivity. The lead oxide, which is present in this one glass, may be responsible for this discrepancy.

In the disruptive region, it is a firmly established fact that conduction has no effect on breakdown,—the breakdown mechanism is of an entirely different character. The excellent correlation between breakdown gradient in the disruptive region and $SiO_2$ content might lead one to surmise that glass breakdown in this region is due to a disruption of the $SiO_2$ molecule. Such an idea, however, is pure speculation. It is interesting to note that ordinary sodium-lime glass, which has the largest alkali content and the lowest resistivity, and which is decidedly the poorest insulator in both thermal and intermediate regions, has a much higher disruptive breakdown strength than G-1 glass. This is in agreement with the respective $SiO_2$ contents.

The critical temperatures $\theta_{c1}$ and $\theta_{c2}$ have also been tabulated. These are the temperatures at which transition occurs from one type of breakdown to the next. There appears to be no correlation between these temperatures and composition. This might be expected because a critical temperature depends not on one breakdown mechanism but on two.

That the three types of breakdown are distinct and separate and are not merely modifications of one or two mechanisms is indicated by many of the above curves.

6. V. Fock, "Zur Wärmetheorie des elektrischen Durchschlages," *Archiv. f. El.*, 19, 1927, p. 71.

7. Moon and Norcross, *loc. cit.*

TABLE VI
CHEMICAL COMPOSITION AND BREAKDOWN STRENGTH

| Material | % $SiO_2$ | % $Na_2O$ + % $K_2O$ + % CaO | log $\rho_{25}$ | Kilovolts per cm. | | | Deg. cent. | |
|---|---|---|---|---|---|---|---|---|
| | | | | Disruptive | Intermediate[1] | Thermal[2] | $\theta_{c1}$ | $\theta_{c2}$ |
| Fused quartz | 99.8 | trace | 19.0[4] | 5,000 | 1815 | 560[3] | −31 | 270[3] |
| Pyrex | 80.8 | 4.5 | 13.8 | 4,800 | 1050 | 200 | −20 | 140 |
| G-1 glass | 66 | 13.8 | 14.9 | 3,100 | 1200 | 102 | +22 | 150 |
| Cover glass | | | 12.7 | .... | 730 | 60 | +20 | 165 |
| Lime glass | 69.7 | 21.0 | 11.5 | 4,500 | 355 | 32 | −33 | 217 |
| Celluloid (125 $\mu$) | | | | 2,500 | 420 | .... | −10 | 140 |
| India mica | | | 16.3 | 10,600 | | | +100 | .. |

NOTE. $\rho_{25}$ is the resistivity at room temperature (value of $A$ at 25 deg. cent., approximately).

1. For 300 $\mu$ and 100 deg. cent.
2. For 300 $\mu$ and 300 deg. cent.
3. With non-polarizing electrodes. Ordinary electrodes would probably give a higher breakdown gradient in the thermal region and a greater $\theta_{c2}$.
4. Obtained from R. B. Sosman, "Silica," Chem. Catalog Co., 1927, p. 528.

A summary of the experimental facts upon which this statement is based is given below:

*Disruptive and Intermediate Regions* are distinct as shown by the effects of

1. *Temperature.* No effect in disruptive but decided effect in intermediate region.
2. *Thickness.* Breakdown voltage varies as the first power for disruptive but as the ⅔ power for intermediate.
3. *Composition of Glass.* Disruptive breakdown seems to depend on $SiO_2$ content.

Intermediate and Thermal Regions are distinct as shown by the effects of

1. *Temperature.* Breakdown voltage varies much more rapidly with temperature in the thermal region than in the intermediate.
2. *Thickness.* Breakdown voltage varies as the ⅔ power of thickness in the intermediate region but as the ½ or lesser power in the thermal.
3. *Time.* Has no apparent effect (20 volts/sec. to 1000 volts/sec.) in the intermediate but marked effect in the thermal region.
4. *Polarization.* Has no effect in intermediate but decided effect in thermal.
5. *Edge Breakdown in Air.* At temperatures below $\theta_{c2}$ all punctures occur at electrode edge.

## CONCLUSIONS

The elimination of edge breakdown greatly increases the puncture voltage of solid dielectrics. Within the limits of experimental error, the same results are obtained with the different methods of edge-effect elimination: hollow spheres, also flat sheets in semi-conducting baths. Repeated checks with various semi-conducting baths show that all baths give the same breakdown voltage provided the resistivity is adjusted to prevent failure at the electrode edge.

In the disruptive region the breakdown gradient is independent of both temperature and thickness.

In the intermediate region the breakdown voltage varies approximately as the ⅔ power of the thickness and exponentially as the reciprocal of the absolute temperature.

In the thermal region the voltage varies as the ½ or lesser power of the thickness and as an exponential function of the reciprocal of the absolute temperature.

The rate of voltage rise has no effect on the breakdown voltage in the disruptive and intermediate regions. This statement applies only to the range of voltage rise from about 1000 volts/sec. to 20 volts/sec. and is not to be construed as applying to transients. In the thermal region, the rate of voltage rise has a very marked effect for rates which give breakdowns in less than five or ten minutes.

No effect of electrode area could be detected with glass spheres having a range of areas of about 10:1. This conclusion, of course, applies only to homogeneous materials.

Electrode material has no apparent effect on breakdown voltage in the disruptive and intermediate regions. In the thermal region, however, it may have considerable effect.

Electrolytic polarization does not appreciably alter the disruptive and intermediate breakdown voltages. However, non-polarizing electrodes greatly increase the conductivity of glass and thus decrease the puncture voltage in the thermal region.

There appears to be a direct correlation between the $SiO_2$ content of a glass and the disruptive breakdown strength. In the thermal region a similar correlation can be found between total alkali content and breakdown gradient.

In conclusion the authors wish to express their thanks to those whose help has made this paper possible. To Dr. V. Bush, under whose direction the research was conducted, the authors owe much. Thanks are also due to Mr. M. O. Porter, Jr. for permission to use the data which he obtained on the breakdown of celluloid (Fig. 6) and to Mr. L. A. Bingham for most of the work on fused quartz (Fig. 4). Messrs. R. A. Swan and W. F. Bartlett are responsible for the data on Pyrex, while Messrs. W. E. Creedon and W. E. Lowery obtained the results on lime glass at − 60 deg. cent. We also wish to thank the Corning Glass Works which made the flat sheets of G-1 glass especially for this investigation, and the Thermal Syndicate, Ltd. which furnished the Vitreosil tubing.

## Discussion

**R. W. Atkinson:** I think perhaps the one curve you saw on the board must represent a greater number of individual points and of individual tests showing dielectric strength than any other published data, and undoubtedly this paper represents a greater amount of systematic and careful study of dielectric strength than anything previously published.

The authors mentioned very briefly their methods of eliminating edge effects. I have been very much interested in these methods as described at some committee meetings in Boston, and I think that if the subject matter of the paper itself had not been so important you would have been equally interested in the description of these methods and of hearing what a large problem the elimination of edge effects is, and how difficult it becomes at the tremendous stresses to which these authors were able to carry their tests. Of course, in connection with the magnitude of the voltage which they were able to secure, it is worth while to remember that the voltage was direct. That gave them an opportunity to use one method that might not be available with alternating current. But, on the other hand, there are methods of eliminating edge effects with alternating current that might not have been as valuable with direct. At any rate it will be very worth while sometime for them to publish the data in reference to this subject also.

One important thing, as the authors have brought out by their data, and which we wish specifically to single out, is their demonstration of three ranges of breakdown. The range of breakdown which has been discussed at very great length of recent years is the pyroelectric. There are several reasons for the large amount of discussion of pyroelectric failure. One is that under a wide range of conditions that have existed and materials involved, and within the range of temperature and with the thicknesses of materials used, and with the dielectric losses obtained, the usual type of failure in the testing to destruction of certain types of specimens has been pyroelectric failure, and in all cases the characteristics were similar to the right hand side of the curves which you observed. Some very prominent and capable engineers even suggested that this is characteristic of all failures under dielectric stress. I think that the best evidence that this is not true is the three slopes on these curves. Of course, we may find that all three types of failures are related in a certain degree.

Another thing which has caused it to be given more attention is that the pyroelectric failure as given on the right hand side of the curve follows a definite law with reference to the temperature and that when the thermal and dielectric loss characteristics of the insulation are taken into account, the law of pyroelectric failure for any thickness of a given material can be predetermined by comparatively low voltage measurements. Of course, sometimes we can measure it very much easier than we can calculate it, but any physical problem which can be reduced to a mathematical one, is very much easier understood.

The other two ranges are much less known. We do not know just what it is that produces either of the others. Incidentally though, in these tests the authors have approached very much more closely some values of breakdown as suggested by some mathematicians who have taken the fundamental physical characteristics of the material and have calculated theoretical breakdowns quite out of range of those obtainable in ordinary tests.

There was one thing mentioned in the discussion by Professor Kouwenhoven regarding dielectric loss measurements about the necessity of shielding with a certain type of measurement. I should like to make one comment. The methods of shielding have been associated in many cases with the method of measurement. I have felt that the method of shielding is primarily a function of other things than the method of measurement. The amount of shielding that is required is a function of the *sensitivity and accuracy* that is wanted. It may also be expressed as a function of the thickness of dielectric and the capacitance of the specimens of the amount of voltage across the detecting element of the measuring circuit. In the case of the Wien bridge, this is the amount of voltage across one of the arms of the bridge, or in the case of the dynamometer instrument, the voltage across the dynamometer, or we may say more broadly the amount of voltage between the low tension plate of the condenser and ground. A general solution of the requirements for shielding can be made independently of the exact type of measuring instrument.

**M. C. Porter, Jr.:** Although the problem of eliminating edge breakdown has received much attention, Messrs. Moon and Norcross are the first to present a great number of tests giving full consideration to this problem. When we consider that the voltage-temperature curves for dielectric breakdown have heretofore shown two regions, no better illustration of the importance of the problem can be offered than what we have just heard.

At present, there are not a great many satisfactory methods of eliminating edge breakdown. The various methods may be classified into two rather inclusive groups according to the type of specimen tested: (1) shaped specimens, and (2) flat specimens.

In the first group, we may place the hollow glass spheres just described. The success of this method finds its most probable explanation in the fact that the change of thickness throughout the specimen is so infinitely gradual.

In this group we find also specimens made by machining or molding a spherical cavity in a block of the dielectric. Mathematical analysis shows that a spherical contour will not eliminate "edge-effect," and the results of many experimental investigators using this method, seem to verify this analysis. The failure of this method most probably lies in the choice of a spherical cavity whose diameter is necessarily small because of the size of specimens chosen.

Rogowski, using the well-known Maxwell equations for plotting the electrostatic field about a thin plate electrode, has used electrodes for tests in air, shaping the electrodes to follow an equi-potential contour. I have employed such electrode shapes in making several tests on amber bakelite and celluloid, where the cavity machined in a block of the material followed an equi-potential contour. Although the tests on bakelite were not satisfactory, apparently because the contour chosen too nearly approximated a circle of relatively small diameter, the celluloid samples were entirely satisfactory. These samples were shaped to follow a comparatively flat contour. The gradients obtained check with my corresponding tests when using a semi-conducting bath. This method of shaping samples is apparently satisfactory but is much too expensive when compared with other simpler methods. The method, however, emphasizes the importance of discarding a spherical contour for the electrode edge and shows that the apparent vagaries encountered in endeavoring to eliminate "edge-effect" are amenable to calculation.

The second group includes a far more attractive method of making tests, inasmuch as specimens in the form of thin flat sheets can readily be obtained for most insulating materials. The method of immersing the electrodes and specimen in a semi-conducting bath is a very simple and effective one. In making my tests on celluloid, for instance, I was able to eliminate edge breakdown over a temperature range of from approximately − 60 deg. to 150 deg. cent., a range sufficiently wide to disclose the existence of three mechanisms, as already shown (see Fig. 6 of the above paper).

At the lower temperatures, some difficulty was experienced in obtaining a bath that had a low enough resistivity and yet would not freeze. After trying a number of baths, a bath of toluene and valeric acid, with the valeric acid added to reduce the resistivity, was found to be entirely satisfactory. The temperature was varied by dropping lumps of solidified $CO_2$ into the bath. It is probable that such a bath will be found satisfactory for tests at a low enough temperature to disclose the disruptive

region of breakdown for almost any dielectric, since the resistivity of this bath may be varied within fairly wide limits.

Serious limitations of the semi-conducting bath are encountered at the higher temperatures. Although the difficulty of eliminating "edge-effect" begins to decrease as the temperature increases, the temperatures are frequently so high as to be above the flash-point of the bath.

There is a definite need for a method of testing flat sheets of dielectric in air. Such a method is especially desirable for commercial purposes. I have designed and built what may be called a *distributed-potential electrode*. This electrode is made from a short section of a Westinghouse transformer bushing which consists of thirty-one concentric layers or rings of tinfoil insulated from each other and wound around a central brass tube. The one end of the section is carefully machined and scraped and to the other end there are applied to each of the thirty-one concentric rings various potentials obtained by tapping a two million ohm wire-wound resistance bank. One end of this resistance bank is connected to ground and to the outer layer or ring of the electrode; the other end is connected to the central electrode of the bushing and to the high-potential side of a 100-kv. kenotron set. A calculated potential distribution is used that follows a Rogowski equi-potential contour. The sample to be tested is placed on the machined end of the bushing and a ground plate placed on top of the sample. A specially constructed relay quickly opens the circuit at breakdown.

After proper care was exercised in machining and scraping the surface of the electrode so as to obtain contact between the tinfoil layers or rings and the sample, it was found that "edge-effect" was satisfactorily eliminated. The punctures occur rather consistently at the center electrode and the breakdown gradients check with those obtained when using a semi-conducting bath. Tests have been made on six thicknesses of dielectrics, the dielectrics being celluloid, cellulose acetate, and "Kodaloid." So far as I am aware, this distributed-potential electrode represents the first successful method of testing flat sheets of homogeneous dielectrics in air.

I plan to submit a paper which will give certain more detailed information regarding these various methods along with the design of the distributed-potential electrode.

All my work was done under the supervision of Dr. V. Bush.

**F. M. Clark:** I desire to call attention to a paper published by V. M. Montsinger and myself in the *General Electric Review*, Vol. 28, 1925, p. 286. This paper concerns itself with the a-c. strength-thickness relation in fibrous insulation as a function of the testing conditions. With increased size of parallel plane electrodes, the strength changes from the two-thirds, or seven-tenths power of the thickness to the first power. With specially constructed electrodes to eliminate the edge effect, we also obtained breakdown as a function of the first power of the thickness. These results may assume increasing importance in the light of the present researches of Moon and Norcross.

**J. B. Whitehead:** I think one must be impressed by the definiteness of the results that are presented on celluloid in spite of an unwillingness to accept so abrupt a variation in the law of the electric breakdown as is shown by the three sections of the curve. Nature doesn't usually work that way. The results are very definite and it is to be hoped that the work will be carried further and the matter cleared up as to just how definite the conclusion is when extended to other materials.

The initial portion of the curve is called the region of disruptive breakdown. There is a theoretical disruptive breakdown of all materials. A most interesting analysis of the conditions of equilibrium within the molecule and atom of a crystal has been made by the German electrician, Rogowski. He attempts to explain the gap between what he calls the technically observed breakdown gradients and the theoretical breakdown gradients as determined from the condition of electrostatic equilibrium as related to the kinetic relationships under the kinetic theory. He calls attention to the fact that the difference between these two values is by a factor anywhere from 20 to 100. In other words, the technically observed breakdown stresses fall to a fraction of about 1/100, at best to a twentieth, of the computed values as based on our best theory. The breakdowns described in the paper of Messrs. Moon and Norcross are, of course, the technical breakdowns.

Rogowski explains the discrepancy, by assuming that all breakdown results from secondary ionization occurring in fissures and local imperfections in the material. I ask the authors whether they have examined their values of breakdown as related to the theoretical explanation as given by Rogowsky and let us know whether the gap between theory and experiment has been made any smaller.

**Wm. A. Del Mar:** (communicated after adjournment) One of the reasons why the behavior of dielectrics under high stress has not been brought within the scope of any law is that up to the present time it has not been possible to test a pure dielectric and all of the experimental results which have been obtained have been tests of impurities rather than of the material being studied. Messrs. Moon and Norcross have arrived at the point where they are apparently testing the dielectric proper and therefore their results are of unusual value.

I do not feel, however, that they have fully proved their claim that there are three regions of dielectric breakdown. Two regions are known, one of which is characterized by the direct puncture without preliminary deterioration and the other by gradual deterioration preceding puncture. These are the two extreme regions of the authors' curves.

They do not state the physical characteristics of the failures which occur in the intermediate region. If there is a true intermediate region, the failures occurring therein should have some characteristic by which they may be identified other than the shape of the curves between temperature and breakdown voltage. Whenever one encounters angularities in the graphs of natural process, it is advisable to examine closely into the facts because such discontinuities are rare.

In looking over the data presented by the authors, we find Figs. 2A, 3A, and 4A resembling gun-shot diagrams, with the possibility that the lines representing averages might be moved up or down without violating the probabilities. It is only in Fig. 6 that we find the points following the average line with such closeness as to really substantiate the idea of discontinuity. Even here it is quite possible to draw a smooth curve through the points without doing violence to the facts.

In view of the erratic behavior of dielectrics under stress, it seems unlikely that the authors will obtain a better curve than that shown in Fig. 6 and therefore in order to prove their case they should look for some other characteristic of the third region of breakdown which will differentiate it from the other two and prove that it is not merely a combination of the two known regions.

**P. H. Moon:** Everyone who has made breakdown tests on solid dielectrics knows that the most uniform materials obtainable tested with the utmost care will not give unlimited accuracy. Our points are necessarily scattered considerably more than we could wish, and thus the question of whether the curves should actually break sharply or should have rounded corners is one which our data are incapable of answering.

Our idea, advanced in the Franklin Institute paper, is that there are three distinct mechanisms of breakdown, each following its own laws as shown in Fig. 1 herewith. Here *I* is disruptive breakdown which, presumably, could be obtained at any temperature provided the other types of failures could be suppressed in some way. Curve II represents the intermediate type of puncture, and III is the thermal type. We believe I, II, and III to be separate entities rather than combinations of two mechanisms because of the various differences observed (see "Summary of Results"). The reason, then, that the actual breakdown follows

the solid curve is merely that the mechanism is always selected which results on the lowest breakdown voltage. If this is the correct interpretation, then curves such as Figs. 2, 3, 4, 5, and 6 would necessarily result.

Dr. Whitehead mentions the work of Rogowski on disruptive breakdown, and I think a very brief sketch of the results of that paper might be of interest. Because of the large amount of information which is available on the constitution and properties of NaCl, Rogowski chose to make his calculations for that material. He considered a perfect crystal and found that under

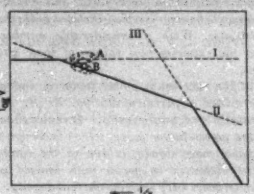



Fig. 1

the action of a sufficiently strong electric field a condition of instability might obtain with resulting disruption of the crystal lattice. For the disruptive breakdown strength he obtained 290, 190, or $150 \times 10^6$ volts/cm. depending upon the assumptions made. The lowest of these values is about 15 times as great as the highest we obtained.

However, it is known that rock salt crystals are not perfect but contain sub-microscopic cracks. Using a length of fault of $10^{-6}$ cm. as estimated by Smekal, Rogowski found a breakdown gradient of

$$E > 1300 \text{ kv./cm.}$$

This seems to be of the right order of magnitude, our lowest value being 2500 kv./cm.

It is scarcely necessary to point out that there is no justification in applying calculations made on rock salt at our tests which were on quite different materials. Breakdown tests on NaCl with edge effect carefully suppressed would be valuable, though I am not aware of any having been made.

To me one of the outstanding aspects of insulation breakdown is the great improvement that has been made in test methods in the last few years, and the tremendous simplification which has resulted in the specification of the results of insulation tests. It was only two or three years ago when to specify the results of a breakdown measurement required, besides the gradient, all the data as regards the particular test method and apparatus used. That is, one had to specify besides the breakdown gradient the thickness of the sample, the temperature, the rate of voltage rise, the electrode area, and the particular way in which the electrodes were shaped. Also he had to tell whether the tests were made in air or in oil, because the results were entirely different under these two conditions.

Contrast that with what can be done now. For instance, in the paper by Mr. Norcross and myself, Table V gives the disruptive breakdown strengths of various materials, and we thoroughly believe that these values are the true disruptive strengths; that is, they appear to be the highest gradients that can be obtained on these materials, at least in any thicknesses that can be used in engineering work. We believe these disruptive breakdown strengths to be independent of time within a very wide range. They are independent of temperature as long as we stay in the disruptive region. They are independent of thickness, and they are independent of the size and shape of the electrode. We have tried sharp-edge electrodes and rounded-edge electrodes and have obtained the same results with both. We have also used at least a dozen different baths in which we have immersed the samples and have obtained the same breakdown voltages with all of them, provided, of course, that edge effect was eliminated. So modern advances in experimental technique have tremendously simplified our specification of the results of dielectric breakdown.

I have been talking about the disruptive region. Of course in the intermediate and thermal regions there are a few more variables. That doesn't cause us any worry as far as the thermal region goes, for there is a fairly adequate theory for thermal breakdown. In the disruptive region and the intermediate region there is no satisfactory theory at the present time, but it seems likely that these improved test methods and improved results will help the development of satisfactory theories in these other regions.

**A. S. Norcross:** Failure of insulation due to deterioration as mentioned by Mr. Del Mar undoubtedly exists in cables but we do not believe this factor had any influence on our results. At high temperatures we are convinced that failure is due to heating and that these results are governed by laws obtained only from thermal considerations.

Mr. Del Mar excellently pointed out the fact that sufficient accuracy to prove the existence of three types of breakdown are difficult to obtain even with homogeneous materials. It has also been suggested by several that our curves representing the disruptive and intermediate regions of breakdown could have been drawn to indicate one type of breakdown. However, we believe that the most logical arrangement for these curves is as they are drawn.

Other characteristics supporting the idea of two distinct regions for the disruptive and the intermediate region of breakdown are given in the summary of our paper. The most important of these are as follows:

1. Temperature had absolutely no effect on the values of breakdown in the disruptive region and did have a very marked effect in the intermediate region.

2. Breakdown of all the materials tested varied with the first power of the thickness in the disruptive region and approximately with the two-thirds power of the thickness in the intermediate region.

3. The disruptive value of breakdown seems to depend upon the $SiO_2$ content of the glass as indicated in Table VI while there is no such correlation in the intermediate regions.

We believe our results indicate the above characteristics very definitely and I should like to ask those who question the existance of the third region of breakdown how to explain those facts except by concluding that the change in characteristics marks the transition point from one type of breakdown to another.

In one region of breakdown it is not reasonable to expect temperature to have no effect on breakdown between certain limits and to have a very decided effect between certain other limits.

Likewise, in one region of breakdown, it is not probable that the breakdown voltage will vary with the first power of the thickness for one range of thickness and with the two-thirds power for another range of thickness.

Also, in one region of breakdown, it is not likely that the breakdown voltage of glass will vary in some direct manner with the $SiO_2$ content for certain values of temperature and thickness and not follow this same relation for other values.

In closing it may be of interest to some to know that at the present time work is in progress in Cambridge for the purpose of determining these same relations under alternating stresses of 60-cycle frequency.

It is hoped that these results will contribute something to this perplexing problem of dielectric breakdown.

# Ionization Studies in Paper-Insulated Cables—III

BY C. L. DAWES* and P. H. HUMPHRIES†
Member, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—This is the third report to be presented before the Institute of the research investigation of ionization phenomena in paper-insulated, high-voltage cables, which is being conducted at the Harvard Engineering School under the auspices of the Impregnated Paper-Insulated Cable Research Committee. This paper is a report of progress and will be followed by further reports as the work continues.*

*The total power dissipated in impregnated-paper insulation may be separated by the graphical method into the component dissipated in the solid dielectric and that dissipated in the ionized gas films, and also may be separated analytically into these two components by selecting three suitable points on the power curve. This separation gives the three characteristic cable constants.*

*When the power curve of a cable is analyzed into its two components, the ionization-power curve itself should be a straight line. Frequently, however, the ionization-power curve is concaved upwards. This is probably due to the non-linear characteristic of power loss caused by longitudinal and tangential stresses. Hence, it may be assumed when the ionization-power curve is concaved upwards, that longitudinal and tangential stresses exist within the cable. This theory is substantiated by investigations with cable models.*

*The value of the maximum power factor and of the voltage at which it occurs are shown to be very simple functions of the three characteristic cable constants. With a considerable number of cables, the calculated and the experimental values of these quantities are in close agreement.*

*The fact that the maximum power factor is independent of gas pressure, determined experimentally by E. S. Lee, is verified both experimentally and analytically. It is also shown that the general shape of the power-factor curve, which increases to a maximum and then decreases more slowly, is due to the combination of an invariable solid dielectric in series with ionized gas films whose electrical characteristics vary with the current density.*

* * * * *

## Introduction

In the paper preceding this one,[1] it was shown that at room temperature the total power loss in a cable in which ionization exists may be analyzed into two components, the loss in the solid dielectric and the loss in the ionized gas films. This analysis is based on the fact that at room temperature the loss in the solid dielectric varies as the square of the voltage or as a constant power of the voltage, and incidentally that the relationship between ionization power and voltage is a linear one. It also assumed that the cable current is proportional to voltage, that is the variation of capacitance with voltage is small.

Under these conditions the equation giving the total power loss in such a composite dielectric becomes

$$P = KE^2 + K_1 (E - E_0) \text{ watts} \qquad (1)$$

where $E$ is the voltage, $K$ is the solid-dielectric-loss coefficient, $K_1$ is the ionization-loss coefficient, and $E_0$ is the constant which gives the intercept of the ionization-power curve with the voltage axis. The constants $K$, $K_1$, and $E_0$ are called *the three characteristic cable constants.*

The first term in (1) gives the power loss in the solid dielectric and the second term gives the loss in the ionized gas films.

## Analytical Method of Determining Characteristic Cable Constants

In the preceding paper[1] a graphical method was employed to separate the total loss in the cable into its two components. It is possible, however, to determine the three characteristic cable constants, $K$, $K_1$, and $E_0$, and hence to separate the losses, by substituting appropriate values of the variables $P$ and $E$ in Equation (1). These values are ordinarily obtained from the power curve. For example, in Fig. 1 are shown the power-factor curve P. F. and the power curve $P$ plotted as functions of voltage $E$. Corresponding values of $P$ and $E$, for substitution in Equation (1), may be obtained from such a power curve. In obtaining these

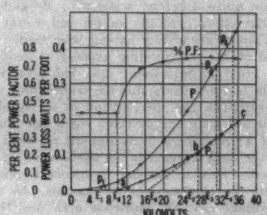



Fig. 1—Analysis of Cable Characteristics Test 4. Cable 19

values from the power curve it must be remembered that practically, Equation (1) is not a continuous function. For values of $E$ which are less than $E_g$, the ionization voltage, the ionization loss is zero, and the second term vanishes. Hence, the second term cannot be used with values of $E$ less than $E_g$. By taking a value of power $P_1$ at a voltage $E_1$, Fig. 1, well below $E_g$, the constant $K$ is readily found from the first term of Equation (1). The value of $E_g$ is less than $E_0$, the

*Assistant Professor in Electrical Engineering, The Harvard Engineering School, Cambridge, Mass.

†Research Associate in Electrical Engineering, The Harvard Engineering School, Cambridge, Mass.

1. For references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

intercept of the ionization-power curve $P_i$ with the voltage axis. This is illustrated in Fig. 1.

Again, the graph of ionization power does not become a straight line until all the gas films throughout the dielectric have become ionized. That is, the curved portion $a\ b$ of the curve $a\ b\ c$, Fig. 1, is due to the successive ionization of the gas films from the conductor outwards. (See Bibliography 1, Fig. 11.) Practically, Equation (1) is not applicable for values of $E$ between $E_s$ and $E_2$, Fig. 1. Thus, to determine constants $K_1$ and $E_0$, two points on the total power curve $P$ should be chosen for voltages which are well above voltage $E_2$,

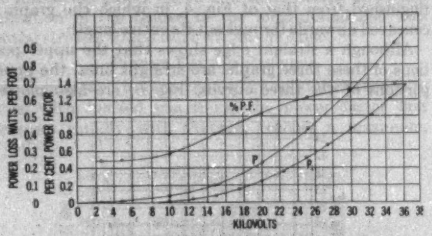



Fig. 2—Power-Factor and Power Curves Test 21. Cable 25

such as points $P_3$ and $P_4$ corresponding to voltages $E_3$ and $E_4$. This gives two simultaneous equations, from which $E_0$ and $K_1$ are readily determined. This method was used in conjunction with the graphical one to compute values in Table II.

## Losses due to Longitudinal and Tangential Stresses

Careful tests of gas films[1] have shown that, except at very high current densities, ionization loss in such films is a linear function of the voltage, (also see Fig. 5). Furthermore, similar linear functions are obtained with glass cable models in which no longitudinal or tangential stresses can exist. (See Figs. 20B and 22, Bibliography 1.) At times, however, it is found in cables that the $P_i$-curve shows a tendency to be concaved upwards. Fig. 2 shows the power and power-factor curves for a 10-ft. length of cable having a cross-section of 600,000 cir. mils and a 6/32 in. (4.76 mm.) wall of impregnated-paper insulation. These curves were obtained after the cable had been on life test for 282 hr. at 42.5 kv., corresponding to an average stress in the dielectric of 225 volts per mil. (The operating voltage of this cable would be approximately 7000 volts.) Also, the ionization-power curve $P_i$ for this cable is shown, this curve being obtained by the methods of analysis just described. It will be noted that this curve, instead of becoming linear ultimately as does the $P_i$-curve in Fig. 1, is distinctly concaved upwards over its entire length. This effect was also noted by W. V. King[2] in single-phase tests made by him with three-conductor cables. The authors first attributed this effect to heating during test, which would increase the loss in the solid dielectric and cause the $P_i$-curve to be concaved upwards after the solid dielectric power had been deducted from the curve of total power. Careful tests did show that temperature might affect the shape of the curve to a very small extent. However, when tests were so conducted that the effect of temperature was eliminated, $P_i$-curves having the tendency to be concaved upwards were still obtained with certain cables. In the discussion at the last Winter Convention, the authors suggested that this effect with the three-conductor cable might be due to losses caused by tangential stresses. Losses caused by creepage currents resulting from stresses which are either longitudinal or tangential to the insulating surfaces might very well increase faster than the linear law.

In order to investigate this effect, two cable models were made. Impregnated-paper insulation was used with both models. Model 1A consisted of a cylindrical brass tube, 0.5 in. (1.27 cm.) diameter, wound with 36 layers of impregnated-paper tapes having a width of 0.75 in. (1.905 cm.). Fourteen tapes were wound in one direction, 14 in the reverse direction, then 4 tapes in the original direction and 4 again in the reverse direction. The tapes were wound with considerable space between their butt edges as is indicated in Fig. 3, which is not drawn to scale. In order to accentuate the voids within the insulation, 2 tapes, one superposed on the other, were wound simultaneously, thus making the radial thickness of the voids equal to twice the thickness of a single tape. It has already been shown that such spaces between the butt edges of the tapes produce longitudinal stresses. That is, after ionization begins, the voltage across $P\ P'$ becomes nearly constant and may actually decrease with large current densities, while the voltage across $Q\ Q'$ always increases propor-

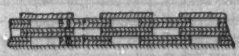


Fig. 3—Longitudinal Stresses in Cable Insulation

tionately to the applied voltage. Hence, longitudinal stresses are produced between $Q\ P$ and $Q'\ P'$ (see Fig. 25, Bibliography 3). The outer electrode consisted of tin foil wound tightly about the paper tapes and cuts were made at the ends to provide guard rings. The over-all length of the model was 21 in. (53.4 cm.) and the active length inside of guard rings was 15 in. (38.1 cm.). Fig. 4 shows the ionization ($P_i$) curve for this cable model 1A at atmospheric pressure. It will be observed that this curve concaves upwards throughout its entire length.

The tangential losses in this cable model are undoubtedly considerable, but in order to impart appreciable curvature to the $P_i$-curve, they must be very large in comparison with the ionization-power loss.

Although the application of a straight edge to large-scale plots of Fig. 4 shows distinctly that this graph is curved throughout its entire length, a more sensitive criterion and a qualitative idea of the degree of curvature can be obtained by plotting the curves on logarithmic paper. This is done in Fig. 7, (see curve I), the origin being taken at the ionization voltage $E_p$, Fig. 4. Since the logarithmic plot of Fig. 4 is a straight line

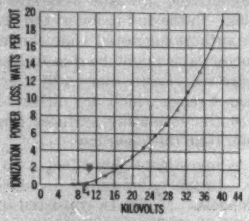



Fig. 4—Ionization-Power Curves for Cable Model with Longitudinal Stresses

having a slope of 1.83, the power curve, Fig. 4, must increase as the 1.83 power of the voltage in excess of $E_p$. Moreover, if the curve, Fig. 4, showed even a slight tendency to become linear towards its upper end, the logarithmic curve would show a pronounced tendency to bend downwards at its upper end. Curve I, Fig. 7, shows no such tendency.

Cable Model 2 was approximately the same size as

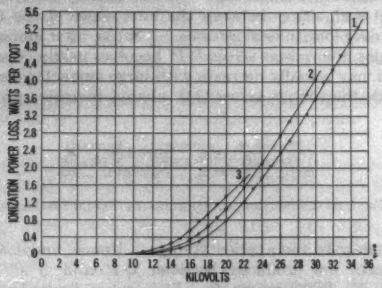



Fig. 5—Ionization-Power Curves for Cable Model without Longitudinal Stresses

Cable Model 1A. In order that longitudinal and tangential stresses might be practically eliminated, it was wrapped with a continuous sheet of impregnated paper, rather than wound with paper tapes. Obviously, considerable air was occluded during the wrapping, as was intended, so that the ionization losses were large. The diameter of the center cylindrical conductor was 0.5 in. (1.27 cm.) and the paper was wound to a thickness of 0.225 in. (0.572 cm.). An outer wrapping of tin foil with suitable cuts formed the outer electrode and the guard rings. The total length was 27 in. (68.6 cm.) and the effective length was 15 in. (38.1 cm.). It was possible to place this model in the iron dome described in Bibliography 1, Fig. 1, so that tests at different pressures could be made.

Fig. 5 shows the ionization-power ($P_i$) curves for this model, taken at three different air pressures, 769, 589, and 420 mm., respectively. An examination of these curves shows that their lower portions are curved, being concaved upwards, due to the successive ionization outwards of the gas films. When such ionization is completed throughout the model, however, the graphs all become straight lines. This effect should be distinguished from that of Fig. 4, in which the graph is concaved upwards throughout its entire length.

Although a straight edge shows that the upper portions of these three graphs are straight lines, the upper portions of the three curves, Fig. 5, are also plotted

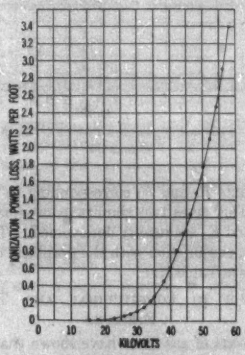



Fig. 6—Ionization-Power Curve for Three-Conductor Cable

logarithmically in Fig. 7, (curves II) in order to determine if any tendency to curvature exists. The values of voltage used are those in excess of $E_0$. The resulting graphs are straight lines having a slope of unity, showing that the power-voltage relationship in this cable model becomes linear.

In order to investigate tangential stressess till further, and also to verify the tests of W. V. King, a power-voltage test was made on a three-conductor belted type cable between one conductor which was at high voltage and the other two conductors which were at low voltage. The sheath was grounded. It is well known that high tangential stresses exist under these conditions and if the theory of tangential losses is correct, the ionization-power curve should be concaved upwards. Fig. 6 shows this curve ($P_i$) and it is obvious that it does have the predicted curvature. In order to determine its exponential law and also to test for any tendency of the curve to become linear, this curve is

plotted on logarithmic paper, Fig. 7, (curve III). The abscissas are voltages in excess of the ionization voltage $E_g$. The logarithmic graph for this curve is also a straight line having a slope of 3.2, showing that under these conditions, the combined ionization power and tangential losses increase as the 3.2 power of the voltage in excess of $E_g$. Moreover, this logarithmic curve shows no tendency to bend downwards at its upper end. This shows that over the range of the curve, Fig. 6, no tendency to become linear exists, but that the curve is concaved upwards over its entire length.

Hence, it would seem that the curvature upwards of the ionization-power curve of a cable should give some indication of the degree of the longitudinal and tangential stresses which exist within the cable.

## Power-Factor Curves

It is now well known that when solid dielectric is in series with ionized gas films, the power factor first increases rapidly with voltage, reaches a maximum,

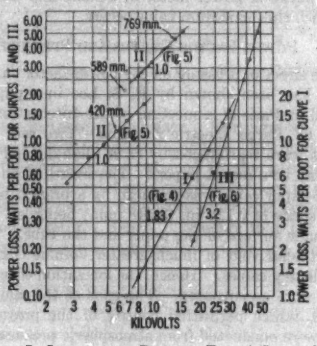



Fig. 7—Logarithmic Plots of Figs. 4, 5, and 6

and then decreases. Mathematically, the power factor approaches that of the solid dielectric as a limit, but with most dielectrics the stress in the solid dielectric exceeds its rupturing value long before this limit is reached (see Fig. 23—Bibliography 1). When the maximum power factor is reached, many interesting relationships are found to exist among cable quantities.

In previous papers,[1,2] the increasing and decreasing characteristic of the power-factor curve was explained analytically from two different points of view; first, that at constant frequency and temperature the voltage across the solid dielectric is always proportional to the current, whereas the voltage across the ionized gas film becomes constant after it reaches some definite value, (see Equation (5) in Bibliography 3); and second, that the power-voltage relationship in the solid dielectric is given by a parabola and the power-voltage relationship in the ionized gas films is a linear one, such as is given in Equation (1). Under these conditions the equation for power factor becomes,

$$\text{P. F.} = \frac{K E^2 + K_1 (E - E_0)}{E^2 C \omega} \qquad (2)$$

where $C$ is the capacitance in farads and $\omega$ is $2\pi$ times the frequency in cycles per second, (see Equation (12), *et seq.* in Bibliography 1).

At the present time this equation for power factor is the more useful, since each term in the equation is a known function of voltage.

Since the two foregoing papers were presented, the authors have had opportunity to investigate further the application of the various equations to a considerably greater number of cable samples and thus to determine their accuracy and applicability.

The maximum power factor may be found by differentiating Equation (2) with respect to voltage and equating the first differential coefficient to zero, (see Equation (11) in Bibliography 1). Under these conditions, the equation from which the voltage $E_m$ at maximum power factor may be derived is

$$E^2 C [2 K E + K_1] - [K E^2 + K_1 (E - E_0)] \left[ 2 C E + E^2 \frac{d C}{d E} \right] = 0 \qquad (3)$$

If the term $E^2 \dfrac{d C}{d E}$ within the last bracket, which is proportional to the rate of change of capacitance with voltage, becomes zero, the voltage at maximum power factor becomes,

$$E_m = 2 E_0 \qquad (4)$$

a very simple relationship.

It is known, however, that with ionized gas films, the capacitance increases continuously with increase in voltage. Hence, the term $E^2 d C/d E$ cannot equal zero. However, if this term is small compared with the term $2 C E$, Equation (4) is approximately true. Since $E$ is a common factor of each term, the same result is obtained if $E\, d C/d E$ is small compared with $2 C$. The change of capacitance of a cable with voltage is very small. Computations with values obtained from actual cables were necessary, however, to determine the relative magnitudes of $2 C$ and $E\, d C/d E$. The value of $d C/d E$ was determined graphically by finding the slope of the capacitance-voltage curve at or very near the voltage corresponding to maximum power factor.

The results of these computations for cable samples having varying degrees of ionization are given in Table I. These samples, selected from the large number which we have already tested, are representative in that they show small, intermediate, and large degrees of ionization.

TABLE I

| Cable No. | Copper cir. mils | Wall in. | $E$ at max. P. F. kv. | Cap. per ft. $\mu\mu$ f. | $E\frac{dC}{dE}$ | Ratio $E\frac{dC}{dE}/2C$ |
|---|---|---|---|---|---|---|
| 14 | 500,000 | 3/16 | 25.0 | 113.8 | $1.00 \times 10^{-12}$ | 0.0044 |
| 12 | 500,000 | 16/64 | 27.5 | 120.3 | $1.38 \times 10^{-12}$ | 0.0057 |
| 19 | 300,000 | 6/32 | 29.0 | 126.8 | $1.84 \times 10^{-12}$ | 0.0073 |
| 17 | 300,000 | 6/32 | 29.0 | 117.7 | $3.60 \times 10^{-12}$ | 0.0153 |
| | 00 | 9/32 | 47.0 | 48.6 | $3.53 \times 10^{-12}$ | 0.0363 |

It will be observed that with cables having little ionization, such as Cable 14, the ratio $\frac{E\,(d\,C/d\,E)}{2\,C}$ is less than one-half of one per cent. With the last cable, which has the highest degree of ionization of the large number that have been investigated, this ratio is less than four per cent. In view of the fact that impregnated-paper insulation is somewhat unstable, making precise calculation of its electrical characteristics almost impossible, even this ratio of four per cent may be considered negligible. Hence, for any practical purpose, the last term in Equation (3) may be neglected and $E_m = 2\,E_0$.

Substituting this value of $E_m$ in (2) gives the maximum power factor.

$$\text{P. F.}_{max.} = \frac{K}{C\,\omega} + \frac{K_1}{4\,E_0\,C\,\omega} \qquad (5)$$

The maximum power factor is the sum of two terms, one of which is proportional to the solid dielectric-loss coefficient $K$ and the other is proportional to the ionization-loss coefficient $K_1$.

A considerable number of cables has been studied with reference to their maximum power factors, the voltages at which maximum power factor occurs, and the corresponding voltage gradients. The results of this study are tabulated in Table II.

With the exception of the first two, the cables in Table II were sent to us by a public utility for the purpose of making life tests, and they are representative of several manufacturers. The results which are presented are taken indiscriminately from this set of cables as the consecutive numbers indicate. If several different tests on the same cable showed considerable change as the life tests progressed, these tests showing such change are given. For example, Cable 25 showed very little change from Test 1 until after Test 16 was completed, whereas Cable 21 showed marked progressive change in consecutive Tests 2, 3, and 4.

A study of the columns giving the maximum power factor and the voltage at which maximum power factor occurs shows, with one or two exceptions, remarkable agreement between observed and computed values, particularly when it is considered that the dielectric properties of impregnated paper are not generally susceptible to accurate quantitative analysis. It appears, therefore, if the three characteristic cable constants and the capacitance be known that it becomes a comparatively simple matter to determine the maximum value of power factor of a cable and the voltage at which this maximum value occurs.

## Power-Factor Curves and Pressure

The effect of pressure on the power-factor curves of a cable has been shown by E. S. Lee in a paper[4] presented in Paris at a meeting of the International Congress on Large Electric Systems. Two sets of these curves were reproduced by G. B. Shanklin and G. M. J. Mackay in a recent paper.[5] The sheath of an impregnated-paper cable was replaced by a brass tube, a uniform space of 0.120 in. (3.048 mm.) being left between the outer surface of the paper and the tube. This left an artificial void of much greater volume than occurs in ordinary cables. Hence, the ionization effects in the cable were accentuated. The ends of the sample were sealed, which permitted control of the pressure, and tests were conducted from atmospheric pressure to very low pressures.

TABLE II
POWER FACTOR PROPERTIES OF CABLES

| Cable | Test No. | Cross Section cir. mils | Wall in. | $E_0$ kv. | $K$ ($\times 10^{10}$) | $K_1$ ($\times 10^{8}$) | $*C_m$ $\mu\mu$ f. | $\frac{K}{C\,\omega}$ | $\frac{*K_1}{4\,E_0\,C\,\omega}$ | Max. P. F., Per Cent computed | Max. P. F., Per Cent observed | Kv. at Max. P. F. computed | Kv. at Max. P. F. observed | $G_m$ † |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 500,000 | 16/64 | 18.0 | 1.62 | 8.8 | 111.5 | 0.0039 | 0.0291 | 3.30 | 3.30 | 36 | 36 | 144 |
| 12 | 1 | 500,000 | 16/64 | 12.5 | 2.24 | 1.25 | 120.3 | 0.0049 | 0.0057 | 1.06 | 1.05 | 25 | 25 | 100 |
| 17 | 3 | 300,000 | 6/32 | 14.0 | 1.80 | 3.02 | 117.7 | 0.0045 | 0.0145 | 1.90 | 1.63 | 28 | 29 | 155 |
| | 4 | | | 12.0 | 2.42 | 3.48 | 118.3 | 0.0054 | 0.0163 | 2.17 | 2.16 | 24 | 25 | 143 |
| 19 | 2 | 300,000 | 6/32 | 14.0 | 2.13 | 1.80 | 126.8 | 0.0046 | 0.0068 | 1.14 | 1.05 | 28 | 29 | 155 |
| | 3 | | | 14.0 | 2.00 | 1.14 | 126.8 | 0.0042 | 0.0043 | 0.85 | 0.88 | 28 | 29 | 155 |
| 20 | 2 | 300,000 | 6/32 | 16.5 | 1.69 | 0.42 | 119.8 | 0.0037 | 0.0014 | 0.51 | 0.52 | 33 | 35 | 187 |
| | 3 | | | 17.0 | 1.58 | 0.44 | 119.8 | 0.0035 | 0.0013 | 0.48 | 0.48 | 34 | 35 | 187 |
| | 5 | | | 16.5 | 2.11 | 0.65 | 120.0 | 0.0047 | 0.0022 | 0.60 | 0.73 | 33 | 37 | 197 |
| 21 | 2 | 300,000 | 6/32 | 15.0 | 1.58 | 0.93 | 117.4 | 0.0036 | 0.0035 | 0.71 | 0.74 | 30 | 30 | 160 |
| | 3 | | | 18.0 | 1.86 | 0.746 | 117.6 | 0.0042 | 0.0022 | 0.65 | 0.66 | 36 | 37 | 197 |
| | 4 | | | 19.2 | 2.45 | 0.733 | 117.8 | 0.0055 | 0.0022 | 0.77 | 0.79 | 36 | 36 | 197 |
| 22 | 1 | 600,000 | 6/32 | 25.0 | 1.79 | 3.25 | 154.5 | 0.0031 | 0.0056 | 0.87 | 0.75 | 50 | 40 | 213 |
| | 4 | | | 18.0 | 2.44 | 2.41 | 153.9 | 0.0042 | 0.0058 | 1.00 | 1.01 | 36 | 33 | 176 |
| 23 | 1 | 600,000 | 6/32 | 18.0 | 1.87 | 3.20 | 153.8 | 0.0032 | 0.0077 | 1.09 | 1.12 | 36 | 40 | 213 |
| | 4 | | | 18.0 | 2.65 | 2.44 | 152.6 | 0.0046 | 0.0059 | 1.05 | 1.06 | 36 | 38 | 203 |
| 25 | 1 | 600,000 | 6/32 | 19.0 | 2.61 | 1.12 | 143.8 | 0.0048 | 0.0027 | 0.75 | 0.78 | 38 | 35 | 187 |
| | 16 | | | 23.0 | 2.88 | 2.76 | 145.6 | 0.0053 | 0.0055 | 1.10 | 1.37 | 46 | 36 | 192 |

*$C_m$ = capacitance at maximum power factor.

†Average gradient at maximum power factor—volts per mil.

The operating voltage of Cables *A* and 12 is 10 kv. to ground; the operating voltage of the other cables is approximately 7 kv. to ground.

Two of the power-factor curves obtained with this sample are reproduced by curves $A_1$ and $B_1$ in Fig. 8. Curve $A_1$ was obtained at 760 mm. pressure and curve $B_1$ was obtained at 200 mm. pressure. Curves taken at several other pressures are given in the original papers, but these are chosen as being representative and also because we happen to have air-film data taken near these two pressures. It will be noted that as is usual after ionization begins, both curves attain rapidly a maximum value and then decrease more gradually with

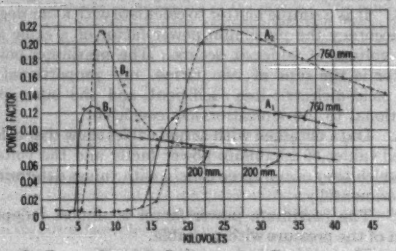



Fig. 8—Power-Factor Curves from Paper by Shanklin and Mackay

continued increase in voltage. Furthermore, both curves have the same maximum value. In the original papers, the several curves obtained at other pressures all have the same general characteristic as is shown by curves $A_1$ and $B_1$. Moreover, all curves reach the same maximum power factor. Hence, it appears that the maximum power factor is independent of the gas pressure

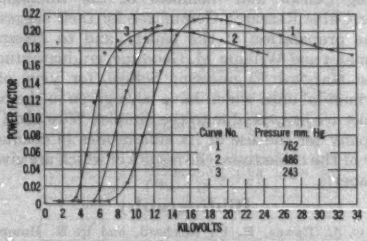



Fig. 9—Power-Factor Curves for Cable Model 1

within the cable. The authors have also found experimentally that this is approximately true. For example, cable model 2 and a cable model 1, similar to cable model 1A, were tested at three different air pressures. Where it was possible to carry the voltage to a sufficiently high value to obtain maximum power factor, the maximum power factors were all very nearly equal. This is shown in Fig. 9, which gives the power-factor curves for model 1.

Shanklin and Mackay attribute the ultimate descending portion of these power-factor curves to the fact that the voltage-ampere characteristic of the ionized gas space has a negative slope; that is, the voltage-ampere characteristic of the gas space becomes an arc characteristic. (See Bibliography 6, p. 358.) Although some cables now in service do operate at current densities sufficiently high to make the voltage-ampere characteristic of the gas film within the insulation attain slight negative slopes at some pressures, this is not true of the gas space in the cable on which Lee conducted his experiments. Computations show that in his experiments, the maximum current density attained in the air space was 3.5 microamperes per sq. cm. Fig. 10 shows the voltage-ampere characteristics of a 1.62 mm. air film for five different pressures, one at atmospheric pressure, one at a pressure greater than atmospheric, and three at pressures less than atmospheric. These curves were obtained in our laboratories under carefully controlled

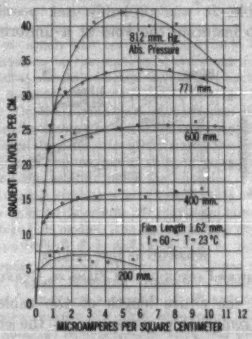



Fig. 10—Voltage-Ampere Characteristics of Air Films

conditions. It will be noted that, except at the pressure of 200 mm., the slope of all the voltage-ampere characteristics is decidedly positive up to the current density of 3.5 microamperes per sq. cm. Moreover, the current densities at the maximum power factor for curves $B_1$ and $A_1$, Fig. 8, are only 0.7 and 1.6 microamperes per sq. cm. respectively. Hence, the explanation by Shanklin and Mackay of the foregoing power-factor curves as being due to the negative voltage-ampere characteristic of the gas space does not appear to be adequate. The character of such power-factor curves is due merely to the combined effect of an invariable solid dielectric in series with an ionized gaseous medium, the slope of whose voltage-ampere characteristic merely decreases with increase in current density. Moreover, using electrical data obtained experimentally in our laboratories with ionized gas films and employing the dimensions of the cable given in the Shanklin and Mackay paper, we have been able to compute power-

factor curves for the two pressures of 760 mm. and 200 mm., corresponding to those for curves $A_1$ and $B_1$ in Fig. 8. It was assumed that the dielectric constant for the solid dielectric was 3 and the power factor was 0.006 and constant. The computations are based on the cylindrical solid dielectric being in series with an ionized air film. The results of these computations are plotted and are shown by curves $A_2$ and $B_2$, Fig. 8. Although, quantitatively, these computed curves have ordinates approximately 65 per cent greater than those obtained experimentally by Lee, their general characteristics are identical, and the maximum values for each of the two pressures occur very nearly at the same values of the voltage, as do the curves obtained by Lee. The numerical discrepancy is undoubtedly due to the fact that our data were taken for dry air, whereas in the actual cable the voids contained some vapors and gases other than air, evolved from the impregnating compound. Also, our assumptions may not have been absolutely correct. Furthermore, with the tests made on the cable, it was probably not possible experimentally to maintain the void at a uniform thickness

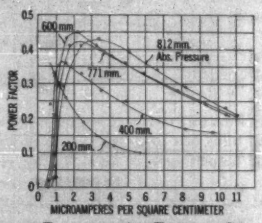



Fig. 11—Power-Factor of Air Films vs. Current Density

throughout the entire length of the cable. In any event, the remarkable agreement in the character of the curves does show, we believe, that the negative slope attained by the power-factor curve at the higher current densities does not necessarily depend on the gas films having negative voltage-ampere characteristics.

A much more definite relationship of the power-factor curves of a series combination of solid dielectric and ionized gas film to the voltage-gradient curves across the air films is shown in Fig. 11. These curves show the power-factor curves of the combination of the air film, whose characteristics are given in Fig. 10, and a slab of glass 4.99 mm. (0.1965 in.) thick in series. Since both Fig. 10 and Fig. 11 have the same scale of microamperes as abscissas, it becomes a simple matter to compare the two sets of curves. It will be observed that at every pressure, the power-factor curves attain negative slopes at current densities corresponding to positive slopes of the corresponding voltage-ampere characteristic of the gas films.

Hence, it seems almost certain that the character of the power-factor curves, such as are given in Fig. 8, is due primarily to the invariable electrical character of the solid dielectric and the discrete electrical characteristics of the gas films combining in series, rather than particularly to the negative slope which the voltage-ampere characteristics of the gas films may attain at high current densities.

## Conclusions

1. The three characteristic cable constants $K$, $K_1$, and $E_0$ are very readily determined analytically as well as graphically.

2. Although the relation of ionization loss to voltage is a linear one, the loss due to longitudinal and tangential stresses increases more rapidly than the voltage.

3. It is a simple matter to calculate with a fair degree of accuracy the maximum power factor of a cable and the voltage at which it occurs. The maximum power factor is the sum of two terms, one proportional to the solid-dielectric-loss coefficient, and the other proportional to the ionization-loss coefficient.

4. Data obtained with actual cables show that calculated values of maximum power factor and the voltage at which they occur agree closely with values determined experimentally.

5. The maximum power factor is almost independent of the pressure within a cable.

6. The decreasing portion of the power-factor curve, occurring after the maximum value is reached, is due to the combination of the electrical characteristics of a solid dielectric and ionized gas films in series, and not essentially to the negative voltage-ampere characteristic of ionized gas films.

The authors are indebted to the New York Edison Company, who, through the courtesy of Mr. Carroll H. Shaw, submitted most of the cable samples used in our tests; to Professor H. E. Clifford of the Harvard Engineering School and members of the Impregnated-Paper Cable Research Committee for their suggestions in the preparation of the paper; and to Messrs. V. Thiemann and William M. Goodhue, graduate students in the Harvard Engineering School, for some of the experimental data which have been given in the paper. Thanks are likewise due to the Simplex Wire and Cable Company for the use of its laboratories in conducting many of the cable tests, the results of which are given in the paper.

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## Discussion

**T. F. Peterson:** Professor Dawes has spoken of the by-pass filters encountered when his paper was reviewed. I have been working theoretically, along lines more or less parallel with those followed by Professor Dawes in the laboratory. Although the results of some of my mathematical considerations of ionization in insulation containing gases have been presented previously, I think that the intimate bearing which they have on the subject at hand will warrant their repetition and amplification at this time.

The second term of the expression in Equation (2) is the value of the increase in power factor due to the losses in air spaces. It is obtained without consideration of the progressive ionization from the conductor to the surface of the sheath. The equation which I have derived assuming equally sized void spaces and progressive spreading of ionization from the conductor to the outer surface of insulation can be reduced to

$$\text{P.F.}_{increase} = k\left[\frac{\pi}{4} - \frac{1}{2}\left(\frac{E_{g1}}{E}\sqrt{1-\left(\frac{E_{g1}}{E}\right)^2} + \sin^{-1}\frac{E_{g1}}{E}\right)\right] = k\left[\frac{\pi}{4} - f\left(\frac{E}{E_{g1}}\right)\right]$$

In this the value of $E$ corresponding to $E_{g1}$ is the voltage at which ionization takes place at the conductor surface. This equation holds until $E = E_{g2}$ at which all voids are ionized, is reached. Then the power factor increase is equal to

$$k\left[f\left(\frac{E}{E_{g2}}\right) - f\left(\frac{E}{E_{g1}}\right)\right]$$

In Fig. 1 herewith these equations are plotted. The striking similarity to the power factor curves obtained practically is at once

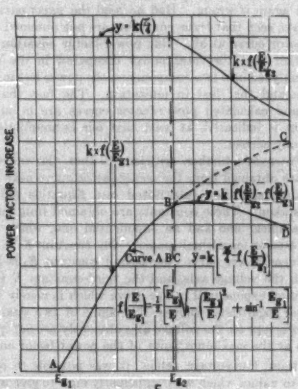


Fig. 1

evident. It is believed that these equations are somewhat more exact than those of Professor Dawes. They confirm, in a measure, some of the assertions made in the paper. In the first place the negative slope of the right hand portion of the power factor curve is obtained without the introduction of, or the need for, consideration of the arcing characteristics of gas spaces. Indeed, the equations given above are based on the assumption of an equal gradient throughout the void spaces at all current densities. The flat characteristics of the curves in Fig. 10 serve to justify these assumptions. The negative slope is therefore pretty well established.

Furthermore, it is quite easily shown that changing the pressure within the cable merely shifts this power factor curve in a horizontal direction and at the same time the maximum value is not changed appreciably. This checks the curves of Fig. 9. It is not to be construed, however, that the loss does not change with pressure. The power factor may be the same, that is, the maximum power factor, but this occurs at lower voltages, the lower the pressure and hence the actual power loss will be lower.

I cite these points in order to substantiate a criticism which I wish to offer. Equation (2) is admittedly approximate over a certain range. On the second page of the paper, in the first paragraph, it is pointed out that the equation does not apply between $E_0$ and $E_1$ of Fig. 1. Turning now to Fig. 1, it will be observed that $E_0$ is approximately 10 kilovolts and $E_1$ is 27 kilovolts.

Referring now to the power factor curve, it is seen that the equation does not apply for the portion of the curve which, to say the least, is very interesting and really constitutes an important part of the curve. It is assumed that the first part of the power factor curve is flat and, if the equation does not hold between the points $E_1$ and $O$ voltage, its actual worth may be questioned. The same comments apply to Fig. 2.

In commenting on the figures in the table at the bottom of the fifth page, the authors compliment themselves, or at least indicate a degree of satisfaction, at the agreement between the computed and observed values for the maximum power factor and voltage at which this occurs. Going back to the point previously raised as to the portion of the curve for which the equations hold, it should be noted that in getting the constants $K_1$ and $E_0$ it is necessary to take points from the initial power factor curve. On the second page of the report it is indicated that these constants must be obtained using a value of $E$ considerably greater than $E_1$. In other words the portion of the curve very close to the maximum value of power factor is used in determining the constants for the equation. If, then, the equation containing constants obtained in this manner is differentiated in order to determine the maximum power factor and voltage at which this occurs, it is not surprising that agreement between computed and observed values will be very close.

**D. W. Roper:** Professor Dawes in his paper refers to the Impregnated Paper Insulated Research Committee. This committee has supervised a number of research investigations at three colleges during the past nine years. The financial support was obtained from the N. E. L. A. and the Association of Edison Illuminating Companies. The A. I. E. E. has not contributed financially to these investigations, but it has cooperated by appointing this committee as a subcommittee of the appropriate committee of the A. I. E. E. The chairman of one of these committees recently asked for a statement concerning the value of these research investigations. Ordinarily it is impossible to answer such a question directly, but in connection with one of the investigations a method has been found of calculating the value of the information obtained in a very simple way.

About nine or ten years ago, in discussing cable specifications, the representatives of the manufacturers and the operating companies were unable to agree, and the maximum temperature formula 85 deg. cent. minus $E$ (where $E$ is the operating voltage in kv.) was adopted as a compromise. It was further agreed that it was desirable to obtain, by test, information which could be used as a basis for further discussion. These investigations to determine the maximum permissible operating temperature of impregnated paper insulation were conducted at the Massachusetts Institute of Technology, and the findings permit an increased rating of the cables.

The reports which are made to the A. E. I. C. include a statement of the number of feet of cable inspected by one reporting agency, the cable being classified according to voltage. Taking these figures as a basis and calculating the increased value of the installed cable due to the increase in the maximum permissible

operating temperature, we find in a recent year that the total increase in value is about $70,000. The total cost to the N. E. L. A. and A. E. I. C. of the investigations at M. I. T. is about $18,000. The cost of the M. I. T. research to the industry is, therefore, being returned to the industry about four times per year.

**J. B. Whitehead:** Reading this paper one would assume that the authors attribute to the presence of ionization anything in the nature of a rising power factor voltage curve. The paper dwells so particularly on the constancy and fixity of the losses in the solid dielectric as related to those due to ionization, that I venture to call attention to the rising power factor curves often found in materials in which there is no air and no gaseous ionization, and also to the occurrence of maxima in their power factor voltage curves.

In particular in our paper today we show that in one sample of oil the relation between the continuous current and voltage is not a linear one. There is a definite relation between loss and this current as it is observed on the oscillograph, and in those circumstances, under alternating stress we have a rising power factor curve. It is quite possible to observe such rising power factor curves in studies on oil. The rise is not very rapid but it is distinctly a rising curve and it is especially noticeable in oil which has deteriorated.

Moreover, in the case of the power voltage of voltage curve of carefully impregnated paper insulation, at sufficiently high stress, the power factor goes up extremely rapidly. These are instances in which we have rising power factor curves which are in no sense due to the presence of air but to the presence of an anomalous conductivity which does not obey Ohm's law.

Then, as to the maximum, some of the curves which I have presented under a research supported by the N. E. L. A., for carefully impregnated paper insulation at ordinary temperature 20 to 40 deg., show remarkably flat curves. Then as the temperature is carried to higher values we get curves with definite maxima, so that at 80 deg. we have descending power factor curves of very marked characteristics.

The maxima rarely was above one per cent power factor, while the maxima in the curves presented by Professor Dawes are of the order of 15 or 20 per cent. So we have here a quite different type of phenomenon. We have attributed our maxima to the fact that the conductivity of carefully impregnated paper insulation is extremely limited in its value, and that with increasing stress there is a tendency to a saturation condition; as we go higher in voltage the capacity current increases and so we have a descending power factor curve. The mobility of the ions is greater at high temperatures, consequently the phenomenon comes out more definitely under the increased conductivity associated with higher temperatures.

**C. L. Dawes and P. H. Humphries:** Mr. Peterson states that in our power-factor equation (2) no consideration is given to the progressive ionization out from the conductor to the sheath, and offers the further criticism that this equation therefore does not apply between points $E_s$ and $E_i$ in Fig. 1. The power factor in this region is a function of the distribution of the voids throughout the dielectric. We have already derived the equation for this portion of the curve, based on the uniform distribution of the voids throughout the insulation. Since the voids as a rule are not so distributed we have refrained from drawing definite conclusions until we have given the matter more study, both theoretically and experimentally. For example, the characteristics of the cables given in Figs. 12 and 13 of last year's paper (Bibliography 1) show that the ionization is almost spontaneous. This indicates that most of the void space is concentrated at one radius. Furthermore, study of a large number of cables shows no constant value of voltage gradient at the surface of the conductor at the beginning of ionization. If the voids were uniformly distributed throughout the insulation, then at constant pressure, this gradient would be constant.

Moreover, it is usually possible to determine the lower portion of the power-factor curve experimentally, so that an equation for it is not highly essential. On the other hand, those portions of the curve which correspond to high voltages frequently cannot be determined experimentally, owing to the limiting dielectric strength of the cable. Hence, it is particularly desirable to be able to express such portions of the power-factor curve analytically and our Equation (2) is particularly applicable to such portions of the curve. Mr. Peterson further states at the beginning of his discussion that his equation is theoretical only. Later he states that his equation is more exact than ours. His equation is derived in the A. I. E. E. Trans., Vol. 47, July 1928, p. 741. He assumes that the voids are distributed uniformly throughout the insulation. This assumption is correct only occasionally. He further assumes that the ratio of the dielectric constant of the air voids is always unity and is constant. This assumption is grossly in error. It is well known that the dielectric constant of ionized air is greater than unity and is variable; it may go as high as 4 when the air film is considered as a resistance and capacitance in parallel as Mr. Peterson has done in the derivation of his equation. Hence his equation must be fundamentally incorrect. Our equation does not assume that the gas films are distributed uniformly throughout the insulation but takes into consideration their distribution as it actually occurs. Our equation is not based on the variable and unknown dielectric constant of the ionized gas films but on the known variation of the power with current density. Moreover, our equation has been verified by application to a considerable number of curves determined experimentally, and the laws of power loss and current density in the gas films have been verified many times in cables and in segregated gas films.

Mr. Peterson also states that the constants $K_1$ and $E_0$ are obtained from the initial experimental power-factor curve. Mr. Peterson again is wrong. Had he read the paper carefully, he would have seen that these constants are not obtained from the power-factor curve at all. Our power-factor equation is based on the fact that the total power dissipated in the dielectric can be analyzed into two components, the power lost in the solid dielectric and that lost in ionization. The fact that experimental and calculated power-factor curves are in substantial agreement is indicative at least that our assumptions are approximately correct.

Mr. Peterson's further criticism is that the constants $K_1$ and $E_0$ are obtained from the power-factor curve near its maximum value, and then substituted into Equation (2). Again he is mistaken. These constants are obtained from two power curves, a linear one and an exponential one, which is linear when plotted on logarithmic paper. One constant $K_1$ is the slope of one linear power curve; the second constant $E_0$ is its intercept with the voltage axis, and the third constant $K$ is the exponent of an exponential power curve which is merely the slope of a linear logarithmic curve. The slope of two straight lines and an intercept on the voltage axis obviously are not quantities obtained at the maximum point of the power-factor curve.

With these low-voltage cables, it was possible to carry the voltages to values which were sufficiently high to give maximum power factor and beyond. Opportunity is thus offered to verify the accuracy of our power-factor equation and the theory underlying its derivation. As has already been stated, with the higher-voltage cables it is not always possible to carry the voltage to the high values necessary to obtain maximum power factor. With our equation, the maximum values of power factor and the voltages at which they occur can be determined with a fair degree of accuracy, merely by substituting quantities in relatively simple equations.

Mr. Roper's statements as to the monetary value which results from pure research are very pertinent. Many of our most valuable inventions have resulted from research pursued with the object merely of determining new scientific laws, and not with

any idea that such discoveries might later become of commercial value.

Dr. Whitehead assumes that our theory of analysis is based on constant power factor for the solid dielectric. One might very well come to this conclusion, for, so far, all of our published results are given for tests made at room temperature. In all the cable compounds (in combination with paper) which we have so far tested, the power factor at room temperature has been substantially constant up to 300 volts per mil, provided the samples were carefully prepared so that no air was occluded. Curves for samples tested under similar conditions by Dr. Whitehead and his colleagues also show this same characteristic. Under these conditions the power loss varies as the voltage squared. However, further study has shown that at higher temperatures the power lost in the solid dielectric usually does not increase as the square of the voltage but as some other constant power of the voltage. If this be true, the method which we give is applicable at higher temperatures. We are now making further experimental tests on paper, impregnated with various cable compounds in order to obtain further data regarding this exponential law. So far we have found only one compound whose power loss under all conditions did not increase as some constant power of the voltage. In this one instance the departures were slight and occurred only at the highest voltages on the two curves taken at the two highest temperatures. This compound contained 5 or 6 per cent of rosin.

The power factor of impregnated paper without voids may be expressed as follows:

$$\text{P. F.} = \frac{K\,E^n}{E^2\,C\,\omega} = \frac{K\,E^{n-1}}{C\,\omega}$$

when $K$ is the solid-dielectric loss coefficient, $C$ the capacitance, and $\omega$ is $2\,\pi$ times the frequency.

$C$ varies only slightly with voltage. Hence the power factor is a function of the voltage to the power $(n - 2)$. At the higher temperatures, $n$ may be greater or less than two. Even with the same compound, at the lower temperatures $n$ may be less than 2 and at the higher temperatures it may be greater than 2. If $n$ is less than 2 the power-factor curve has a negative slope; if $n$ is greater than 2 the power-factor curve has a positive slope. This I believe gives the same type of power-factor curves which Dr. Whitehead mentions. We have obtained similar curves ourselves. We expect to analyze this particular aspect of the power and power-factor relationships after we have accumulated further data. As we state in the Synopsis, this paper is a report of progress.

# Loading Transformers By Temperature

BY V. M. MONTSINGER*

Fellow, A. I. E. E.

*Synopsis.—It is pointed out that safe loading of transformers by temperature requires not only an accurate knowledge of the thermal laws but also a knowledge of what is a safe temperature limit to be maintained continuously which condition seldom, if ever, happens with the present method of limiting the load to nameplate rating. In view of our present knowledge and experience the author questions the advisability of loading transformers continuously up to the present A. I. E. E. limit of 105 deg. cent. hot spot and argues for the establishment of a differential of 10 deg. cent. between the limit to be maintained continuously by means of overloads and the limit to be reached occasionally with rated load. In other words, for continuously maintained maximum temperatures the hot spot should not exceed 95 deg. cent.*

*It is shown by the use of the thermal laws that without increasing the maximum or hot spot temperature, transformers can be overloaded 1 per cent for each degree centigrade by which the ambient is below 30 deg. cent. (air) for self-cooled transformers, 25 deg. (water) for water-cooled transformers.*

*The results of laboratory aging tests conducted on class A insulations in air and in oil are given. These tests show that the rate of aging is roughly double for each 8 deg. cent. increase in temperature. By the use of these data and by integrating the hot spot temperature rise curve resulting from different load factors the permissible peak load which causes the same deterioration in the insulation as a steady load is obtained.*

*By combining the two rules, increased kv-a. with lower ambients and increased kv-a. with lower load factors, there is obtained a series of loading curves giving the permissible kv-a. capacities for different cooling mediums and load factors. On the average, these curves are conservative because they apply to transformers having quite a wide range of characteristics which affect the temperature rise.*

*Maximum and minimum bi-monthly and average annual outdoor temperatures as furnished by the Bureau of Standards are given for various localities throughout the United States.*

* * * * *

FOR several years there has been a demand on the part of the American central station engineers to operate transformers on a temperature basis. By temperature basis is meant that the load be limited only by the maximum winding temperature rather than by the nameplate rating.

In response to this demand all leading American manufacturers have developed temperature indicators for observing the winding temperature or its equivalent under load conditions. In fact, an indicator of the a-c. type was developed[1] and first applied† in service in 1918. Since that time many hundreds of these indicators have been supplied.

This question has now progressed to the point where definite rules or recommendations for operating transformers on a temperature basis have been drawn up by the transformer sub-committee of the Electrical Machinery Committee.‡ It is proposed that these rules (published in the A. I. E. E. JOURNAL, August 1928), be given in the form of "Recommendations for Service Conditions" in an Appendix to the main body of the standards.

Such a radical departure from what has been standard practise of loading transformers by nameplate rating for many years brings up some very important points for consideration because, if this new method becomes standard practise, in the first place, it is going to result in higher average temperatures being maintained, and the present A. I. E. E. limit of 105 deg. may not be safe. In the second place it will, no doubt, eventually involve other types of apparatus. At the beginning, however, it is thought best to confine the subject to transformers, as this class of apparatus is best suited for this method of loading. In fact, a transformer's output is limited almost, if not entirely, by the maximum temperature, whereas revolving apparatus may have mechanical limitation. Also, on account of the non-interchange of heat flow directly from the copper to the iron and vice versa (as in a generator where the windings are embedded in iron slots) if the transformer oil and winding rises are known for any given load the rise for any other load can be estimated as accurately as it can be determined by tests. This applies to either transient or stable conditions.

Again such a radical change forces upon us the necessity of carefully considering what temperature limit should be adopted for continuous service. The reason for this is self-evident. By the present method of loading by nameplate rating, the A. I. E. E. limit of 105 deg. cent. hot spot can be maintained continuously for self-cooled transformers* only in case the following four conditions occur simultaneously:

1. 40 deg. ambient.
2. rated load continuously.
3. tested rise of 55 deg. cent. by resistance.
4. maximum conventional allowance for hot spot.

*Development and Research Engineer, General Electric Company, Pittsfield, Mass.

†So far as known, this is the first general application of an indicator to indicate actual temperatures of transformer windings under service conditions.

1. See Bibliography for references.

‡Members of subcommittee completing the work were: W. H. Cooney, W. M. Dann (Chairman), J. B. Gibbs, A. H. Kehoe, J. A. Johnson, H. C. Louis, L. C. Nichols, V. M. Montsinger, and J. F. Peters.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

*Water-cooled and forced oil-cooled transformers are not involved in this discussion for the reason that the ambient temperature is 15 deg. less than the ambient for self-cooled transformers.

It is very unlikely that all four of these conditions will occur together.

On the other hand, if a transformer is loaded by temperature, it is obvious that a condition can be brought about that is equivalent to these four conditions occurring simultaneously. The question then is, what temperature limit is safe for this new condition? And have we had sufficient experience to show that the present maximum limit is safe for continuous service?

The solution of this problem, as all others of similar nature, depends mostly upon the results of experience with transformers in service. Laboratory tests give us valuable information, but such tests do not take into account all the factors encountered in the field. As to whether we have had any cases in service where the maximum limit has been maintained continuously, it is very doubtful if we have. In the first place, 40 deg. ambient does not often exist continuously, nor does 100 per cent load factor occur as a general rule, unless for some special kinds of service, as for instance the manufacture of ice, electrolytic, or furnace work. Again, transformers do not always test 55 deg. cent. rise; nor is there always the maximum conventional allowance between the average and hottest spot in the windings. The chances of all of these maximum conditions occurring at the same time and continuously, is possible but remote; therefore, it is questionable if we have sufficient data for assuming that this maximum temperature limit could be maintained continuously with a satisfactory resulting life of the apparatus. By satisfactory life is meant at least fifteen years and perhaps twenty or twenty-five years. We have had maximum rated (55 deg. rise) transformers only since 1913.

When the present standards for rating and temperature limits were established in 1913, no one, of course, knew at that time just what the exact temperature limit should be. Papers presented on the subject of temperature at this memorable meeting of the Midwinter Convention give very meager data on this point. Experience since that time, however, has shown that for average service conditions, the standards were well chosen, and it would be unfortunate if the standard rise of 55 deg. cent. for nameplate rating should be disturbed. Even if loading by temperature should become standard practise, it is quite necessary to retain a standard temperature rise for test purposes (with rate kv-a.) in order to have some measure of the material in a given transformer. The present rise of 55 deg. should not be disturbed.

Regardless of the method of loading transformers, it is quite logical to have a differential in the temperature limits for *continuous* and for *periodic service*. For example, if 105 deg. cent. is satisfactory for continuous service, at least 10 deg. cent. higher temperature if not more should be permissible for short time peak loads. However, we have no experience that would justify us at this time in increasing the limit of 105 deg. even for short time service; consequently, if we establish a temperature differential, it seems that it would be best to be on the safe side and first adopt a lower limit for continuous service, and retain the 105 deg. for periodic service, especially if this can be done without disturbing the present standards. In a few years, it may be found that these limits can be raised.

At this point it is well to comment on the seeming inconsistency in the proposed rules given in Appendix A. For instance, Paragraph 13-601 says that a transformer is suitable for carrying rated load continuously provided that the cooling medium does not exceed 40 deg. cent. for air. In other words this says that it is all right to maintain continuously a temperature measured by resistance of 95 deg. (55 + 40)—which is inconsistent with paragraph 13-602 which says that for all overload conditions the temperature limits should be 10 lower than those that would result with rated load in a 40 deg. cent. air temperature. In other words according to the rules 95 deg. is all right for rated load but 85 deg. must not be exceeded even for a small overload. This requires an explanation.

In the first place, in order not to disturb the present standards of 55 deg. rise and 40 deg. ambient, it was necessary to leave this statement essentially the same as it is in the present standards No. 13 (paragraph 13-50) of the 1925 edition.

To be consistent with the part giving recommended temperature limits for overloads it would have been necessary either to limit rated load to a cooling medium of 30 deg. cent. for air or reduce the temperature rise of all self-cooled transformers from 55 deg. to 45 deg. cent., either of which is unnecessary. It is not necessary because the chances are that so long as rated load is not exceeded the average temperatures in the future will remain pretty much the same as in the past It has already been pointed out that satisfactory results have been obtained under the present practise of operating under usual service conditions. Whatever is said in the rules will have little or no effect on service conditions.

Another reason why a lower limit should be adopted for overload conditions is that as the overload increases the difference between the average and hot spot increases. Some allowance for this should be made. Attention is called to this in the footnote under paragraph 13-603 in the Appendix.

Considering the above points and that the proposed rules are in the nature of an experiment and are to be used for the purpose of obtaining operating experience, it seems that we are fully justified in making the rules as they are.

It is the object of this paper* to present and justify the proposed rules for loading transformers by temperature. In view of the present tendency to overload at low ambients it seems very desirable to standardize overload values and temperature limits which are safe, rather than let the situation drift along with the result

*Companion to paper by W. M. Dann entitled, *Operating Transformers by Temperature.*

that in some cases unsafe valves may be used. To allow the operator to assign the rating to an expensive apparatus depending upon the operating conditions is a very important matter and anything that can be done to make it safe is worth while. It is hoped that the data given in the paper will serve a useful purpose in guiding the practise.

The writer has gone somewhat further than the proposed rules of allowing overloads at low ambients in that it is proposed to allow overloads under low load factor conditions (the ambient remaining constant) which will use up the apparatus at approximately the same rate or less than that for a given constant load factor.

This should enable an operator to determine at what rate he is utilizing the life of the apparatus, under certain special conditions. Under some conditions it may be advisable to utilize the life of the apparatus at a much faster rate than under average conditions, or it may be advisable in some cases to be more conservative.

## Method of Loading by Temperature

Two general methods of loading by temperature are recommended in the proposed rules, namely, (1) by temperature indicator, and (2) by a loading curve where the load in per cent of nameplate rating is dependent upon the ambient temperature.

*Loading by Temperature Indicators.* It will be noted that the proposed rules give three temperature limits 85, 90, and 95 deg. cent., depending upon whether the indicator is calibrated in terms of average temperature, embedded detector, or hottest spot temperature. In each case the limit is 10 deg. cent. less than that resulting from a maximum rated 55 deg. cent. rise transformer operating in a 40 deg. room. For water-cooled transformers where the ambient (ingoing water) is 25 deg. cent. this permits loading continuously at a load to give 60 deg. cent. rise by resistance.

*Loading Based on Ambient Temperature.* To determine safe loading as a function of the ambient temperature it is necessary to know how the kv-a. varies with temperature rise for the different types of transformers.

*Kv-a. vs. Temperature Rise.* In transformers of the oil-immersed (self-cooled and water-cooled) types, there are two distinct and main divisions or steps to be considered in determining the temperature rise of both the windings and the iron over the cooling medium. That is, the copper rise under load is the sum of (1) the oil rise over the cooling medium, and (2) the copper rise over the oil. Likewise, the iron rise is the sum of (1) the oil rise and (2), the iron rise over the oil. These rises must always be dealt with separately. It is obvious that the oil rise is dependent upon both the copper and iron losses while the copper and iron rises over the oil are each dependent mainly upon their respective losses.

This simplified thermal condition in oil-immersed transformers should be kept in mind because it is on this account that it is possible to predict the temperature rises under different loading conditions to a greater degree of accuracy than in most other types of apparatus

The writer has found during many years experience in cooling and heating problems that the temperature rise *vs.* loss can, in almost every case, be expressed by a simple exponential equation. It seems to be one of natures's laws that loss of heat by natural cooling in either a gas or liquid is generally proportional to the temperature rise raised to some power* usually greater than 1.0. But in forced cooling, loss is always directly proportional to temperature rise, *i. e.*, the power is 1.0.

The formula is:

$$P = K\theta^n \qquad (1)$$

where $P$ is the loss,

$K$ a constant,

$\theta$ the temperature rise, and

$n$ a numerical value depending upon the condition of cooling.

Expressed in the reverse order, Equation (1) becomes

$$\theta = K^1 p^{n'} \qquad (2)$$

where $K^1$ is a new constant, and

$$n' = 1/n$$

For oil immersed core type transformers and for constant conditions and within the usual working range of oil temperatures, many tests have shown that $n$ and $n^1$ have the following approximate values:

| | $n$ | $n'$ |
|---|---|---|
| *Self-Cooled:* | | |
| 1. Tank surface or oil rise over room | | |
| a. with plain tank | 1.19 | 0.84 |
| b. with irregular (corrugated, etc.) surfaces | 1.25 | 0.80 |
| 2. Winding rise either by resistance or hot spot over oil— | | |
| a. Having vertical coils | 1.00 | 1.00 |
| b. Having horizontal coils | 1.25 | 0.80 |
| *Water-Cooled:* | | |
| 1. Oil rise over ingoing water (for a constant water rise) | 2.0 | 0.5 |
| 2. Winding rise either by resistance or hot spot over oil | | |
| a. With vertical coils | 1.0 | 1.0 |
| b. With horizontal coils | 1.25 | 0.80 |

When applied to the oil rise, $P$ represents the sum of the copper and iron losses at the operating temperatures, but when applied to the windings, $P$ represents the copper loss only at the operating temperature. The value of the constant $K$ of $K'$ must, of course, be determined from the observed or assumed values of $\theta$ and $P$ for a given load.

The values of 1.19 and 1.25 for $n$ for the oil rise of tanks with plain and irregular surfaces respectively agree with what would be expected. For instance, when the surface of a tank is irregular, most of the loss

*Radiation of heat in air does not quite follow this law though when considering a limited range in temperature, it is close enough for practical purposes.

75 per cent or more, is dissipated by convection, the remaining being radiated. Loss of heat by convection is proportional to the temperature rise raised to the 1.25 power. Therefore, unless the vertical oil gradient changes materially for different loads, and there is no reason why it should, the oil rise should follow the same law as that of loss by convection. For a plain tank, it is a little different because the effect of the radiation pulls the exponent down since the loss by radiation is approximately one-half the total loss, and the exponent for radiation over the range of temperature considered† is about 1.12. Tests check very closely the average value (1.19) of these two exponents. Later on, in making calculations of oil rise *vs.* loss, the value of 1.25 for $n$ is used for the reason that the tanks for all self-cooled power transformers have irregular surfaces. Fig. 1 shows the rise of oil of a water-cooled transformer rated WC-60-500-13,200; first for a 10 deg. cent. rise in the circulating water, and second for a 20 deg. cent. rise in the water, and third, a curve for the oil rise of a WC-60-1000-44,000 volt transformer with a 10 deg. cent. rise in the water. These curves show that $n'$ varies from 0.47 to 0.525. Experience shows that 0.5 gives results close enough for practical purposes.

The temperature rises of both the oil over the room and the windings over the oil are influenced to some extent by the change in viscosity of the oil as its temperature changes, though, generally speaking, this effect can be neglected for the oils used in America, unless the temperature is below about 25 deg. or 30 deg. cent. because the increase in resistance of the copper as the temperature increases is approximately neutralized by the effect of the decrease in oil viscosity. The amount of oil has no effect on the rise after conditions become constant for the reason that the oil generally has approximately a uniform temperature, Fig. 2, along its entire path of flow from near the core and windings to all points above the windings to within about ¼ in. of the cooling coils and tank surfaces.

The total winding rise over the ambient may be calculated for any load other than normal by the following formula:

$$T = C - A = T_o (L N R^2 + 1)^{n_o} + T_c L R^{2n_c} \qquad (3)$$

in which—

T = temperature rise (either hot spot or average) of windings over ambient
$C$ = copper temperature in deg. cent.
$A$ = ambient temperature in deg. cent.
$T_o$ = temperature rise of oil (either top oil or average oil) over ambient at rated load
$N$ = ratio of copper to iron loss at rated load
R = ratio of overload to rated load
$T_c$ = temperature rise of copper over oil at rated load (either hot spot or average)
$n_o$ = 0.8 for self-cooled transformers
= 0.5 for water-cooled transformers
$n_c$ = 0.8 for horizontal windings
= 1.0 for vertical windings

$$L = \frac{234 + A + T}{234 + A + T_o + T_c}$$

In cases where Equation (4) is used and where the copper resistance increases with the temperature, it is, of course, necessary to determine the value of $L$ for each kv-a. value by trial; but when used for the condition where the hot spot is constant (the kv-a. varying with the ambient) $L$ = 1. 0.

For the condition where $n_o = n_c$, that is, for self-cooled transformers with horizon talcoils (and lettering)

$$\left.\frac{1}{n_o} = \frac{1}{n_c} = m \right\} \text{and when } L = 1.0$$

$$R = \frac{T^m (N + 1) - T_o^m}{T w^m (N + 1) + N T_o^m} \qquad (4)$$

If we desire to determine the available capacity for any given ambient, the equation becomes

$$R = \frac{(C - A)^m (N + 1) - T_o^m}{T w^m (N + 1) + N T_o^m} \qquad (5)$$

The difference in the oil and winding rises resulting from assuming, first, that these rises are not proportional to the loss and, second, that they are proportional to the loss (as is sometimes done[5]) is given in Table I.

TABLE I
COMPARISON OF KV-A. VS. TEMPERATURE RISE OF OIL AND WINDINGS BASED ON TEMPERATURE RISE BEING:

(1) Not proportional to loss. (2) Proportional to loss.

| | Self-cooled* | | | | | | |
|---|---|---|---|---|---|---|---|
| | Oil rise deg. cent. over ambient | | Hot spot rise deg. cent. over: | | | | |
| | | | Oil | | Ambient | | |
| R | $n_o = 0.8$ | $n_o = 1$ | $n_c = 0.8$ | $n_c = 1$ | $n_o = 0.8$ $n_c = 0.8$ | $n_o = 1$ $n_c = 1$ | Dif. |
| 1.00 | 45 | 45 | 30 | 30 | 65 | 65 | 0 |
| 1.25 | 55 | 57.5 | 28.6 | 31.2 | 83.6 | 88.7 | 5.1 |
| 1.50 | 66.4 | 73.3 | 38.3 | 45.0 | 104.7 | 118.3 | 13.6 |

| | Water-cooled* | | | | | | |
|---|---|---|---|---|---|---|---|
| | Oil rise deg. cent. over ambient | | Hot spot rise deg. cent. over: | | | | |
| | | | Oil | | Ambient | | |
| R | $n_o = 0.5$ | $n_o = 1$ | $n_c = 0.8$ | $n_c = 1$ | $n_o = 0.5$ $n_c = 0.8$ | $n_o = 1$ $n_c = 1$ | |
| 1.00 | 35 | 35 | 30 | 30 | 65 | 65 | 0 |
| 1.25 | 39.6 | 45 | 43 | 46.8 | 82.6 | 91.8 | 9.2 |
| 1.50 | 44.5 | 56.5 | 57.4 | 67.5 | 101.4 | 124. | 22.6 |

*Ratio cu. to iron losses 1:1 when R = 1.0

These results show that the error, introduced by assuming $n_o$ and $n_c$ equal to unity is in some cases too large to neglect, especially for water-cooled transformer.

Figs. 3 and 4 give curves of the variation in kv-a. *vs.* temperature rise of the windings and oil, above the room, of a self-cooled transformer with (1) horizontal and (2) vertical windings, assuming three different ratios of copper to iron losses. The rises were

†See Equation (9), Bibliography 3.

calculated by the above formulas with the following assumed data at 100 per cent load:

40 deg. cent. top oil rise over the room,

*25 deg. cent. hot-spot winding rise over top oil,

Tank with irregular surface ($n = 1.25$)

1:2, 1:1, and 2:1 ratios of copper to iron loss at rated load.

In estimating these kv-a. values, the increased copper loss due to the increasing resistance (with temperatures) was taken into account.

Fig. 5 shows similar curve for representative water-

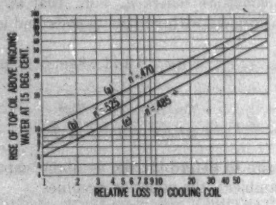


FIG. 1—CURVES SHOWING OIL RISE OF THE WATER COOLED TRANSFORMERS FOLLOWING

(a) WC—60— 500—13,200, 20 deg. cent. water rise
(b) WC—60— 500—13,200, 10 deg. cent. water rise
(c) WC—60—1000—44,000, 10 deg. cent. water rise

cooled transformers having vertical coils, different ratios of copper to iron losses, and the following assumed data at 100 per cent load.

1. 30 deg. cent. top oil rise over in-going water temperature.

2. 35 deg. cent hottest spot winding rise over top oil.

3. 1:1, 2:1, and 4:1 ratio of copper to iron loss.

4. 90 per cent of loss being carried away by the water, remaining 10 per cent being dissipated to the air by the tank.

5. A constant rate of flow of cooling water, this rate being such as to give a 10 deg. cent. rise at 100 per cent load.

The conditions assumed in item (5) give conservative results because if the water were increased with the load, as is often the case, the resulting oil rise would be less. (The winding rise over the oil is, of course, constant for any given load for any rise in the water.) The change in the oil rise is not proportional to the change in the maximum water rise because it is dependent more nearly on the average rise of the water. Generally, the oil rise increases approximately 0.7 as fast as the maximum water rise and vice versa. See Fig. 1. For example, if with a 10 deg. cent. water rise, the oil rise is 30 deg. cent. and the amount of water is reduced one-half to give a 20 deg. cent. rise, the oil rise is increased to about 37 deg. cent.

*It is assumed that the hottest spot over the average temperature is 10 deg. cent., thus leaving an average winding rise of 55 deg. cent. over the room.

## KV-A. *VS.* COOLING MEDIUM TEMPERATURES TO PRODUCE A GIVEN MAXIMUM OR HOT SPOT TEMPERATURE

By subtracting various ambient temperatures from a given average maximum, say 80 deg. cent. (25 plus 55 = 80), or a given hot spot 90 deg. (25 plus 55 plus 10 = 90) for water-cooled transformers, or 85 and 95 deg. cent., maximum and hot spot temperatures respectively for self-cooled transformers in a 30 deg. cent. ambient, we obtain by the aid of the curves of kv-a. *vs.* temperature rise the available kv-a. capacities for the various ambients. These are shown in Tables II and III.

It will be noted that for all the conditions assumed for ratios of losses, etc., the following simple rule will be met:

"The capacity can be increased 1 per cent for each degree that the ambient is below 25 deg. cent. for water-cooled and 30 deg. cent. for self-cooled transformers."

In fact, the rule is more conservative for present day

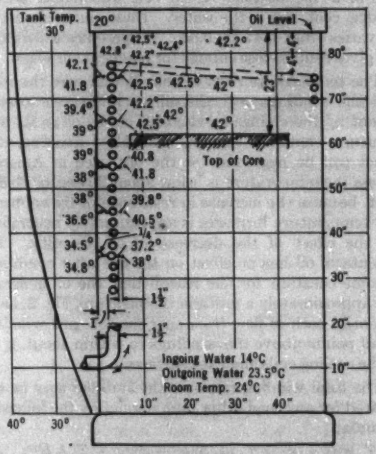


FIG. 2—TEMPERATURE GRADIENT OF OIL IN WATER COOLED TRANSFORMER

WC—60—2100.—13,900—2300 volts

high efficiency units than it appears to be from the values given in Tables II and III, because it is assumed that (1), the hot spot is 10 deg. cent. whereas on account of the low copper densities used, the hot spot is perhaps more nearly 5 to 7 deg. cent. instead of 10 deg. cent. Again it is assumed that the tested rise is 55 deg. cent. at rated load, which is not always the case. This 1 per cent rule was pointed out by the writer in the June 1918 issue of the *General Electric Review*, in the following statement:

". . . . . an increase of approximately one per cent

in the kilovolt-amperes capacity of self-cooled transformers can usually be obtained for each degree that the ambient temperature is below 40 deg. cent., without exceeding the normal hot-spot limit. The same approximate rate of increase in capacity applies to water-cooled transformers for each degree that the

TABLE II
WATER-COOLED TRANSFORMER RELATIVE KV-A. CAPACITIES VS. INGOING WATER TEMPERATURES TO PRODUCE A GIVEN WINDING TEMPERATURE

| Assumed characteristics at 100 per cent load | | | Per cent kv-a. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ratio of copper to iron loss | | | 1:1 | | | 2:1 | | | 4:1 | | |
| Oil rise over room deg. cent | | | 30 | 35 | 40 | 30 | 35 | 40 | 30 | 35 | 40 |
| Average winding rise over oil deg. cent | | | 25 | 20 | 15 | 25 | 20 | 15 | 25 | 20 | 15 |
| Hot spot rise over oil deg. cent | | | 35 | 30 | 25 | 35 | 30 | 25 | 35 | 30 | 25 |
| Ingoing Water temp. deg. cent. | Position of windings | Based on winding temp. of | | | | | | | | | |
| 35 | Vert. | 80-deg. av'g. | 85. | 83. | 81. | 86.5 | 85. | 83.5 | 87.5 | 86.5 | 85. |
| | Horiz. | " " | 83. | 81. | 79. | 84.5 | 83. | 81.5 | 86. | 85. | 84. |
| | Vert. | 90-deg. hot spot | 88.5 | 87.5 | 86.5 | 89. | 88. | 87. | 90. | 89. | 88. |
| | Horiz. | " " " | 86.5 | 85.5 | 84.5 | 87. | 86. | 85. | 88.5 | 88. | 87.5 |
| 25 | Vert. | 80-deg. av'g. | 100. | 100. | 100. | 100. | 100. | 100. | 100. | 100. | 100. |
| | Horiz. | " " | " | " | " | " | " | " | " | " | " |
| | Vert. | 90-deg. hot spot | " | " | " | " | " | " | " | " | " |
| | Horiz. | " " " | " | " | " | " | " | " | " | " | " |
| 15 | Vert. | 80 -deg. av'g. | 113.5 | 115. | 116.5 | 112. | 113. | 114. | 111.5 | 112.5 | 114. |
| | Horiz. | " " | 115.5 | 117. | 118.5 | 114. | 115. | 116. | 113. | 113.5 | 114.5 |
| | Vert. | 90-deg. hot spot | 110.5 | 111.5 | 113. | 110. | 110.5 | 111. | 109.5 | 110. | 110.5 |
| | Horiz. | " " " | 112.5 | 113.5 | 114.5 | 111.5 | 112. | 112.5 | 110.5 | 111. | 111.5 |
| 0 | Vert. | 80-deg. av'g. | 131. | 134. | 137. | 129. | 131. | 133. | 127. | 129. | 131. |
| | Horiz. | " " | 136.5 | 139.5 | 142. | 133.5 | 135.5 | 137.5 | 131.5 | 133. | 134.5 |
| | Vert. | 90-deg. hot spot | 125. | 127. | 129 | 123.5 | 125. | 126.5 | 122.5 | 124. | 125.5 |
| | Horiz. | " " " | 130.5 | 132. | 134 | 128.0 | 129.5 | 131. | 126.5 | 127.5 | 128.5 |

TABLE III
SELF-COOLED TRANSFORMER RELATIVE KV-A. CAPACITIES VS. ROOM TEMPERATURES TO PRODUCE A GIVEN WINDING TEMPERATURE

| Assumed characteristics at 100 per cent load | | | Per cent kv-a. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ratio copper to iron loss | | | 1:2 | | | 1:1 | | | 2:1 | | |
| Oil rise over room deg. cent | | | 45 | 40 | 35 | 45 | 40 | 35 | 45 | 40 | 35 |
| Average winding rise over oil deg. cent | | | 10 | 15 | 20 | 10 | 15 | 20 | 10 | 15 | 20 |
| Hot winding rise over oil deg. cent | | | 20 | 25 | 30 | 20 | 25 | 30 | 20 | 25 | 30 |
| Room temp. deg. cent. | Position of windings | Based on winding temp. of: | | | | | | | | | |
| 40 | Vert. | 85-deg. avg. | 74 | 78 | 81.5 | 80 | 82.5 | 84 | 84.5 | 85.5 | 86.5 |
| | Horiz. | " " | 71 | 75.5 | 77.5 | 78.5 | 80.5 | 82 | 83 | 83.5 | 85 |
| | Vert. | 95-deg. hot spot | 82.5 | 85 | 87. | 86 | 87. | 88 | 88 | 89. | 89.5 |
| | Horiz. | " " " | 80.5 | 82 | 84 | 84 | 85 | 86 | 87 | 87.5 | 88 |
| 30 | Vert. | 85-deg. avg. | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | Horiz. | " " | " | " | " | " | " | " | " | " | " |
| | Vert. | 95-deg. hot spot | " | " | " | " | " | " | " | " | " |
| | Horiz. | " " " | " | " | " | " | " | " | " | " | " |
| 20 | Vert. | 85-deg. avg. | 121 | 118 | 115.5 | 117 | 115 | 114. | 114 | 113 | 112 |
| | Horiz. | " " | 123 | 120.5 | 118.5 | 118 | 117 | 114.5 | 115 | 114 | 113.5 |
| | Vert. | 95-deg. hot spot | 115 | 113 | 111.5 | 112.5 | 111.5 | 110.5 | 111 | 110 | 109.5 |
| | Horiz. | " " " | 117 | 115.5 | 114 | 114.5 | 113.5 | 112.5 | 112 | 111.5 | 111 |
| 10 | Vert. | 85-deg. avg. | 139 | 133.5 | 130 | 131 | 127.5 | 126 | 126 | 124.5 | 123 |
| | Horiz. | " " | 143 | 138.5 | 135 | 134 | 132 | 130 | 128 | 127 | 126.5 |
| | Vert. | 95-deg. hot spot | 128 | 125 | 123 | 123.5 | 122 | 120.5 | 121 | 119.5 | 118.5 |
| | Horiz. | " " " | 132 | 129.5 | 127.5 | 127 | 125.5 | 124.5 | 123 | 122.5 | 122 |
| 0 | Vert. | 85-deg. avg. | 154.5 | 148 | 143 | 145 | 141 | 137.5 | 138 | 136 | 134 |
| | Horiz. | " " | 161.5 | 155.5 | 151 | 149 | 146 | 144 | 141 | 137.5 | 138.5 |
| | Vert. | 95-deg. hot spot | 139.5 | 135.5 | 133 | 134 | 131.5 | 129.5 | 130 | 128.5 | 127 |
| | Horiz. | " " " | 146 | 143 | 140 | 139 | 137 | 135.5 | 134 | 133 | 132 |
| −10 | Vert. | 85-deg. avg. | 169 | 161.5 | 155.5 | 158 | 153 | 148.5 | 149 | 146 | 143.5 |
| | Horiz. | " " | 178.5 | 171 | 165.5 | 163 | 159.5 | 157 | 153 | 151 | 159.5 |
| | Vert. | 95-deg. hot spot | 151 | 146 | 142 | 144 | 141 | 138.5 | 139 | 137 | 135 |
| | Horiz. | " " " | 159 | 155 | 152 | 150 | 148 | 146 | 143.5 | 142.5 | 141.5 |

temperature of the ingoing water is below 25 deg. cent."

*Loading as Function of Load Factor.* We have seen that the variation in load can be expressed as a simple relation of the ambient temperature. This idea can be carried further by making the load a function of the load factor, although it is not quite so simple to do so. It requires a knowledge of the rate of aging or deterioration of insulation with temperature. With this information at hand and with a curve or set of curves giving the hot spot temperature for various load factors, the relative aging can be determined for the load factor by integrating these areas, and multiplying by the relative aging. The relative life of the apparatus is represented of course by the reciprocal of the value so obtained.

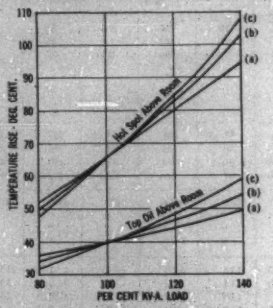


FIG. 3—CURVES SHOWING VARIATION OF KV-A. *vs.* TEMPERATURE RISE IN WINDINGS AND OIL

For self-cooled transformers having vertical coils and copper to iron loss ratios at 100% load as follows:

(a) 1:2
(b) 1:1
(c) 2:1

## 1. EFFECT OF AGING OF INSULATION ON LIFE OF A TRANSFORMER

Insulation obviously performs two functions; it provides both electrical and mechanical strength between turns, between coils, and from coils to ground.

Aging is a function of both time and temperature, and eventually renders the insulation unfit to perform either duty. In other words, contrary to the sometimes expressed statement that "aging does not begin until a definite temperature has been exceeded, aging goes on at all temperatures, even room temperatures, the rate of course increasing as the temperature increases.

Numerous laboratory tests have demonstrated that insulation does not seriously deteriorate electrically until the material has lost all mechanical strength and has become charred and sufficiently weakened and brittle to crumble; in other words, until it has passed beyond a condition that is safe. In fact, generally, the dielectric strength increases until the material cracks.

Consequently, it is hopeless to judge even the rate of deterioration of insulation by its electrical strength. This leaves us with only the mechanical strength to judge the insulation.

It is doubtful if the "actual" life of a transformer can ever be determined, even by the most carefully conducted laboratory test, due to the lack of a proper criterion by which to judge whether an insulation has reached an unsafe degree of deterioration.

It is the writer's opinion that the mechanical deterioration (such as tensile tearing and bursting strength) of insulation can be used to best advantage only in one way to help us out in the problem of loading transformers by temperature. This is to determine the "rate of deterioration" at different temperatures and use this in conjunction with some temperature which average service conditions have shown a transformer to give a reasonable life, and judge from this how long it ought to last if continuously operated at some other temperature, say 10 deg. cent. lower or 10 deg. higher. Again, if such a curve is rational, it should be possible to estimate roughly how fast one is using up the life of a certain piece of apparatus on short time, heavy over-loads, etc. Or one can estimate the permissible peak loads under various load factor conditions to produce approximately the same degree of deterioration, as 100 per cent load, or nameplate rating continuously in a given ambient. Of course, it is obvious that this method is not rigidly correct (as no method can be), yet it offers the only means of arriving at even an approximate answer to the problem, and enables us to make progress.

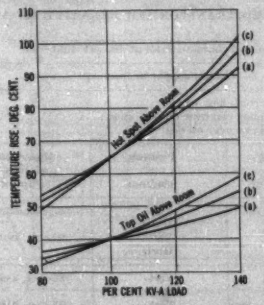


FIG. 4—CURVES SHOWING VARIATION IN KV-A. *vs.* TEMPERATURE RISE OF THE WINDINGS AND OIL FOR SELF COOLED TRANSFORMERS

Having horizontal coils and copper to iron loss ratios at 100% load as follows:

(a) 1:2
(b) 1:1
(c) 2:1

Figs. 6 and 7 show the decrease in tensile strength of black and yellow varnish cloths when subjected to 90, 100, and 110 deg. cent. in air and in oil for a period of 68 weeks.

These and many other aging curves show that the time necessary to reduce the insulation at a given temperature to a definite per cent of its initial strength when plotted on semi-log paper against the temperature falls approximately on a straight line (the time being on the log scale).

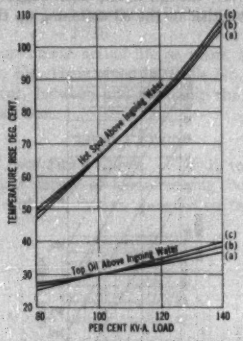


FIG. 5—CURVES SHOWING VARIATION IN KV-A. VS. TEMPERATURE RISE OF THE WINDINGS AND OIL

For water cooled transformers having vertical coils and copper to iron loss ratios at 100% load as follows:

(a) 1:1
(b) 2:1
(c) 4:1

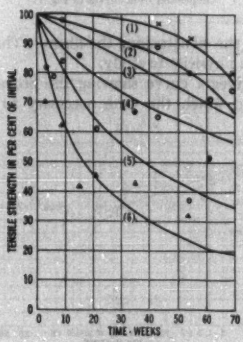


FIG. 6—AGING CURVES FOR 0.012 IN. YELLOW VARNISHED CAMBRIC

(1) In 90 deg. cent. air
(2) In 100 deg. cent. air
(3) In 110 deg. cent. air
(4) In 90 deg. cent. oil
(5) In 100 deg. cent. oil
(6) In 110 deg. cent. oil

The equation is $$Y = A\,e^{-mx} \qquad (6)$$

where $Y$ = time.
$A$ = constant.
$e$ = base of naperian logarithm.
$m$ = constant = (0.088).*
$x$ = temperature deg. cent.

The form of Equation (6) means, of course, that deterioration goes on at some definite rate at all temperatures, and doubles every so many degrees increase, or vice versa. For example, if the curves shown in Figs. 6 and 7 are re-plotted on semi-log paper, Figs. 9 and 10, it will be noted that for each 7.5 deg. or 8 deg. cent. increase in temperature, the rate of aging doubles. These data were obtained in 1921.

Practically about the same rate of aging was found by the Massachusetts Institute of Technology, Department of Electrical Engineering (direction of Dr. V. Bush) in the series of tests which was conducted in 1923 on "The Deterioration of Cable Paper when Subjected to Temperature Only." These tests were made with the collaboration of the N. E. L. A. and the results are given in a report to the Impregnated Paper Insulated Cable Research Committee, National Electric Light Association. One set of curves in this report is replotted and given in Fig. 8. This shows that the rate of aging doubles approximately every 8 deg. cent. increase in temperature for all the lines ranging from 90 per cent of the initial strength down to 20 per cent of initial strength. The 8 deg. cent. rule is the general average of several other curves in this report. Considering the fact that the two sets of aging tests were made independently of each other, and check so well adds confidence in some such a rule.

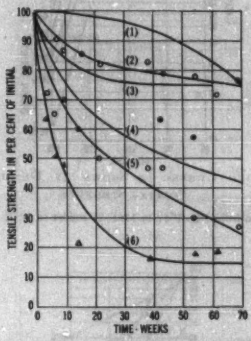


FIG. 7—AGING CURVES FOR 0.012 IN. BLACK VARNISHED CAMBRIC

(1) In 90 deg. cent. air
(2) In 100 deg. cent. air
(3) In 110 deg. cent. air
(4) In 90 deg. cent. oil
(5) In 100 deg. cent. oil
(6) In 110 deg. cent. oil

*See Fig. 11.

The tests, Figs. 9 and 10, indicated that the same law holds for aging in both air and oil. These curves are replotted from the curves which represent an average of the test points shown in Figs. 6 and 7 respectively. It will be noted, however, that insulation ages faster in oil than in air which result was rather surprising at first. It was thought that some error had been made. Many other tests, however, have confirmed these results even though air was kept away from the oil to prevent oxidation and consequent increase in the acidity of the oil. High acid contents in the oil will hasten the aging but even if oil is kept strictly neutral, tests show that the aging is faster so that it cannot be explained in this way. No completely satisfactory explanation has ever been given for this shorter life of insulation in oil than in air, though it has been suggested that it may be due either to the oil softening up the fibers or the acids in the oil attacking the fibers. This is a good subject for a physicist to study.

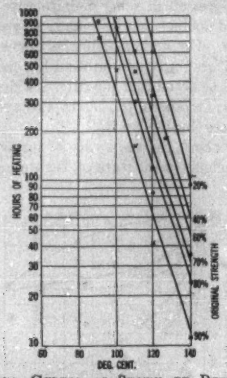


Fig. 8—Aging Curves as Shown by Deterioration in Folding Strength

(Taken from Fig. F-37 in M. I. T. report to N. E. L. A.)

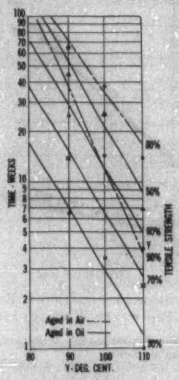


Fig. 10—Aging Curves for 0.012 In. Black Varnished Cambric

(Replotted from curves in Fig. 7)

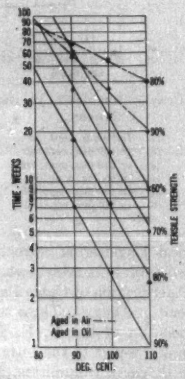


Fig. 9—Aging Curves for 0.012 In. Yellow Varnished Cambric

(Replotted from curves in Fig. 6)

Fig. 11 gives a curve showing the probable life of insulation in which the time necessary to cause the material to become practically useless in oil at various temperatures is shown. From zero time up to about 20 years the line used later follows the 8 deg. cent. rule but at this point it is drawn downward such that at 25 deg. cent. the life is 100 years. It does not seem that insulation could have very much life left at the end of approximately 100 years even at room temperature.

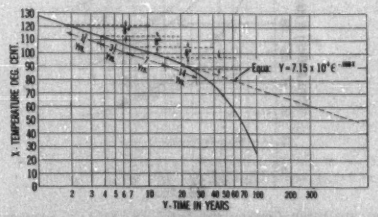


Fig. 11—Effect of Temperature on Relative Life of Class A Insulation (Actual Life Very Approximate) or Time to Cause Complete Destruction in Oil

Whether or not this is correct is not vitally important to the present problem.

The equation of the straight line in Fig. 11 is

$$Y = 7.15 \times 10^4 \, \epsilon^{-.088x} \qquad (7)$$

where $Y$ = time in years

$x$ = temperature in deg. cent.

$\epsilon$ = 2.718

The approximate actual life as taken from the full line curve, Fig. 11, is given in Table No. IV for each 10 deg. cent. between and including the limits of 30 and 120 deg. cent.

TABLE IV

| Temperature deg. cent. | Approximate time in years required to reduce life of insulation to zero (in oil) |
|---|---|
| 30 | 94 |
| 40 | 82 |
| 50 | 70 |
| 60 | 58 |
| 70 | 46 |
| 80 | 35 |
| 90 | 23 |
| 95 | 16 |
| 100 | 10.5 |
| 105 | 7. |
| 110 | 4.5 |
| 120 | 1.9 |

## Load Factors

*Typical Load Factor Curves.* Figs. 12 to 17 inclusive show typical curves of loads ranging from about 25 to 90 per cent load factors observed on the New York

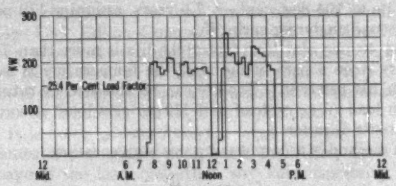


Fig. 12

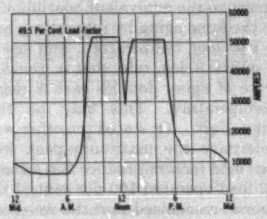


Fig. 15

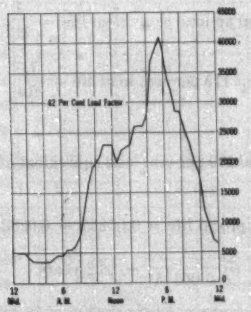


Fig. 13

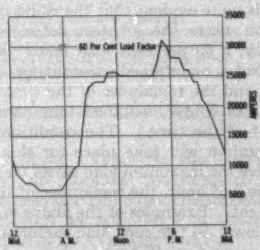


Fig. 16

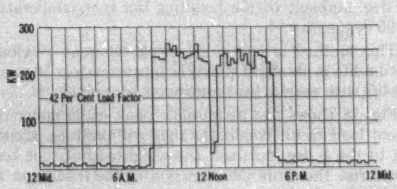


Fig. 14

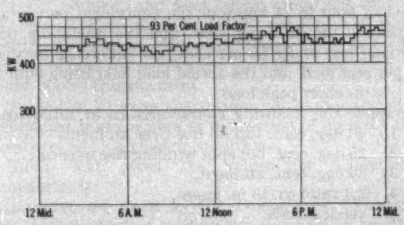


Fig. 17

Figs. 12 to 17—Typical Load Curves of Various Load Factors on New York Edison Company's System

Edison Company's System. Table V shows these together with some other load factors for various kinds of service on the same system.

The data in Table V show that for general power and light, and for the usual industrial purposes, the load factor seldom exceeds about 60 per cent. For ice and sugar manufacturing purposes, however, the load factor is high, in fact, close to 100 per cent.

*Maximum or Peak Loads at Various Load Factors to be the Equivalent of 100 per cent Load Factor.* As previously pointed out, the deterioration of insulation is a function of both time and temperature. Therefore, if we are to determine the effect of temperature resulting from various load factors on the deterioration of the insulation, we must first know what the hot spot temperature is during the cycle of loading, and second, we must determine the equivalent continuous load that will produce the same aging by integrating by parts the area of the hot spot temperature, and use the aging curve based on the 8 deg. rule, that is, the curve which shows the rate of aging doubles each 8 deg. cent. increase in temperature. This may be termed the weighted aging effect. Or stated the other way around, we must determine the maximum peak loads under which various load factors produce the same deterioration as rated load operated 100 per cent of the time.

It is, of course, recognized that the weighted aging is not the same even for a given load factor, but may vary depending on the duration of the peak load. For example, it is quite evident that the worst condition or the condition where the greatest deterioration takes place for, say, a 50 per cent load factor is where the maximum load is maintained constant for 50 per cent of the time, and the remainder of the time the load is zero. (It is, of course, assumed that core loss is on 100 per cent of the time.) The condition where the least deterioration will take place for this same load factor is where the maximum load exists for a period of, say, only one half hour, the remainder of the time the load being light. Examples of the above cases may be taken as follows: 50 per cent load factor worst condition, maximum load on 12 hours a day, or 15 days in a month, or 187 days in a year, core-loss on remainder of the time. The best condition, maximum load on one-half hour in 24 hours or the equivalent percentage of time in the days per year, and the remaining time the load just under 50 per cent, the difference between 50 per cent load, and the actual load held being equivalent to the short peak load.

Assume the following characteristics at rated load:

1. 40 deg. cent. top oil rise over ambient.
2. 25 deg. cent. hot spot winding rise over oil.
3. 30 deg. cent. ambient.
4. 2:1 ratio cu. to fe. losses.
5. vertical coils.
6. tank with irregular surface ($n = 1.25$)
7. oil rise varies as 0.8 power of loss.
8. coil rise over oil varies directly with loss.
9. 40 per cent load factor (rectangular load curve; *i. e.*, 100 per cent on 40 per cent of time, no load 60 per cent of time).
10. 15 deg. coil rise by resistance over oil.

*No Load*

No load loss = fe. loss = 1.0.

Full load loss = fe. + cu. = 1 + 2 = 3.

Top oil rise = $40\ (1/3)^{.8}$, = 16.6 deg. cent.

Top oil temp. = 30 + 16.6 = 46.6 deg. cent.

Life at 46.6 deg. cent. = 70 years (see Fig. 11) assuming no-load losses on during entire life.

*110 Per Cent Load*

Copper loss = $1.1^2 \times 2 = 2.42$

Iron loss = 1.0

Total loss = 2.42 + 1 = 3.42

Hot spot temp. = $1.1^{.8}\ (25 + 40) + 30 = 104$ deg. cent.

Life at 104 deg. cent. = 7.5 years, assuming 110 per cent load on during entire life.

At 40 per cent load factor the life is more than 7.5 years since a part of the time the temperature is less than 104 per cent. The life can be obtained by rating each load (*i. e.*, no-load and 110 per cent load) according to its duration.

A method of accomplishing this is given below:

$$\text{Equivalent no-load life} = \frac{70}{0.6} = 117 \text{ years.}$$

$$\text{Reciprocal no-load equivalent life} = \frac{1}{117} = 0.00855.$$

$$\text{Equivalent 110 per cent load life} = \frac{7.5}{0.4} = 18.75 \text{ years.}$$

$$\text{Reciprocal 100 per cent load equivalent life} = \frac{1}{18.75} = 0.0532.$$

Total reciprocal life = 0.00855 + 0.0532 = 0.06175.

$$\text{Total life} = \frac{1}{0.06175} = 16.2 \text{ years.}$$

16.2 years corresponds to the life of 16 years as given in Fig. 11 with normal load applied continuously in a 30 deg. ambient with a resulting hot spot temperature of 95 deg. cent.

This method is continued using different overloads until a life is obtained which is approximately 16 years, the life with normal load continuously applied.

Fig. 18 shows the permissible peak loads under different load factor conditions that will produce, according to the 8 deg. rule and the weighted hot spot temperatures, the same deterioration of the insulation for the best load cycle condition, the worst daily load cycle, and the worst load cycle under any condition. The best condition is where the maximum or peak load is a narrow high rectangle extending over a short time not

over one-half hour while the remaining time the load is fairly light.

The worst condition naturally comes where the load is zero part of the time and maximum the remainder of the time—a rectangular shaped cycle. The reason the worst daily load cycle is not as severe as the worst cycle under any condition is because the winding temperature due to the time lag is not at the maximum value for say 50 per cent of the time for a 50 per cent daily load factor as it would be if we had a 50 per cent weekly or monthly load factor.

The curves in Fig. 18 show the difference between the worst and best daily load cycles found in service. The curve for the worst daily load factor is based on typical load and winding hot spot temperatures as shown in Fig. 19, for different load factors which correspond roughly to the load curves obtained from the New York Edison Company, although the lines have been smoothed out and reblocked in a manner to enable the calculations to be more easily made. It will be noted that there is quite a variation in the permissible peak loads between the extreme conditions.

It is quite evident from the large differences in the values of permissible peak loads depending upon the shape of the load cycle that any rule expressing the overload as a function of the load factor must be very

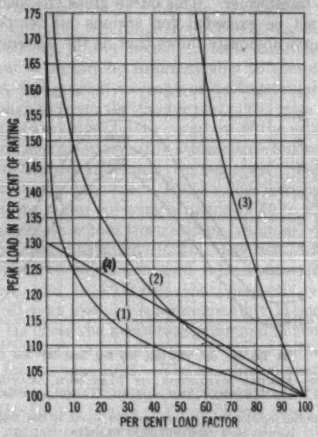


Fig. 18—Curves of Permissible Peak Loads for Various Load Factors and Assumed Conditions

1. Worst condition for weekly or seasonal cycle
2. Worst condition for daily cycle
3. Best condition for any cycle
4. Assumed safe loads for condition (2)

conservative; otherwise the transformer might be damaged.

We might select the worst daily load cycle and formulate a rule. This shows that we can place on a transformer 3 per cent above rated load for each 10 per cent decrease in the load factor below 100 per cent. Thus for example, at 80, 60, 40, and 20 per cent load factors

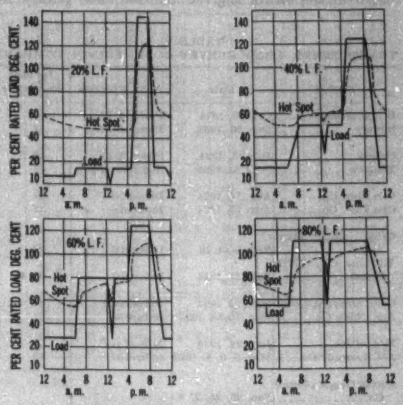


Fig. 19—Typical Load and Winding Hot Spot Temperatures for Different Load Factors

In each case the transformer ages at the rate which would occur with rated load on all the time

Assumptions:

1. Self-cooled transformers
2. Core loss on all the time
3. 30 deg. cent. ambient temperature
4. Ultimate full-load top oil rise is 40 deg. cent.
5. Ultimate full-load hot spot over top oil rise is 25 deg. cent.
6. Thermal time constant 3 hr. for top oil rise
7. Thermal time constant 5 min. for hot spot over top oil

the peak overloads would be 6, 12, 18, and 24 per cent, respectively.

## Permissible Kv-a. Capacities for Different Load Factors and Cooling Mediums to Produce Approximately the Same Deterioration of Insulation as for 100 Per Cent Load Factor in an Average Cooling Medium

We can now combine or add the 1 per cent and 3 per cent rules and construct a set of overload values for different ambient and load factor conditions that will be the equivalent in aging of 100 per cent load factor, limiting the load at 100 per cent load factor to 30 deg. cent. ambient for self-cooled and at 25 deg. cent. for water-cooled transformers.

Table No. VI gives the various values of overloads of self-cooled transformers as a function of ambient temperatures and load factor conditions.

Table VII gives the values for water-cooled transformers:

*Limiting the Load by Oil Temperature.* The most practical method of loading the transformer by its oil temperature is to provide a curve which gives the permissible load without exceeding a definite maximum winding temperature or hot spot temperature for

various oil temperatures, assuming, of course, that the winding rise over the oil is constant. No definite rule can be stated that would cover all cases because the coil rise over the oil for a given load varies so greatly for different transformers. Hence, in cases where this method is applied, the characteristics of the transformer in question must be carefully considered. Furthermore, if it is to be applied to a transformer which has been in service for a few years, the age of the transformer must be taken into consideration because it is obvious that a transformer which has been in service 15 to 20 years, for instance, cannot be safely loaded as high as a new transformer. This method of loading a transformer by actual oil temperature rather than by oil temperature rise automatically includes all factors or conditions that affect the oil temperature or oil rise, such as the ambient, rate of water flow in water-cooled transformers, or incrustation of cooling coils, etc.

TABLE V
TRANSFORMER LOAD CURVES—N. Y. EDISON COMPANY

| Station | Date | Kind of service | Per cent load factor |
|---|---|---|---|
| E 51st Street | Oct. 30, 1924 | Power & Lt. | 60 |
| Bowery | Dec. 20, 1923 | Power & Lt. | 42 |
| Crosby | July 15, 1924 | Power & Lt. | 49.5 |
| Yonkers | June 20, 1922 | Sugar Company | 92 |
| Otis Elev. Co. | Aug. 14, 1924 | Industrial | 34 |
| Otis Elev. Co. | Aug. 13, 1924 | Industrial | 32 |
| Cable Co., 138rd Street | Sept. 6-14, 19 | Industrial | 60 |
| Williams Co., 177th Street | Sept. 18, 1924 | Industrial | 25.4 |
| Cons. Shipping. Corp. | Sept. 22, 1924 | Industrial | 42 |
| Am. Chicle Co. | Mar. 10-11, 1925 | Industrial | 57 |
| Mfg. of Ice | June 28, 1923 | Mfg. of Ice | 93 |
| AM Eveready Co. | Mar. 2, 3, 4, 1925 | Industrial | 46 |
| Anchor Cap & Closure Co. | Feb. 25, 26, 27, 1925 | Industrial | 38.5 |
| Loft Candy Co. | Mar. 10, 11, '25 | Industrial | 61.3 |

TABLE VI
SELF-COOLED TRANSFORMERS PEAK LOAD IN PER CENT OF NORMAL

| Ambient deg. cent. | 0 | 10 | 20 | 30 |
|---|---|---|---|---|
| Load factor | | | | |
| 100 | 130 | 120 | 110 | 100 |
| 80 | 136 | 126 | 116 | 106 |
| 60 | 142 | 132 | 122 | 112 |
| 40 | 148 | 138 | 128 | 118 |
| 20 | 154 | 144 | 134 | 124 |

TABLE VII
WATER-COOLED TRANSFORMERS PEAK LOAD IN PER CENT OF NORMAL

| Ingoing water temperature deg. cent. | 0 | 5 | 10 | 15 | 20 | 25 |
|---|---|---|---|---|---|---|
| Load factor | | | | | | |
| 100 | 125 | 120 | 115 | 110 | 105 | 100 |
| 80 | 131 | 126 | 121 | 116 | 111 | 106 |
| 60 | 137 | 132 | 127 | 122 | 117 | 112 |
| 40 | 143 | 138 | 133 | 128 | 123 | 118 |
| 20 | 149 | 144 | 139 | 134 | 129 | 124 |

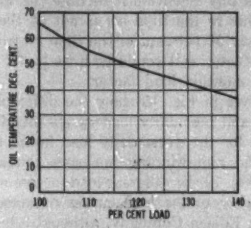


FIG. 20—CURVE SHOWING PER CENT LOAD THAT CAN BE HELD WITHOUT HOT SPOT EXCEEDING 90 DEG. CENT.

Assuming:
(1) 25 deg. hot spot rise over oil at 100 per cent load
(2) Hot spot rise over oil varying as square of load

Fig. 20 shows a typical curve drawn up for a water-cooled transformer. This curve gives the loads which must not be exceeded for various oil temperatures. This curve obviously shows that as the oil temperature increases, the permissible kv-a. load decreases. It does not mean, as might appear at first sight, that as the value of the load decreases the oil temperature increases, because the opposite of course is true. As stated above, this method of loading is applicable only to specific cases where the condition and characteristics of the transformer are known.

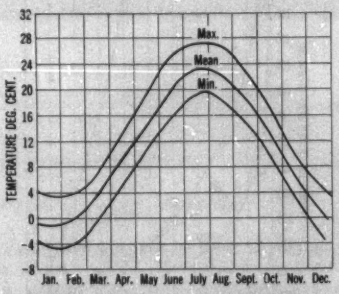


FIG. 21—ANNUAL VARIATION OF MAXIMUM, MINIMUM, AND MEAN MONTHLY ATMOSPHERIC TEMPERATURES

For an outdoor location near the sea coast at about 40 deg. latitude based on records of 10 to 50 years

TABLE VIII
MEAN BI-MONTHLY OUTDOOR TEMPERATURE DEG. CENT.

| Location | Jan. | | March | | May | | July | | Sept. | | Nov. | | Avg. No. annual temp. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. |
| Albany, N. Y. | − 2.3 | −11 | 7.5 | − 2.3 | 23 | 10.5 | 27.5 | 17.5 | 23.8 | 13 | 9 | 1.0 | 14.4 | 3.1 |
| Birmingham, Ala. | 12. | 3.5 | 18.4 | 7.9 | 27.2 | 17 | 32 | 21 | 31.5 | 19.5 | 10 | 8.1 | 23.4 | 12.8 |
| Bismarck, N. D. | − 7.3 | −19.1 | 2 | − 7.3 | 20 | 8.5 | 27 | 13.2 | 23.5 | 9.3 | 4.5 | − 3. | 11.6 | .4 |
| Boise, Idaho | − 2.4 | −11 | 8.6 | − 0.5 | 21 | 6.5 | 33 | 15.6 | 28 | 10 | 8.4 | − 3. | 16.1 | 3.0 |
| Boston, Mass. | 1.3 | − 6.9 | 9 | 0 | 21.5 | 11 | 26.5 | 18 | 23 | 14 | 15.2 | 3 | 16 | 6.5 |
| Charleston, S. C. | 12.6 | 4.9 | 19 | 11. | 26.5 | 19 | 32 | 24 | 28.5 | 21.5 | 20 | 11.5 | 23.1 | 14.5 |
| Chicago, Ill. | 0.5 | − 8.5 | 7.5 | 1.0 | 21.6 | 14 | 26.5 | 19.8 | 24.5 | 17.7 | 9.9 | 4 | 15.1 | 8.0 |
| Cleveland, Ohio | 0.5 | − 7.5 | 8.5 | −1.0 | 20 | 12.5 | 26. | 18. | 15. | 19. | 3.5 | 6.7 | 12.2 | 5.0 |
| Dallas, Texas | 10.5 | 2 | 19. | 7.2 | 29 | 19. | 34.5 | 23.5 | 32.5 | 20.5 | 19. | 9 | 23.7 | 13.5 |
| Denver, Colo. | 4. | − 8.9 | 11.5 | − 2.0 | 20.7 | 8. | 29.5 | 15. | 26. | 11.5 | 8.2 | − 3 | 16.7 | 3.4 |
| Detroit, Mich. | 0 | − 8.9 | 7.0 | − 2.8 | 22 | 12.5 | 27. | 18. | 24.5 | 14.5 | 9. | 3. | 14.7 | 6.1 |
| Fresno, Calif. | 9.5 | 1.5 | 16.5 | 6 | 27.5 | 12.5 | 38. | 19.5 | 35.5 | 17. | 16. | 5.5 | 23.8 | 10.3 |
| Jacksonville, Fla. | 16. | 8. | 22.5 | 14. | 29. | 20.5 | 32 | 23.5 | 28 | 21.5 | 29 | 14. | 24.9 | 17 |
| Louisville, Ky. | 5.1 | − 3.5 | 14 | 5. | 25.5 | 16. | 30 | 20 | 27 | 17 | 13.5 | 5. | 19.2 | 10 |
| Minneapolis, Minn. | − 6. | −15. | 4 | − 3.5 | 22.5 | 12.5 | 26.3 | 16 | 24.5 | 13 | 7 | 1.5 | 13. | 2.4 |
| New Orleans, La. | 17. | 9.5 | 21.5 | 12.5 | 28 | 20.5 | 32 | 24.5 | 30.5 | 23.6 | 23 | 15.5 | 25.3 | 17.7 |
| New York, N. Y. | 2.0 | − 5.3 | 9 | 1 | 22.5 | 12.6 | 26.5 | 18.5 | 23.5 | 16. | 11 | 4 | 15.7 | 8.7 |
| Oklahoma City, Okla. | 7 | − 3.5 | 15.5 | 3.5 | 25. | 15.5 | 34 | 21.6 | 32 | 18. | 16. | 5.5 | 21.5 | 10. |
| Omaha, Nebraska | 0 | − 9.5 | 10 | 0 | 23.5 | 13 | 28.5 | 18 | 27.5 | 16. | 11 | 2.5 | 16.5 | 6.5 |
| Philadelphia, Pa. | 3 | − 4 | 11 | 2 | 24.5 | 14 | 28.5 | 20 | 25 | 16.5 | 12.5 | 5 | 15.5 | 9.0 |
| Phoenix, Ariz. | 16.5 | 2 | 21.4 | 6.5 | 34 | 21 | 38 | 25.2 | 37.4 | 21.5 | 21.5 | 4 | 28 | 15.2 |
| Portland, Ore. | 5.5 | − 1.3 | 10 | 3.5 | 20 | 9 | 26.5 | 13.7 | 23.5 | 12 | 9.7 | 3.5 | 16 | 6.7 |
| Raleigh, N. C. | 8 | − 5 | 17 | 6 | 26 | 15 | 30.6 | 21 | 26 | 17 | 16 | 5.5 | 20.5 | 10.7 |
| St. Louis, Mo. | 4.5 | − 5.5 | 12.2 | 4.6 | 25.5 | 16 | 31 | 21 | 28.6 | 17.6 | 13 | 5.2 | 15.8 | 10 |
| Spokane, Wash. | − 2.2 | −10 | 7.5 | − 2.2 | 19 | 6 | 31 | 15 | 24.5 | 9.5 | 5.3 | − 1.5 | 15. | 3.0 |

Average max. mean = 13.3 deg.
Average min. mean = 8.2 deg.

*Cooling Medium Temperatures under Service Conditions.* The two principal cooling mediums for transformers are, of course, air and water. The extreme annual temperature of the air throughout North America probably will range from 25 to 30 deg. cent. below, to 50 deg. above zero. In fact, the range is so large that it would be impracticable to consider any part but the general average or perhaps some value high enough to cover the greater part of the cases.

Fig. 21 shows the annual variation of the maximum, minimum, and mean monthly atmospheric temperatures for an outdoor location near the sea coast (New York) at about 40 deg. latitude. These values were based on observations taken covering a period of 10 to 50 years. These curves show that the minimum value is − 4.5 deg. cent., and the maximum + 27.8 deg. cent., while the average of the minimum and maximum values are − 1.1 deg. and + 23.4 deg. cent. respectively. The general all year average is approximately 11 deg. cent. Table VIII gives the mean maximum and minimum bimonthly outdoor temperatures as given by the Weather Bureau for the year 1922. The locations were selected, and weighted approximately according to the population of the United States. These figures show that the general annual outdoor temperature is about 13.2 deg. cent. The average indoor temperatures (*i. e.*, in station,) while no figures are available are perhaps around 25 deg. cent., though in some few cases it may be as high as 40 deg. cent., or in exceptional cases 50 deg. cent. for a part of the time. An average room temperature of 30 deg. cent. it appears would cover the great majority of both indoor and outdoor cases.

The temperature of water used to cool water-cooled and forced-oil-cooled transformers will range from 0 to perhaps 30 or 35 deg. cent. in extreme cases. An all year average is probably not over 15 deg. cent.

ACKNOWLEDGMENT

The writer wishes to acknowledge the valuable assistance rendered by Mr. W. H. Cooney in the preparation of the data given in the paper.

## Appendix A†

### RECOMMENDATIONS FOR THE OPERATION OF TRANSFORMERS, INDUCTION REGULATORS, AND REACTORS

13-600 *Limiting Observable Temperature of Oil.* The oil in which apparatus is permanently immersed should under no circumstances have a temperature, observable by thermometer, in excess of 90 deg. cent.

13-601 *Operation at Rated Load.* Apparatus conforming with the Standards for rating is suitable for carrying rated load continuously provided that the temperature of the cooling medium does not exceed 40 deg. cent. for air or 25 deg. cent. for water.

13-602 *Operation with Cooling Air and Water Exceeding 40 Deg. Cent. and 25 Deg. Cent. Respectively.* For apparatus conforming with the Standards for rating, the load should be reduced 2 per cent below the rated load for each degree that the temperature of the cooling air exceeds 40 deg. cent., or that the temperature of the cooling water exceeds 25 deg. cent. However, the use of apparatus in cooling water exceeding 35 deg. cent. or in cooling air exceeding 50 deg. cent. shall be considered as special.

†As published in A. I. E. E. JOURNAL, August, 1928.

13-603 *Operation at Loads Greater than the Rated Load.**

(a) Apparatus Not Equipped with a Winding Temperature Indicator:—Apparatus not equipped with a winding-temperature indicator may be loaded continuously 1 per cent above rated load for each degree centigrade that the temperature of the cooling medium is below 30 deg. cent. for air or 25 deg. cent. for water.

Thus, for example, when the temperature of the cooling medium is 0 deg. cent., the permissible continuous load is 130 per cent of rated load for air-cooled apparatus and 125 per cent of rated load for water-cooled apparatus.

Loads greater than 130 per cent of rated load for air-cooled apparatus or 125 per cent of rated load for water-cooled apparatus shall not be applied under any conditions even though the temperature of the cooling medium be lower than 0 deg. cent.

(b) Apparatus Equipped with a Winding-Temperature Indicator: Apparatus equipped with a winding-temperature indicator may be loaded continuously in excess of rated load provided the indicated winding-temperature does not exceed the following limits:

| For indicators marked in terms of: | |
|---|---|
| Hottest-spot temperature | 95 deg. cent. |
| Embedded detector temperature | 90 deg. cent. |
| Resistance method temperature | 85 deg. cent. |

(c) Oil temperatures: Oil temperature alone is an inadequate criterion of the winding temperature because of the increased temperature drop through the insulation at low temperatures of the cooling medium and of the time lag between the winding and oil temperatures. Loading apparatus on the basis of oil temperature alone as a guide is not recognized by the A. I. E. E.

13-604 *Conditions Affecting Constructional or Protective Features.* There are conditions which, while not usually affecting the rating, may require special consideration, principally with respect to constructional or protective features. Where such conditions exist it is recommended that they be brought to the manufacturer's attention.

Among such conditions are:

(a) Exposure to damaging fumes.
(b) Operation in damp places.
(c) Exposure to excessive dust.
(d) Exposure to gritty dust.
(e) Exposure to steam.
(f) Exposure to excessive oil vapor.
(g) Exposure to explosive gases.
(h) Exposure to salt air.
(i) Exposure to abnormal vibration or shocks.

*Since the operation of apparatus at loads greater than rated load increases the probability of maintaining the limiting temperature for a greater portion of the time, and because the life of insulation is a function of both its temperature and the time of subjection to that temperature, the operating temperature of the winding should be limited to a lower value than for operation in which the rated load is never exceeded.

Also, under these conditions, the temperature difference between the observable temperature and the hottest spot temperature increases.

For these reasons, the limits specified in Par. 13-603 which are 10 deg. cent. lower than the highest observable temperature recognized for apparatus whose rated load is never exceeded, have been agreed upon for purposes of standardization.

## Bibliography

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3. *Effect of Barometric Pressure on Temperature Rise of Self-Cooled Induction Apparatus*, by V. M. Montsinger, A. I. E. E. Trans., Vol. XXXV, 1916, p. 599.

4. *Predetermination of Self-Cooled Oil-Immersed Transformer Temperatures Before Conditions are Constant*, by W. H. Cooney, A. I. E. E. Trans., Vol. 44, p. 1324.

5. *Safe Loading of Oil-Immersed Transformers*, by E. T. Norris, A. I. E. E. Trans., Vol. 48, October 1929, p. 1206.

## Discussion

**F. W. Gay:** For the last ten years, the operating man has been asking for increased ratings on transformers operating at low ambient temperatures. Up to the present time the designers have not seemed to fully realize the importance of such increased ratings. Twenty-five years ago power was generated and distributed at 2400 volts and was either used directly by the customer at this voltage or it passed through only one transformation. In the next step, power was generated at 13,200 volts and was distributed to substations where it was stepped down to 2400 volts and distributed as before. These early substations fed both industry and domestic consumers so that the individual used power from a substation during his working hours at the factory or office and from the same substation at his home during the night. At the present time power is generated at 13,000 to 22,000 volts, then passes through transformers and is stepped up, as for instance to 66,000 or 132,000 volts, it is then carried a few miles and again transformed to say 13,200 volts. It is then distributed to substations and still again transformed to say 4150 volts. It is then distributed and still again transformed to the customer's voltage. In addition to this multiplication of voltage transformations, the citizen has changed his habits of living so that now he requires service from two substations. One must supply him with power at office and factory and is practically shut down during the night while another substation in the suburbs supplies his night requirements. The utilities are forced to use many times as many transformers today as were used twenty-five years ago for an equivalent service.

Another factor which is operating to increase the transformer costs on the utilities' system, is the demand for reduced core loss. In the last 25 years the core losses on power transformers have been reduced approximately 50 per cent. This has been accomplished in part by the use of low loss iron and in part by a reduction of magnetic densities in the core. For instance, it is entirely practical to manufacture a transformer operating with a core density of 15,000 gausses. It is probable, however, that the best grades of modern power transformers operate more nearly at 7500 gausses.

We suggest that transformers be designed having two coils per winding, adapted for series multiple operation so that a transformer may be operated at say 7500 gausses at light load (coils in series) and at say 15,000 gausses at heavy loads (coils in parallel). It would thus be possible to double the output of a transformer bank without any sacrifice in efficiency.

For instance, consider a 30,000 kv-a. transformer bank operating

normally (at light load) with core density at 7500 gausses and with coils in series and having a core loss of 100 kw. and a copper loss of 200 kw. Such a transformer when operating at 60,000 kv-a. with coils in multiple and with core density at 15,000 gausses would have its core loss pushed up approximately four times, that is to 400 kw. and its copper loss would be the same, that is, 200 kw. The total loss at 60,000 kv-a. would, therefore, be 600 kw. and the efficiency of the transformer at double rating would be the same as it is at its normal rating. It would only be necessary to provide additional radiation to care for the additional heat generated.

It may be argued that the 30,000 kv-a. bank under favorable conditions of ambient temperature will carry 40 per cent overload or 42,000 kv-a. I should like to call your attention to the fact that this same 30,000 kv-a. transformer bank when equipped with series multiple coils and operated at 60,000 kv-a. (coils in multiple) has the same current density in the copper at 60,000 kv-a. as at 30,000 kv-a. (coils in series). I claim that such a transformer if properly cooled may also carry 40 per cent overload or 84,000 kv-a.

What we, as operating men, want is substantially twice as much transformer for a dollar and we don't want to sacrifice anything in efficiency either.

**D. B. Fleming:** Mr. Montsinger, discussing the effect of load factor on the temperature of the transformers, in Fig. 19 of his paper shows the variation of the hot-spot temperature of the winding for load of various load factors. The data on hot-spot temperature for the above conditions is assumed to be calculated. A number of years ago the engineers of the Hydro Electric Power Commission of Ontario, discussing the problem concluded that transformers might be operated above their nameplate rating if the load factor of the load through them was less than 100 per cent. In order to determine the amount by which the transformer could be overloaded, a number of tests was made on self-cooled, oil-immersed transformers, subjecting the transformers to a load cycle similar to that obtained under service conditions. These transformers had various ratings from 150 to 250 kv-a. and were of different manufacture. The guaranteed temperature rise on the transformers tested was 40 deg. cent. with a two hour overload rating of 25 per cent with 55 deg. cent. rise. The load factor for the load cycle was 60 per cent approximately and the maximum overload placed on the transformer was 35 per cent for one hour. During the test, the rise by resistance on the high-voltage and low-voltage windings and the temperature of the cooling oil were measured at selected intervals. The maximum temperature rise which occurred on the high-voltage winding, was 42 deg. cent. The tests on the various transformers gave uniform results although the ratios of the weights of copper and iron and also the division of loss between core loss and copper loss were somewhat different.

The results of these tests indicated that with self-cooled oil-immersed transformers, it would be possible to load the transformers above its continuous rating if the load factor was reduced at the same time.

We agree with Mr. Montsinger in that the large difference in the value of permissible peak load depending upon the shape of the load cycle, requires that any rule expressing the overload as a function of the load factor should be very conservative. In our test the load cycle to which the transformers were subjected was made more severe than usually found in practise in that the duration of the maximum overload was increased from the usual 20-minute peak encountered, to one hour.

As a result of these tests, we are satisfied to allow transformers, as a general rule, to carry 25 per cent in excess of what had been the practise formerly. Of course, each case is considered individually and if the load cycle or other factors are materially different from the average, special consideration is given to these cases.

Our experience in loading transformers including up to 110-kv. ratings by temperature indicates that it is highly desirable to load transformers by this method. This method should be highly recommended as it postpones capital expenditures for additional capacity without apparently shortening the life of the transformers.

The above considers only the effect of various load factors on the permissible loading of transformers. It is well known that the seasonal cycle on transformers usually is such that the transformers are most heavily loaded when the ambient temperature is lowest. Advantage should be taken of conditions of this kind. We are very pleased to see some action being taken in this direction in an effort to establish some standard practise that will not shorten the life of the transformer, and yet maintain the cost of transformation at a minimum.

**C. J. Fechheimer:** I ask Mr. Montsinger whether he considered the absorption of the casing of the transformer if exposed to strong sun rays. Mr. Montsinger states that for forced cooling the exponent is unity. I think that it is usually less than unity; generally it is of the order of 0.8 in so far as heat transfer is concerned and the exponent is unity for the temperature rise of the air.

There is a statement in Mr. Montsinger's paper to the effect that it appears from the data now obtained, if ordinary fibrous material were operated for a hundred years or so, it would be worthless. That may be true if the operation is under oil, but we have all seen tapestries and linens of various kinds in museums that are several hundred years old and still seem to be in good condition. I should like to hear Mr. Montsinger's views.

**W. M. Dann:** This is a very comprehensive paper on temperature effects in transformers. It includes a number of the facts and theories which were considered by the subcommittee in framing the Institute's operating recommendations for transformers and I think it surely will show that those recommendations are not based entirely on guess work.

The constants for cooling with different tank surfaces which are given on page 782 are pretty well recognized as being substantially correct. I notice that the constants for winding rises are classed in two different classifications, first, for transformers having vertical coils and second for transformers having horizontal coils, and there is a difference in the constants for the two classifications. These constants as they are set forth may be good average figures for the transformers which were used in getting these data together, but if they are intended to apply to types of transformers in general, I think they are open to question.

I have in mind particularly the constant $n'$ for the so-called vertical coils. I presume this classification includes transformer windings having long cylindrical coils with their axes in a vertical direction and those types in which large flat disk type coils are used mounted in a vertical plane; if these types are included in the classification, then I think that the constants should be questioned because there is plenty of evidence from experimental testing and actual design work, to show that winding temperatures with these types of winding do not increase as rapidly as the first power of the load, or as of the square of the load current; in other words, the constant one for $n'$ is too high for this type of winding. In general, winding temperature rises in such transformers increase less rapidly than the first power of the load or the square of the load current. Standard design data used every day by design engineers represent $n'$ constants which are always less than 1. Sometimes they are even less than the 0.8 figure given in the paper for horizontal coils.

There are reasons for making this condition true because with the vertical coils there is a certainly a fine opportunity for an excellent circulation of the oil. Also there is every opportunity for heat in the upper parts of the coil to flow to the cooler parts of the coil at the bottom which tends towards an equalization and a reduction of temperatures.

The data given on page 4 in the table simply show what the calculated results would be if one used either a constant of 1 or a

constant of 0.8. This comparison is interesting but it isn't of practical importance because it does not represent general experience; the rather extensive tabulations on page 781 are important, as Mr. Montsinger has said, as showing the trend of loading possibilities, but the results cannot be taken as being accurate because they are based on calculations which in turn are based as a starting point on questionable constants. Mr. Montsinger himself says in the paper that the constants are approximate.

I think it is a fine thing to have in one paper so many data relating to this problem of loading according to temperature; for instance, the typical load charts, the figures relating to temperatures throughout the whole country, and the very important data on the deterioration of insulation.

The idea of combining an element of load factor along with the rating is also very cleverly worked out and as we go further in the practise of loading by temperature, this idea may become quite useful.

**C. A. Adams:** I want to say just a word in support of the 30-degree limit and as evidence cite some of the curves in Mr. Montsinger's paper.

On page 784 the curve in the lower right-hand side shows that the presumable life of Class A insulation in oil at 105 deg. cent. is seven years; in other words, it would not be feasible to operate a transformer continuously with the insulation at that temperature.

On page 788 the curves of mean temperatures throughout the year show that the maximum average is only 27 degrees. In other words, the actual maximum ambient temperature at which these transformers operate now, with the exception of short intervals of unusually hot weather, is 27 degrees and not 40 degrees, so that our operating experience up to the present time does not warrant us in starting with a 40-degree ambient base from which to calculate the allowable overload for lower temperatures. It doesn't follow, of course, that on this account transformers cannot be operated at higher temperatures than at present, but it seems to me highly important that the upper limit, the base limit, so to speak, on which we figure the temperature for overloads, should be 30 degrees and not higher.

**C. M. Gilt:** The paper presented by Mr. Montsinger is an interesting and valuable contribution to the most economical operation of electrical equipment. Standards for rating set up more or less arbitrary conditions which are never encountered in commercial operation. The guides for operation which are presented afford an incomplete but helpful means of interpreting the Standards in terms of operating conditions and can well be associated by the Institute with the Standards themselves.

It seems to me somewhat unfortunate, however, that it contains the inconsistency of recommending operation at 95 deg. cent. hot-spot temperature for all ambients of 30 deg. cent. and less and permitting 105 deg. cent. when the ambient is above 30 deg. cent. If experience proves that 95 deg. cent. is the maximum hot-spot temperature at which the equipment can be operated continuously with reasonable life, it would seem desirable to recommend against operation above 95 deg. cent. when the ambient is above 30 deg. cent. Certainly, this paper indicates the desirability of abandoning the term "continuous" or "maximum" rating if it is recognized that 105 deg. cent. is too high for "continuous" service according to the dictionary meaning of "continuous."

It may very well be that we have been expecting too much life from some of our equipment and it is certainly true that in this rapidly growing industry much equipment is discarded due to obsolescence before its serviceability has been impaired by operation. The ideal of course would be to have a piece of equipment worn out at the time it is retired as an antique.

There is much to be learned from the use of equipment under conditions which approach continuous service at maximum operating temperatures and it is undoubtedly desirable to be somewhat conservative while obtaining this experience. Certainly, the recognition of logical operation is a step in the right direction of getting the maximum kilowatt hours of service per dollar of investment.

**V. M. Montsinger:** With reference to the first discussion by Mr. Gay, the 10 deg. reduction does not apply to rated load. The rules say that rated load can be maintained continuously in any ambient not over 40 deg. cent. The 10 deg. reduction applies when the maximum temperature is maintained continuously by means of overloads. Considering the fact that the rules allow 25 per cent to 30 per cent overloads in cool ambient temperatures, I think the operator has gained more than he has lost. I believe that on the whole it will result in a higher load factor.

I was quite interested in what Mr. Gay had to say about the possibilities of increasing the loads up to double capacity by changing the ratio of losses.

Mr. Fleming discussed the question of governing the load by load factor conditions. I agree that under certain conditions it should be perfectly legitimate to allow greater overloads where the load factor is low than where the load factor is high. I tried, however, not to give the impression that we could give a single rule that would cover every case. Before attempting to do this, the conditions should be carefully analyzed. Mr. Fechheimer mentions the question of absorption of the sun on transformers operating in hot sections of the country. Recently I gave a paper before the Institute on the effect of color on transformers in service. The conclusion given in this paper was that when operating in the sunshine it makes very little difference whether the tank is painted black, gray, or aluminum.

In connection with the value of the exponent for forced cooling, I have found that for forced cooling either of air or liquids the value of the exponent is very close to unity, whereas the value is less than unity for natural cooling.

Whether insulation will last 100 years when immersed in oil is a very difficult matter to answer because we have not had oil immersed transformers for this length of time. As pointed out in the paper, since insulation appears to age faster in oil than in air, I question very much whether it would be possible to build a transformer and insulate it so that it would have the life of some of these tapestries mentioned by Mr. Fechheimer.

Mr. Dann questions the values of $n$ for vertical coils. My experience has shown that if we use the average oil temperature, the value of $n$ is sometimes as low as 0.7. If the top oil temperature is used, the value of $n$ is generally a little less than unity—perhaps 0.95 is more nearly correct, but in the interests of simplicity I used the value of 1.0. These values, as pointed out in the paper, apply to core type transformer coils, but in view of the fact that the cooling of long, vertical cylindrical windings should be governed by the same laws as those applying to vertical shell type coils, I am unable to see why there should be any large difference in the values of the exponents for the two kinds of vertical coils. I have conducted many tests and have analyzed many more tests made at different loads and have never found that the value of the exponent was lower than 0.9, generally being between 0.9 and 1.

The reasons given by Mr. Dann, as to why we would expect to find a low value of $n$ for vertical coils, I rather question for the following reason. The rate of heat dissipation from the windings to the oil for the different loads under question is purely relative. For the condition where the relative rate increases most we would expect to find the lower exponent value. It seems to me to be entirely reasonable to expect that starting with a low load and a relatively cool oil, the chance for improvement in the thermal cooling would be better with horizontal coils than with vertical coils on account of the fact that the oil is becoming heated up, its viscosity is decreasing and it is easier and easier, relatively speaking, for the oil to escape more rapidly as the load increases. This is the only reason that I have been able to attribute to the difference in the values of the exponents for the two different kinds of windings.

# Operating Transformers by Temperature

BY W. M. DANN[1]

Fellow, A. I. E. E.

***Synopsis.***—*This paper discusses a proposal, sponsored by the Transformer Subcommittee of the Committee on Electrical Machinery, which is intended to serve as a guide in operating transformers by temperature rather than in accordance with their nameplate ratings.*

*There is a real difference between "rating standards" and "recommendations for operation;" one simply specifies the measure of a machine under a definite set of conditions and the other constitutes a guide for loading under the varying conditions of actual service. With this difference in mind, a departure from the practise of the Institute up to this time is suggested; namely, that these operating recommendations be placed in an appendix of the Standards and considered not as rating standards but purely as a guide in loading transformers which have been designed to meet the Standards of Rating.*

*One of the first things that had to be done in framing these recommendations was to settle the maximum safe limiting temperature of the windings for operation in actual service. The aim in making this selection was to provide for reasonable deterioration of the insulation and therefore a reasonably long life for the transformer. For reasons disclosed in this paper, a limiting temperature of 95 deg. cent. was adopted. This limit is 10 deg. below that used in the Standards for Rating.*

*These are the high points of the proposal. But opinion on these matters seems to be rather divided throughout the industry, and the purpose of this paper is to bring them to the attention of all members of the Institute.*

THE A. I. E. E. Standards for Transformers have served a useful purpose in setting up recognized specifications for ratings and acceptance tests: they have brought about a uniform rating practise which makes it possible for the manufacturer more nearly to standardize his product and for the purchaser to know what he is buying and compare bids intelligently.

For rating purposes, the Standards recognize a maximum hottest-spot temperature in the windings of 105 deg. cent. set a number of years ago at what was thought to be the limit of temperature to which fibrous insulation should be subjected continuously for reasonable deterioration. The elements of temperature represented by these Rating Standards are as follows:

| | Air blast and oil-insulated self-cooling | Oil-insulated water-cooled |
|---|---|---|
| Ambient temperature | 40 deg. cent. | 25 deg. cent. |
| Temperature rise | 55 | 55 |
| Limiting observable temperature | 95 | 80 |
| Margin for hot spots | 10 | 10 |
| Maximum limiting temperature | 105 | *90 |

*Since water-cooled transformers are dependent upon artificial means of cooling that might be interrupted and involve a cooling system that might deteriorate on account of scale or deposit from water containing impurities, the Standards for Rating provide for them an extra margin of 15 deg. cent.; this results in a uniform standard temperature rise of 55 deg. cent. for both water-cooled and self-cooled transformers.

It is obvious that if the ambient temperature in actual operation is lower than that used in the rating scheme, the hottest spot temperatures of the windings in a transformer meeting the Rating Standards will be less than the maximum limiting temperature of the scheme. If the limiting temperature of 105 deg. cent. is actually a safe maximum temperature for continuous operation, then it follows that the load may be increased above the nameplate rating to the point where the limiting temperature of 105 deg. cent. is reached.

It has been recognized for a long time that extra output is available when the ambient temperature is low. But no simple and usable rules have ever been established which would give the operator of a transformer a chance to make use of this extra output to suit his own conditions of ambient temperature. For some time there has been a strong feeling that an authoritative set of rules defining a reasonable practise of this kind ought to be available.

The Transformer Subcommittee[2] of the Committee on Electrical Machinery recently spent over two years in preparing a guide for the loading of transformers in actual service, with the hope of formulating a simple set of rules which would allow this latent capacity to be used. These rules were published tentatively in the August 1928 issue of the A. I. E. E. JOURNAL, and they also appear in the Report on Standards for Transformers, Induction Regulators, and Reactors dated August 1928. They are reproduced here in order to make direct and connected references to them.

*Appendix.*—Recommendations for the Operation of Transformers, Induction Regulators, and Reactors.

"13-600 *Limiting Observable Temperature of Oil*—

The oil in which apparatus is permanently immersed should under no circumstances have a temperature, observable by thermometer, in excess of 90 deg. cent.

"13-601 *Operation at Rated Load*—

"Apparatus conforming with the Standards for Rating is suitable for carrying rated load continuously provided that the temperature of the cooling medium

1. Westinghouse Elec. & Mfg. Co., Sharon, Pa.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

2. Members of the Subcommittee completing the work were: W. H. Cooney, J. B. Gibbs, J. Allen Johnson, A. H. Kehoe, H. C. Louis, V. M. Montsinger, L. C. Nichols, and W. M. Dann.

does not exceed 40 deg. cent. for air or 25 deg. cent. for water.

"13-602 *Operation with Cooling Air and Water Exceeding 40 Deg. Cent. and 25 Deg. Cent. Respectively—*

"For apparatus conforming with the Standards for Rating, the load should be reduced 2 per cent below the rated load for each degree that the temperature of the cooling air exceeds 40 deg. cent. or that the temperature of the cooling water exceeds 25 deg. cent. However, the use of apparatus in cooling air exceeding 50 deg. cent. or in cooling water exceeding 35 deg. cent. shall be considered as special.

"13-603 *Operation at Loads Greater than the Rated Load*—*

(a) Apparatus Not Equipped with a Winding-Temperature Indicator:—Apparatus not equipped with a winding-temperature indicator may be loaded continuously 1 per cent above rated load for each degree centigrade that the temperature of the cooling medium is below 30 deg. cent. for air or 25 deg. cent. for water.

"Thus, for example, when the temperature of the cooling medium is 0 deg. cent., the permissible continuous load is 130 per cent of rated load for air-cooled apparatus and 125 per cent of rated load for water-cooled apparatus.

"Loads greater than 130 per cent of rated load for air-cooled apparatus or 125 per cent of rated load for water-cooled apparatus shall not be applied under any conditions even though the temperature of the cooling medium be lower than 0 deg. cent.

"(b) Apparatus Equipped with a Winding-Temperature Indicator: Apparatus equipped with a winding-temperature indicator may be loaded continuously in excess of rated load provided the indicated winding-temperature does not exceed the following limits:

"For indicators marked in terms of

Hottest Spot Temperature.....95 deg. cent.

Embedded Detector Temperature....90 deg. cent.

Resistance Method Temperature.....85 deg. cent.

"(c) Oil Temperatures: Oil temperature alone is an inadequate criterion of the winding temperature because of the increased temperature drop through the insulation at low temperatures of the cooling medium and of the time lag between the winding and oil temperatures. Loading apparatus on the basis of oil temperature alone as a guide is not recommended."

*Since the operation of apparatus at loads greater than rated load increases the probability of maintaining the limiting temperature for a greater portion of the time, and because the life of insulation is a function of both its temperature and the time of subjection to that temperature, the operating temperature of the winding should be limited to a lower value than for operation at rated load.

Also, under these conditions, the temperature difference between the observable temperature and the hottest-spot temperature increases.

For these reasons, the limits specified in Para. 13-603, which are 10 deg. cent. lower than the highest observable temperature recognized for apparatus operated at rated load, have been agreed upon for purposes of standardization.

## Rating Standards and Recommendations for Operation

There is a distinct difference between rating standards and authorized rules for operation. Standards for Rating simply prescribe a measure of a machine under fixed and definite conditions. These conditions may not, in fact they cannot, represent actual operating practise, because in real service, load demands are usually variable and ambient temperatures are not fixed, but rather are changing from hour to hour. Rules for operation should take these changing conditions into account. Therefore, while the two sets of rules are not unrelated, they cannot be one and the same thing. For these reasons, the proposed recommendations for loading transformers by temperature are not to be looked upon as rating standards. They are not intended to be used in the purchase of transformers or to establish performance which is subject to guarantee and demonstration by test. They are offered simply as recommendations for guidance in the safe operation of transformers in service under various conditions of ambient temperature.

It has been planned that if these recommendations are to be sponsored by the Institute, they should be separate and apart from the rules devoted to Rating Standards, and they have been tentatively placed in an appendix to Section 13. In the discussion following the preliminary publication, the opinion has been rather strongly expressed that service recommendations of this kind should not be included in the Institute Standards even when definitely set apart from the Rating Standards. This opinion is based upon the principle that the scope of the Institute Standards is limited to the defining of Rating Standards. At the same time there is an opinion from other quarters that the Institute should go further than simply to set up arbitrary rating standards; that it is proper for it to sponsor and authorize recommendations for the actual operation of machines that are designed in accordance with the Rating Standards. In the face of these conflicting opinions it becomes a matter that the Institute as a whole should become interested in. The broader question developed requires serious consideration because of the possibility of extending the principle to other applications.

The proposed loading recommendations for transformers are based upon engineering data, and actual loading experience has been taken into account as far as it has been possible. The purpose of this paper is to discuss and interpret the recommendations without going into detail as to the data upon which they are based. These data are well illustrated in a companion paper on the subject being presented at this time by V. M. Montsinger.

### Limit of Safe Operating Temperature

The first thing that must be settled when considering recommendations for loading transformers by temperature is the maximum safe operating temperature limit, because temperature affects the rate of deterioration of the insulation, and, barring accidents, it is the thing that determines the useful life of a transformer. In trying to decide this question, one naturally turns to previous experience for guidance. Heretofore the useful life of transformers, speaking generally, has been of satisfactory length, and we have not been hampered by rapid deterioration of insulation. However, operating experience has been confined practically to loads which have not exceeded nameplate ratings, and average loadings have been even less. Couple these considerations with the fact that ambient temperatures are usually less than those of the Rating Standards, and it is found that experience has in general been limited to moderate temperatures, temperatures that are considerably lower than the limit of 105 deg. cent. which was adopted for rating purposes. As a result, no one knows definitely from broad general operating experience just where the maximum limit of temperature for continuous loading should be set to maintain reasonably long useful life.

A higher level of operating temperatures will be the natural result of loading transformers by temperature, because in general greater loads will be carried. The copper losses increase with the square of the increase of load current, and the rise of temperature of the windings increases almost as rapidly. New and unknown factors affecting experience are introduced, and these factors have an influence upon the rate of deterioration of the insulation.

Taking all of these things into account, it was determined that conservatism should be the keynote of these loading recommendations. In keeping with this decision, a maximum limit of 95 deg. cent. for the hottest spot temperature was adopted for operation instead of the 105 deg. limit used for rating purposes. When more experience with the higher level of operating temperature is accumulated, it will be possible to set the limit with greater confidence. It is not impossible that eventually a limit of 105 deg. cent. for actual operation may be found to result in reasonably long useful life.

The difference between the temperature limit for rating and this proposed limit for operation has caused considerable discussion since the preliminary publication of the loading recommendations. It has been said that this difference is illogical; that when one buys a transformer meeting the Standards for Rating he is entitled to operate it up to the limit of 105 deg. cent. continuously because that is what he has bought and paid for. If the point has been successfully made in the preceding discussion that there is a clear-cut distinction between standards for rating, which simply set a measure for uniformity in design, and recommendations for operation, which are intended to serve as a guide in actual operation with all its varying conditions, perhaps it will be conceded that a greater margin of safety is justified in the operating recommendtions until experience has demonstrated whether or not it is needed.

### Operation at Loads Greater than the Rated Load

There are two general classes into which transformers may be divided when considering operation by temperature above the rated load: first, that large class of units that either have no temperature indicators or are equipped with indicators that simply show the temperature of the oil; second, the rapidly increasing class of units that are equipped with winding temperature indicators, giving an indication in some degree of the approximate temperature of the windings.

For the first class of transformers, paragraph 13-603 (a) provides a simple rule which allows one to determine what load may be carried with any prevailing condition of ambient temperature. Within the limits of the recommendations, the "1 per cent rule" conforms quite reasonably in its results with the adopted maximum limit of 95 deg. cent.

No loading above the rated load is recommended for air cooled apparatus unless the ambient temperature is below 30 deg. cent., and this may need explanation. If continuous loading above the nameplate rating were to be recommended between ambient temperatures of 30 deg. and 40 deg. cent., hottest spot temperatures of the windings might exceed the limit of 95 deg. cent. adopted for operation, and the conservatism of the loading recommendations would not be followed out. Air temperatures in the United States, speaking generally, are not as high as 40 deg. cent. They usually do not exceed 20 deg. or 25 deg. cent. except in the warmest periods. Most of the operating experience has therefore been with temperatures of a moderate order. If loads were to be increased for all ambient temperatures below 40 deg. cent., in accordance with the "1 per cent rule," it would mean that most of the self cooling transformers now in service could immediately be loaded well above their nameplate ratings. Following out the principle of conservatism, it was thought better to avoid such a wholesale overloading until more operating experience in loading by temperature has been accumulated.

For ambient temperatures below 0 deg. cent., there is of course some additional overloading possible within the adopted limiting temperature. However, for conservation, overloading is limited in the recommendations to that prescribed for 0 deg. ambient.

Paragraph 13-603 (b) describes the permissible loading above the nameplate rating for the second general class of transformer apparatus, *i. e.*, for apparatus equipped with a winding-temperature indicator. The principle of limiting hottest spot temperatures to the adopted figure of 95 deg. cent. is carried out in this

paragraph, but the actual limiting temperature depends upon the temperature that the instrument really measures, due to its construction and application.

Three different types of winding-temperature indicators are used for power transformers at the present time, each type indicating a different degree of winding temperature. For that reason, three different limiting temperatures were established, each one relating definitely to the kind of instrument used. The following short descriptions will show why these indicated temperature limits are different:

*95-deg. Limit.*—One manufacturer provides a winding-temperature indicator marked in terms of the hottest spot temperature. It includes in its calibration the 10 deg. margin above the average winding temperature at full load which the A. I. E. E. Standards recognize as the conventional allowance for hot spots. The limiting temperature for this type of indicator is set at 95 deg. cent.

*90-Deg. Limit*—Another manufacturer provides a winding-temperature indicator which uses a long strip of high resistance metal wound in with the turns of a coil, usually the top coil of a stack. This strip of metal forms one of the arms of a Wheatstone bridge. It gets its temperature very largely through the insulation of the conductor with which it is in contact. It measures something between the hottest spot temperature and the average temperature of the windings by the resistance method.

The limiting temperature for this type of winding-temperature indicator is set at 90 deg. cent. because parts of the copper in the windings will be somewhat higher in temperature than that indicated.

*85-Deg. Limit*—A third manufacturer provides an indicator having a heating coil which adds to the oil temperature an increment representing the difference between the average winding temperature and the oil. It indicates the average temperature of the winding as it would be measured by the resistance method without any allowance for hot spots.

The limiting temperature for this type of indicator is accordingly set at 85 deg. cent.

Transformers may be safely loaded up to these limiting indicated temperatures regardless of what the ambient temperature may be.

### Operation at Rated Load

Paragraph 13-601 provides that a transformer conforming with the Standards for Rating is suitable for continuous operation at rated load if the ambient temperature does not exceed 40 deg. cent. for air or 25 deg. cent. for water. Assuming the conventional allowance of 10 deg. for hot spots, this statement as it applies to a self-cooling transformer is not consistent with the adopted hottest spot temperature limit of 95 deg. cent. for operation.

However, something may be said in defense of this inconsistency. For loads not exceeding rated load, the actual difference between the hottest spot temperature of the winding and the temperature of the oil (which increases very rapidly with overloads) is usually less than contemplated by the Rating Standards and is not a matter of concern. Also, the operation of standard transformers at rated loads has been satisfactory in the past for the conditions of actual service and bids fair to continue to be satisfactory in the future.

An inconsistency of some kind is inevitable when the limiting temperatures for rating and for operation are different, and for the reasons given it was thought better to be consistent with the Standards for Rating in the case of rated load operation rather than with the adopted operating limit of 95 deg. cent.

### Operations with Ambient Temperatures Above Those of the Rating Standards

Paragraph 13-602 was designed to include the unusual cases where ambient temperatures exceed those set by the Rating Standards. Since the 1 per cent rule is an approximation which gives conservative results for overloads as recommended for low ambients but not for partial loadings at high ambients, it was necessary to make a reduction of 2 per cent in load for each degree by which the ambient temperature exceeds the standard ambients in order to keep within the 95 deg. operating limit.

### Conclusions

The principle function of the Institute as it has been understood up to the present time, is to provide Standards for Rating. The proposal that Recommendations for Operation be included in the Standards as an appendix is an innovation. It is in fact a proposal affecting the policy of the Institution, one which might be far-reaching in its application, if it were adopted. A strong feeling has developed since preliminary publication of the proposal, that the Institute should continue to devote its attention to rating standards and that recommendations for actual operation of apparatus should be sponsored by some other organization.

The selection of a limit of temperature for operation which is lower than the limit recognized for rating purposes may be considered open to question. However, there is ample justification for conservatism in starting a new practise which may involve the possibility of shortened life of apparatus, and it is probably wise to be content with the very reasonable increase of capacity which the lower temperature limit provides until it may be demonstrated that a higher limit is warranted.

## Discussion

**C. J. Fechheimer:** In regard to the standards as recommended by Mr. Dann, it seems to me that it would be better for the manufacturers of the transformer to place a guarantee as to how high the temperature could be run than for the Institute to bind itself to particular temperatures.

**T. C. Lennox:** Mr. Dann stated that some of the operators were rather shocked when the proposal was made to reduce the temperature ambient from 40 to 30 deg. I don't see why that should be because for a great many years it has been the practise

for places where the ambient temperatures are continually high to specify transformers of 45 deg. temperature rise rates, this practise approximating the same degree of conservatism as 55 deg. transformers used for general distribution work.

I believe that at the time this 55 deg. temperature was adopted, it was taken into account by the Institute Committee that the load factors were not 100 per cent, and that the ambient temperatures seldom reached 40 deg. For this reason it was possible to give transformers a maximum rating appreciably higher than the committees at that time felt could be used as a basis of continuous rating. If you look at the performance specifications as used by the trade at the present you will find there is nothing in them guaranteeing that a transformer can be operated at 105 deg. continuously. There is merely a guarantee that if the transformer is operated at its rated load in a 40 deg. ambient, its average winding rise will not exceed 55 deg. There is nothing in the Institute rule or such specifications implying anything beyond this.

**W. M. Dann:** Mr. Fechheimer has proposed that the nameplate be marked to show the maximum temperature for which a transformer is suitable. That proposal has been made before and has been considered. Nameplates on transformers, however, are rather fearfully and wonderfully made. Right now they contain much information of various kinds and there would be a real objection to increasing the amount of information that is put on the nameplate.

# Telephone Interference from A-C. Generators

## Feeding Directly on Line with Neutral Grounded

BY J. J. SMITH*

Associate, A. I. E. E.

*Synopsis.—The problem of telephone interference from a-c. generators feeding directly on the line with neutral grounded is discussed. It is shown that the triple and non-triple harmonics in the voltage wave shape cause currents which flow in different paths on the power system. As a result of this, the induction on paralleling telephone lines per ampere of triple harmonic is greater than the induction per ampere for a non-triple harmonic on a balanced power system.*

*A method of measurement which would allow a rough comparison of the effects to be expected from both types of harmonics is suggested. This is based upon using the apparatus already available and setting up special connections for test. Data are given showing the results of such measurements made in the factory on a number of machines while they were being tested.*

*Analyses are given of the wave shape of machines which gave rise to cases of interference. References are given to some of the data already published on methods which have been applied to relieve such situations.*

### General

During recent years there have been several cases of telephone interference arising from generators which feed directly on transmission systems and have their neutrals grounded. In these cases if the neutral ground is removed from the generator the interference disappears as a general rule. Many times it occurs that the system can be grounded through another generator in the same station and no telephone interference is experienced. In cases where the latter situation has arisen, the power company engineers are liable to regard the machine which gives trouble, and which is generally the newer machine, as one of poor wave shape. Investigation in a number of cases has shown, however, that usually the harmonics in both machines have been small (analyses will be given later) and have been of the same magnitude. The difference between the machines lies, however, in the frequency of the harmonics which are present and in their behavior with respect to the paths through which the harmonic currents flow out on the line and return to the generator.

This type of interference has been experienced also on systems where the generator is connected to the line through *Y-Y* transformers, the neutral of the transformer on the primary side being connected to the neutral of the generator, which may or may not be grounded. The neutral of the transformer on the secondary side is grounded. In this case the percentage harmonics from line to neutral on the secondary side of the transformer are approximately the same as the percentage harmonics in the line to neutral of the generator. The causes and remedies of this type of interference are exactly the same as interference in cases where the generator feeds directly on the line with neutral grounded and therefore will not be discussed separately.

In the design of rotating electrical apparatus an effort is made to keep the harmonics as low as possible, but because it is not practicable to obtain a sine wave distribution of magnetic flux, and since the slots introduce irregularities, harmonics, though they may be small, are always present in the voltage wave of power systems. With perfectly balanced and transposed power systems or perfectly balanced and transposed communication systems there would be no interference with the communication circuits under normal operating conditions of the power circuit. Due to the fact that in actual practise perfect balance cannot be attained, the longitudinal voltages,—that is voltages to ground,—induced on the telephone line by the power circuit, will act upon the unbalances in the telephone circuit to produce noise currents. In general, when either the power system or telephone system uses the ground as part of the circuit the effects of the mutual coupling are greater than when both circuits are wholly metallic. As will be shown by an example later, when the ground is used as part of either circuit, the mutual inductance between the circuits is larger than that between metallic circuits, and in addition, grounded circuits cannot be transposed.

### Difference Between Triple and Non-Triple Harmonics

The harmonics produced by a generator in its phase-to-neutral voltage can be divided into two classes which are essentially different in respect to their behavior on the transmission line. One class is the odd harmonic which are multiples of 3, *i. e.*, the 3rd, 9th, 15th, 21st, etc. We shall call these the triple harmonics. The other, the odd harmonics which are not multiples of 3, (*i. e.*, the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, etc.) we shall call the non-triple harmonics. Let us assume the voltage wave from line to neutral in a balanced three-phase system is given by

$$y_1 = a_1 \sin(\theta + \phi_1) + a_3 \sin(3\theta + \phi_3) + a_5 \sin(5\theta + \phi_5) + \ldots\ldots$$

in phase 1. The voltage wave line to neutral in phase 2 is obtained by increasing $\theta$ by 120 deg. and is thus

$$y_2 = a_1 \sin(\theta + 120 + \phi_1) + a_3 \sin(3\theta + 360 + \phi_3) + a_5 \sin(5\theta + 600 + \phi_5) + \ldots\ldots$$

*Electrical Engineer, General Electric Co., Schenectady, N. Y.

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30-46

Hence the voltage between phases 1 and 2 is

$$y_2 - y_1 = a_1 \sin(\theta + 120 + \phi_1) - a_1 \sin(\theta + \phi_1) + a_5 \sin(5\,\theta + 600 + \phi_5) - a_5 \sin(5\,\theta + \phi_5) + \ldots$$

the 3rd, 9th, 15th, etc., harmonics disappearing, since these harmonics are in the same phase and of the same magnitude in each voltage wave.

Simplifying we get—

$$\begin{aligned} y_2 - y_1 &= +2\,a_1 \cos(\theta + \phi_1 + 60) \sin 60 \\ &\quad + 2\,a_5 \cos(5\,\theta + \phi_5 + 300) \sin 300 + \ldots \\ &= \sqrt{3}\; a_1 \cos(\theta + \phi_1 + 60) - \sqrt{3} \cos(5\,\theta + \phi_5 \\ &\qquad + 300) + \ldots \end{aligned}$$

Thus on a balanced three-phase system the only voltages which can exist between lines are the fundamental and 5th, 7th, 11th, 13th, etc., harmonics which are not multiples of three.

We can also show that the 5th, 7th, 11th, 13th, etc., harmonic currents can flow out on the transmission line on one of the phases and back on the other phases in a way similar to the fundamental as follows. If the current in phases 1, 2, and 3 is $i_1$, $i_2$, and $i_3$

$$\begin{aligned} i_1 &= b_1 \sin(\theta + \phi_1) + b_3 \sin(3\,\theta + \phi_3) \\ &\quad + b_5 \sin(5\,\theta + \phi_5) + \ldots \\ i_2 &= b_1 \sin(\theta + 120 + \phi_1) + b_3 \sin(3\,\theta + 360 + \phi_3) \\ &\quad + b_5 \sin(5\,\theta + 600 + \phi_5) + \ldots \\ i_3 &= b_1 \sin(\theta + 240 + \phi_1) + b_3 \sin(3\,\theta + 720 + \phi_3) \\ &\quad + b_5 \sin(5\,\theta + 1200 + \phi_5) + \ldots \end{aligned}$$

Now,

$$\begin{aligned} &\sin(n\,\theta + \phi_n) + \sin(n\,\theta + 120\,n + \phi_n) \\ &\quad + \sin(n\,\theta + 240\,n + \phi_n) = \sin(n\,\theta + \phi_n) \\ &\quad + 2 \sin(n\,\theta + 180 + \phi_n) \cos 60\,n \end{aligned}$$

If $n$ is an odd multiple of 3, $\cos 60\,n = \cos 180 = -1$ and $\sin(n\,\theta + 180\,n + \phi_n) = -\sin(n\,\theta + \phi_n)$

Hence $b_{3p} \sin(3\,p\,\theta + \phi_{3p}) + b_{3p} \sin(3\,p\,\theta + p\,360 + \phi_{3p}) + b_{3p} \sin(3\,p\,\theta + p\,720 + \phi_{3p}) = 3\,b_{3p} \sin(3\,p\,\theta + \phi_{3p})$

Thus the instantaneous sum of the triple harmonics in the three phases is three times the instantaneous current in one of the phases, and such currents must return to the generating station through a path other than that provided by the phase wires of the system itself. They can return through the neutral connection.

If, however, $n$ is odd but not a multiple of 3

$$\cos 60\,n = \frac{1}{2}$$

and $\sin(n\,\theta + 180\,n + \phi_n) = -\sin(n\,\theta + \phi_n)$

Hence

$$\begin{aligned} &\sin(n\,\theta + \phi_n) + \sin(n\,\theta + 120\,n\,\phi_n) + \sin(n\,\theta + 120\,n + \phi_n) \\ &\quad = \sin(n\,\theta + \phi_n) - \sin(n\,\theta + \phi_n) = 0 \end{aligned}$$

We thus see, what has been demonstrated in other papers before the Institute but what it was thought worth while to again show here, that

(1) On a balanced* three-phase system no triple harmonics can exist in the voltage between lines since these harmonics are equal and opposite in each line to neutral leg and therefore cancel out,

(2) On a balanced three-phase system no triple harmonic currents can flow in the lines unless some other path besides the system conductors is provided for their return flow. This is because, as was shown above, the triple harmonics in each line are in phase and add up at any instant to three times the triple harmonic in any one line. The instantaneous sum of the non-triple harmonics at any instant on the three lines is, however, zero.

If a generator is connected to a $Y$-$Y$ transformer and the neutral of the generator connected to the transformer, it is evident that the triple harmonic voltage existing between line and neutral of the generator will also exist between line and neutral on the primary side of the transformer and hence on the secondary side of the transformer. Thus, the behavior of the harmonics when the neutral of such a transformer is grounded on the secondary side will be the same (except for change in magnitude of voltage and current due to transformer ratio and effects of the transformer magnetizing currents) as if the generator fed directly on the line.

## Path of Flow for Different Kinds of Harmonics

When the neutral of the generator is grounded, the triple harmonic voltage in each leg of the generator exists between line and ground, and since the triple harmonic voltages between each line and ground are in phase we have for these harmonics the equivalent of a single-phase generator feeding out on the three lines in parallel, the path for the return flow being through the capacities of the three lines to ground and through any equipment with grounded neutral and then back through the neutral of the generator. It is evident that since the ground return is one side of the circuit for these triple harmonics, transpositions in the power line will make no reduction in the induced voltage in a neighboring telephone line.

For the non-triple harmonics, since the instantaneous sum of the voltages in the three wires is equal to zero, the amount of current which tends to return through the ground is very much smaller than that which flows when the harmonic is one of the triple series If the wires of the three phases were infinitely close together no harmonic current of the non-triple series would tend to return through the ground. Due to the fact that the wires are spaced some distance apart, a small amount of such current does flow. The magnitude of such currents can, however, be considerably reduced by the introductions of transpositions in the three-phase line. These transpositions balance up the currents which tend to flow through the earth due to each section of the line and thus reduce the electromagnetic induction. Another effect of the introduction of transpositions for the non-triple harmonic voltage is the

*Due to the fact that perfect balance cannot be obtained in practise and also since some slight impedance must exist in actual systems, triple harmonics will usually be found in measurements of line-to-line voltage.

reduction of the residual voltages of these harmonics on the transmission line (which reduces the effect of electrostatic induction). It will not be considered further here, as the considerations applying to it are not the same as those under discussion in this paper.

### Mutual Inductance for Grounded and Non-Grounded Circuits

Since the paths of flow of the triple and non-triple harmonics are in general different, in order to determine the voltage induced on a neighboring telephone line per ampere of harmonic current in the power line, we have to determine the mutual inductance between circuits which only involve currents in the conductors of the power line, and also currents which flow out on the power lines in parallel and return through the ground. Although the study of mutual inductance has been the subject of quite a number of investigations it will be sufficient for our purpose to make fairly broad assumptions in order to illustrate the points involved. The mutual inductance between two parallel wires of length $l$ and separated by a distance $D$ is (see for instance Pender's Handbook, 1922, p. 827)

$$M = 2\,l\left(\log_e \frac{2\,l}{D} - 1 + \frac{D}{l}\right) \text{ abhenries}$$

where $l$ and $D$ are in centimeters and $l$ is large compared with $D$. In order to calculate the voltage induced in a telephone line due to the balanced harmonics on a power line we calculate the values of $M_1$, $M_2$, and $M_3$ for each of the three conductors, then, since we may write the currents

$$i,\ i\left(-\frac{1}{2}+\frac{\sqrt{3}}{2}j\right) \text{ and } i\left(-\frac{1}{2}-\frac{\sqrt{3}}{2}j\right)$$

$$E = 2\,\pi f i\left[M_1 + M_2\left(-\frac{1}{2}+\frac{\sqrt{3}}{2}j\right) + M_3\left(-\frac{1}{2}-\frac{\sqrt{3}}{2}j\right)\right]$$

$$= 2\,\pi f i\left[\left(M_1 - \frac{M_2}{2} - \frac{M_3}{2}\right) + \frac{\sqrt{3}}{2}j\,(M_2 - M_3)\right]$$

It is evident that if $M_1$, $M_2$, and $M_3$ are approximately equal,—that is, if the telephone line is at a considerable distance from the power line,—the resultant induced voltage is very small.

When the return current flows through the ground we may assume as an approximation that it flows in a conductor at a distance of 2000 feet below the surface of the earth. The actual distance of such a conductor below the surface of earth varies in different locations but the figure of 2000 ft. may be taken as a fair average for our purpose.

It will be of interest to work out the mutual inductance for a typical case in order to give some idea of the relative magnitude of these different mutual inductances. As an example, consider a three-wire power transmission line with the conductors in a horizontal plane and a telephone line at a distance of 90 ft. from the nearest conductor. The spacing between the outer conductors of the power circuit is 110 in. (9.17 ft.) and the center conductor is 40 in. (3.33 ft.) from the conductor nearest the telephone line. The mutual inductance for a parallel 100,000 ft. long (approximately 19 mi.) is

$$M_1 = 6{,}080{,}000\left(\log_e \frac{200{,}000}{90} - 1 + \frac{90}{100{,}000}\right)$$

$$= 6{,}080{,}000 \times 6.707 = 40.78 \times 10^6 \text{ abhenries}$$

$$M_2 = 6{,}080{,}000\left(\log_e \frac{200{,}000}{93.33} - 1 + \frac{93}{100{,}000}\right)$$

$$= 6{,}080{,}000 \times 6.671 = 40.56 \times 10^6 \text{ abhenries}$$

$$M_3 = 6{,}080{,}000\left(\log_e \frac{200{,}000}{99.17} - 1 + \frac{99}{100{,}000}\right)$$

$$= 6{,}080{,}000 \times 6.610 = 40.19 \times 10^6 \text{ abhenries}$$

Hence the abvolts induced in the telephone line per $i$ abamperes in each wire of the power circuit at any given frequency $f$ is

$$E_1 = 2\,\pi f i \times 10^6\left[\left(40.78 - \frac{40.56}{2} - \frac{40.19}{2}\right)\right]$$

$$+ \frac{\sqrt{3}}{2}j\,(40.56 - 40.19)$$

$$= 2\,\pi f i\,(404{,}000 + 318{,}000\,j) \text{ abvolts}$$

and the numerical value is

$$E_1 = 2\,\pi f i\sqrt{404{,}000^2 + 318{,}000^2}$$

$$= 2\,\pi f i \times 514{,}000 \text{ abvolts}$$

For a ground return current the mutual inductance between the return current and the telephone line is

$$M_e = 6{,}080{,}000\left(\log_e \frac{200{,}000}{2000} - 1 + \frac{2000}{100{,}000}\right)$$

$$= 6{,}080{,}000 \times 3.625 = 22.04 \times 10^6 \text{ abhenries}$$

Hence the abvolts induced in the telephone line per $i$ abamperes in the ground (assuming ⅓ in each conductor) is

$$E_2 = 2\,\pi f i \times 10^6\left(\frac{40.78 + 40.56 + 40.19}{3} - 22.04\right)$$

$$= 2\,\pi f i \times 10^6\,(40.51 - 22.04)$$

$$= 2\,\pi f i \times 18{,}470{,}000 \text{ abvolts}$$

If $i$ in the above equations is in amperes, the actual volts induced are obtained by dividing the abvolts by $10^9$.

Thus for a current of frequency 900 cycles, which is the 15th harmonic of 60 cycles, flowing in the earth in the case considered above, the volts induced on the telephone line per ampere in the power line would be

$$E_2 = 6.28 \times 900 \times 18{,}470{,}000 \times 10^{-9} = 104.5 \text{ volts}$$

or approximately 5.5 volts per mile of parallel.

If the same current were to flow out on one wire and

back on the other two wires, in three-phase relation the induced voltage would be

$$E_1 = 6.28 \times 900 \times 514{,}000 \times 10^{-9} = 2.80 \text{ volts}$$

or approximately 0.15 volt per mile of parallel.

On comparing $E_1$ and $E_2$ we see that for this particular case the voltage induced by a current $i$ flowing out over the three wires in parallel and back through the earth is approximately 40 times as large as that produced by the same current $i$ flowing out through one of the wires and back through the other wires in three-phase relation, and it is this large ratio between the mutual inductance for metallic return currents and earth return currents which makes the effect of the triple series of harmonics which return through the earth considerably more important in considering inductive effects in telephone circuits than the effects produced by the non-triple harmonic currents. We may reiterate that no amount of transpositions in the power line will be effective in reducing appreciably the value of $E_2$, while on the other hand the value of $E_1$ can be considerably reduced by the use of transpositions in the power circuit.

## Relation of the Frequency of Harmonics to Their Interfering Effect on Telephone Circuits

A curve showing the relation between the interfering effect of harmonics and their frequency has been obtained experimentally and the results obtained are given in a Review of the Work of the Subcommittee on Wave Shape Standard of the Standards Committee of the A. I. E. E., H. S. Osborne, A. I. E. E., Trans., Vol. 38, 1919, p. 261. This committee developed a network called the Telephone Interference Factor Network which weights the various harmonics in proportion to their interfering value obtained experimentally. The Telephone Interference Factor (T. I. F.) of a machine has been defined as the current in microamperes through this network per volt applied to the network.

If reference is made to Mr. Osborne's paper, it will be noted that one of the assumptions made in deriving the Telephone Interference Factor is as follows:

"a. The current induced in telephone circuits by a given voltage or current in the power circuit is approximately proportional to the frequency." (*loc. cit.*, p. 268)

This assumption was actually put into practise by multiplying the interfering effects per ampere of current in the receiver obtained experimentally by a factor proportional to the frequency, which was equivalent to making the assumption that the mutual inductance between the power circuit and the telephone circuit was the same for all harmonics irrespective of their frequency.

In the simple example given above, however, we have seen that the coefficient of mutual inductance for the triple harmonics which flow through the ground was approximately 40 times the coefficient of mutual induction for the non-triple harmonics. We are therefore presented with the problem somewhat as follows: To revise the curve given in Mr. Osborne's paper by multiplying the interfering effect of the triple harmonics by some figure which we will call $T$ (40 in the above example) at the same time leaving the non-triple harmonics as at present. It would appear to be out of the question to design a network similar to the one already designed, first, on account of the great complexity necessary for a network which would have such irregular impedance characteristics, and secondly because even if such a network were designed for say a fundamental of 60 cycles it could not be used on 50 cycles since the triple harmonics are of different frequency.

By using special methods for testing on three-phase systems, it would appear a method can be developed for determining the T. I. F. of a machine using the extra weighting for the triple harmonics. It has already been seen that if the voltages in the three phases of a machine connected delta with one corner open are added, the instantaneous sum of the fundamental and of the non-triple harmonics is negligibly small. The sum of the triple harmonics, however, is three times the amount of harmonic in any phase. Thus, if a machine is connected delta, the voltage measured across the open corner is three times the voltage of the triple harmonics in each phase. If the T. I. F. of the voltage across the opened delta is measured and multiplied by one-third of the voltage across the opened delta this gives the contribution to the current in the T. I. F. network meter due to the triple harmonics in a single phase. If this contribution is multiplied by a factor $T$ and added according to the square root of the sum of the squares to the current in the meter in the network produced when the T. I. F. meter is connected between line and neutral, the resultant divided by the line to neutral volts will be a T. I. F. in which the triple harmonics are weighted approximately $T$ times as heavily as the non-triple harmonics.

As an example of the Application of the above we may consider the following measurements on an *A T B*—4—37500 *M*—1800—15,000 volts—

| | | |
|---|---|---|
| Line to line..... | 11,500 volts | 10 T. I. F. |
| Line to neutral..... | 6,800 volts | 15 T. I. F. |
| Open delta..... | 245 volts | 800 T. I. F. |

Applying the method given above, the following triple harmonic weighted T. I. F. is obtained (assuming a value 40 for $T$)

$$\frac{1}{6800}\sqrt{(6800 \times 15)^2 + \left(\frac{40}{3} \times 245 \times 800\right)^2}$$

$$= \frac{1}{6800}\sqrt{(102{,}000)^2 + (2{,}650{,}000)^2}$$

$$= \frac{2{,}650{,}000}{6800} = 390$$

It may be well to point out that in this method of

TABLE I

| No. | Freq. cycles | Kv-a. | Volts | T. I. F. | | | Volts open delta | Triple harmonic weighted T. I. F. | Armature coil pitch |
|---|---|---|---|---|---|---|---|---|---|
| | | | | L-L | L-N | Open delta | | | |
| 1 | 50 | 54,350 M | 13,200 | 5 | 5 | 750 | 230 | 306 | 0.61 |
| 2 | 50 | 54,350 M | 13,200 | 10 | 15 | 840 | 220 | 337 | 0.61 |
| 3 | 60 | 43,750 | 14,000 | 8 | 13 | 254 | 750 | 309 | 0.85 |
| 4 | 60 | 43,750 M | 13,200 | 9 | 11 | 690 | 305 | 377 | 0.73 |
| 5 | 60 | 37,500 M | 13,200 | 7 | 11 | 447 | 212.5 | 190 | 0.72 |
| 6 | 60 | 37,500 | 12,000 | 3 | 2 | 129 | 24 | 7 | 0.66 |
| 7 | 60 | 37,500 M | 11,500 | 10 | 15 | 800 | 245 | 406 | 0.61 |
| 8 | 60 | 35,300 M | 13,200 | 8 | 11 | 800 | 238.3 | 342 | 0.72 |
| 9 | 60 | 31,250 M | 12,000 | 8 | 15 | 571 | 276 | 318 | 0.76 |
| 10 | 60 | 25,000 M | 13,800 | 9 | 8 | 269 | 243 | 525 | 0.80 |
| 11 | 60 | 25,000 M | 13,200 | 9 | 11 | 488 | 341 | 301 | 0.76 |
| 12 | 60 | 18,750 M | 13,800 | 17 | 22 | 448 | 710 | 553 | 0.87 |
| 13 | 60 | 18,750 M | 11,000/ 12,000 | 5 | 5 | 320 | 405 | 254 | 0.83 |
| 14 | 60 | 18,750 M | 2,300/ 4,000 | 6 | 11 | 976 | 65 | 377 | 0.72 |
| 15 | 25 | 18,750 | 6,000 | 2 | 2 | 165 | 600 | 347 | 0.88 |
| 16 | 60 | 15,625 M | 2,300 | 7 | 10 | 404 | 57.5 | 243 | 0.83 |
| 17 | 60 | 15,625 M | 13,200 | 5 | 8 | 890 | 160 | 251 | 0.72 |
| 18 | 60 | 12,500 M | 6,600 | 20 | 22 | 395 | 5.6 | 28 | 0.66 |
| 19 | 60 | 12,500 M | 14,000 | 5 | 6 | 1574 | 100 | 269 | 0.63 |
| 20 | 60 | 6,250 M | 2,300 | 18 | 19 | 307 | 75 | 302 | 0.55 |
| 21 | 50 | 3,125 M | 2,300 | 9 | 9 | 616 | 70 | 442 | 0.54 |
| 22 | 50 | 3,125 M | 2,300 | 8 | 17 | 390 | 112.5 | 457 | 0.54 |
| 23 | 60 | 2,500 | 2,300 | 12 | 17 | 1030 | 52.5 | 558 | 0.61 |

NOTE: The value of $T$, the triple harmonic weighting factor in the above table, has been taken as 40.

analysis the T. I. F. is referred back to the operating voltage of the generator. Sometimes attempts are made to consider the T. I. F. of the open-delta voltage alone, or for instance it is sometimes stated that the T. I. F. of the neutral current is so much, say 2000.* It is necessary to remember that the effect of the power system on the telephone system is measured by the product of the voltage (or current) and the T. I. F. There are additional factors such as the length of exposure, separation between lines, etc. In the above example the open-delta voltage of 245 volts is largely composed of third harmonic, but the main contribution to the T. I. F. of 800 is made by the higher harmonics which perhaps do not exceed 10 per cent of the third harmonic. It is therefore evident that if the 3rd harmonic were halved, having a value of 122.5 volts, the other harmonics remaining the same magnitude, the T. I. F. of the open-delta voltage would be doubled, giving 1600. In spite of this increase in T. I. F. of two to one, the interference which might be created by these two different machines in any given location would be changed by a much smaller amount and in some cases would remain approximately unchanged. The weighted triple harmonic voltage T. I. F. would be the same for these two machines.

The General Electric Co. for some time past has been accumulating data on the open-delta voltage and T. I. F. of machines which have the neutral brought out. Typical results are given in Table I.

The T. I. F. of a pure sine wave at 60 cycles is approximately 9.0. Some of the T. I. F.'s at 60 cycles in the table are less than this value which is due to the fact that the actual readings obtained on the meter were very small and therefore liable to considerable inaccuracies. It is considered preferable, however, to give the actual values measured rather than to correct them arbitrarily to the minimum value.

It will be noted that in all these machines the T. I. F. of the line-to-line and normal T. I. F. of the line to neutral voltage are very low. In view of the above, it is of interest to examine the actual amount of each harmonic present in cases which have given rise to telephone interference.

## Analysis of Voltage Wave of Generators in Typical Cases

In Table II are given the results of analyses of the voltage wave shape and the resulting neutral current under load of a 7500-kv-a., 13,200-volt generator which gave rise to telephone interference when run with the neutral grounded.

TABLE II

| Frequency | Harmonic | Open circuit line to neutral volts | Neutral current under load amperes |
|---|---|---|---|
| 60 | 1 | 7600 | .... |
| 180 | 3 | 48* | 0.046 |
| 300 | 5 | 5 | .... |
| 420 | 7 | 14 | .... |
| 540 | 9 | 19 | 0.18 |
| 780 | 13 | 6 | .... |
| 900 | 15 | 8 | 0.15 |
| 1020 | 17 | 13 | .... |
| 1140 | 19 | 5 | .... |
| 1260 | 21 | .. | 0.17 |
| 1380 | 23 | 27 | .... |
| 1980 | 33 | .. | 0.2+ |

*There is some doubt as to the accuracy of this measurement owing to the possibility of a third harmonic of approximately this magnitude being generated in the potential transformer used.

In Table III are given voltage wave analyses of no load and under load, and neutral currents under load of two generators in one station. When Generator *A*

*See for example *Power Distribution and Telephone Circuits*, H. M. Trueblood and D. I. Cone, A. I. E. E. TRANS., Vol. XLIV, 1925, p. 1058.

was run with the neutral grounded, noise was experienced on paralleling telephone lines; when Generator B was run with the neutral grounded or Generator *A* with the neutral ungrounded, the telephone noise was negligible.

TABLE III

| | Generator *A* | | | Generator *B* | | |
|---|---|---|---|---|---|---|
| | Line to neutral voltage | | | Line to neutral voltage | | |
| Harmonic | Open circuit | 82 per cent full load | Neutral current | Open circuit | 68 per cent full load | Neutral current |
| 1 | 7010 | 7320 | .... | 7680 | 7380 | .... |
| 3 | 30 | 120 | 4.24 | 31 | 31 | 0.50 |
| 5 | 4 | 50 | 0.27 | 15 | 50 | 0.005 |
| 7 | 5 | 24 | 0.24 | 8 | 7 | 0.155 |
| 9 | 10 | 31 | 3.60 | 3 | 5 | 0.044 |
| 11 | 7 | 37 | 0.15 | 4 | 31 | 0.036 |
| 13 | 0 | Trace | 0.04 | 0 | 7 | 0.012 |
| 15 | 3 | 14 | 3.90 | 0 | 0 | 0.127 |
| 17 | 0 | .... | 0.05 | 4 | 0 | 0.049 |
| 19 | 0 | .... | 0.07 | 4 | 0 | 0.030 |
| 21 | 0 | .... | 3.77 | 0 | 0 | 0.103 |
| 23 | 0 | .... | .... | 6 | 0 | .... |
| 25 | 36 | .... | .... | 42 | 0 | .... |
| 27 | 3 | Trace | 4.69 | 0 | 0 | 0.265 |
| 29 | 30 | .... | .... | 34 | 0 | .... |
| 31 | 4 | .... | .... | 19 | 0 | .... |
| 33 | 0 | .... | 0.19 | 0 | 0 | 0.007 |

In the above measurements, there is again some doubt as to the accuracy of the measurements of the third harmonic, as some may have been generated in the potential transformer used.

The calculated phase-neutral voltage T. I. F. of Generator *A* was 26 at no load and of Generator *B* was 31; which illustrates the fact that the T. I. F. as ordinarily measured bears no relation to the noise experienced in this type of situation.

It will be noticed that in analysis given of line to neutral voltage both at no load and under load the magnitude of the triple harmonic series was in general equal to or less than that found in the best commercial practise in machine design. A study of the magnitude of these harmonics seems to show that none of the ordinary methods open to a designer could be used to reduce these harmonics with certainty to much smaller values. If telephone noise is caused by such a machine, the question of using means for grounding external to the machine should be considered and whether general conditions will warrant radical modifications in machine design as opposed to other methods of wave correction external to the machine.

The largest harmonics of high frequency in Generator *A*,—the 25th and 29th,—did not give rise to telephone noise. It will be noted that the neutral current of the generator was mainly composed of triple harmonics which were all of the same order of magnitude. The prominent harmonics on the telephone circuit were the 15th and 27th and the elimination of either of these by means of a wave trap (to be referred to later) reduced the noise considerably. The neutral currents were measured at the generating station which fed into a large cable network. At the point at which noise was experienced the cable network fed an open wire line which paralleled a telephone toll cable for a distance of approximately five miles. It was not practicable to make measurements of the residual current in the exposure which probably accounts for the fact that although all the triple harmonics were present in approximately the same magnitude at the generator their relative values in the parallel may have been considerably different, thus accounting for the higher intensity of 15th and 27th harmonics in the telephone line.

## Methods Which Have Been Used to Minimize this Type of Interference

In this section references will be given to descriptions of various methods which have been used to relieve such situations. No attempt has been made to make this list of references complete, as to do so would require quite a long bibliography. The various arrangements are more fully discussed in these references. Some of the methods described apply to generators already installed which are found to give rise to interference; others refer to certain points which, if given advance consideration, may avoid later modifications if trouble should develop.

1. Wind the generator with armature coil of ⅔ pitch.

   On referring to Professor Adams' paper, *Electromotive Force Wave Shape of A-C. Generators*, Trans. A. I. E. E., 28, Fig. 9, p. 154, 1909, it will be seen that if ⅔ pitch is used for the armature coils the resultant triple harmonics, 3, 9, 15, etc., in the alternator wave shape are zero.

2. Zigzag connection of alternator.

   The use of this method is discussed in "Connection for Eliminating Triple Harmonics in Alternators," by R. J. Jensen, *Elecktrotech. Zeits.*, 35, p. 649, 1914.

3. The use of resonant shunts on the generator to reduce the magnitude of the triple harmonics.

   A discussion of the use of resonant shunts in this connection is given in "Improving the Wave Shape of Alternator Voltage Waves," by E. W. Marchant and T. H. Turney, *The Electrician*, 91, p. 363, 1923.

4. Use of wave trap or traps to prevent flow of triple harmonics through the neutral ground connection of the generator.

   The use of such wave traps is discussed in
   (a) "Grounding the Neutral," by E. D. Sibley, *Iron and Steel Engineer*, 2, p. 331, 1925.
   (b) "Compensation of Higher Harmonics in an Earthing Connection," *Elektrotech Zeits.* 47, pp. 1479-1482, Dec. 16, 1926.

5. The use of the Petersen Coil.

   This is discussed in
   (a) *The Petersen Earth Coil*, by R. N. Conwell and

R. D. Evans, TRANS. A. I. E. E., Vol. 41, 1922, p. 77.

(b) "The Relation of the Petersen System of Grounding Power Networks to Inductive Effects in Neighboring Communication Circuits," by H. M. Trueblood, *Bell System Technical Journal*, Vol. 1, 1922, p. 39.

(c) *The Neutral Grounding Reactor*, by W. W. Lewis, A. I. E. E. TRANS., Vol. 42, 1923, p. 147.

(d) *Operating Performance of a Petersen Earth Coil*, by J. M. Oliver and W. W. Eberhardt, A. I. E. E. TRANS., Vol. 42, 1923, p. 435.

6. Use of system transformers or a special transformer, usually called grounding transformer, to ground the power system, thus eliminating the ground from the generator.

Various aspects on the use of transformers for grounding are discussed in

(a) *Residual Voltages and Currents in Power Systems*, by L. J. Corbett, A. I. E. E. TRANS., Vol. 48, 1929, p. 92.

(b) "Auxiliary Transformers Reduce Inductive Interference," by L. J. Moore, *Electrical World*, 77, 1921, p. 257.

(c) "Grounded Neutral," by R. Treat, *Proceedings*, Assoc. Iron and Steel Engineers, 1920, p. 187.

(d) "Theory of Grounding," by F. C. Hanker, *Iron and Steel Engineer*, April 1928, p. 147.

(e) "Transmission Line Engineering," by W. W. Lewis.

## CONCLUSIONS

The difference in behavior of the triple harmonics and non-triple harmonics has been illustrated, and it has been pointed out how relatively small amounts of triple harmonic voltage existing from line to neutral may give rise to more noise on paralleling telephone circuits than considerably larger amounts of non-triple harmonic voltages.

A method has been suggested by which separate measurements can be made of the triple harmonics alone, by a special connection of the machine for test. These measurements can be combined, if desired, under certain assumptions which have been given, with the measurements made in the usual way so as to give an extra weighting to the triple harmonic series which would correspond to their greater inductive effect due to the fact that they return through the earth connection.

A number of references to methods which have been used to minimize this type of interference have been given. Some of these are applicable directly to the design of the generator and others involve auxiliary apparatus for the reduction of the harmonics. A little advance consideration of the subject of this paper may sometimes avoid later modifications if trouble develops.

Although the majority of systems in this country at the present time are operating with grounded neutral, the actual cases of this type of telephone interference are relatively few. Many generators, of course, are connected to transmission lines through delta-$Y$ transformers which greatly reduced the possibility of interference due to the triple harmonics. The cases which have occurred have, however, been serious enough to create a real problem.

There are so many factors involved, such as the type of power system, proximity to and length of parallels with telephone circuits, capacitance to ground of power conductors beyond parallel, etc., that it would be extremely difficult to predict beforehand in any given location whether or not this type of telephone interference will arise. In some cases in which a machine gave rise to telephone interference on one system it has been found that a duplicate machine operated for years in another location without giving any trouble. This type of interference has occurred more frequently in the last few years, although it has been common practise to ground systems for many years, and although the wave shape of these large turbo alternators has been gradually improved. It can thus be seen that the problem is quite complicated and worthy of study by operating as well as designing engineers.

## Bibliography*

*(No claim to completeness is made for this bibliography. Additional references may be found in the text of the paper.)

1. *The Grounded Neutral with and without Series Resistance in High-Tension Systems*, by P. M. Lincoln, A. I. E. E. TRANS., Vol. 26, 1907, p. 1585.

2. *Protection of Electrical Equipment*, by P. M. Lincoln, A. I. E. E. TRANS., Vol. 28, 1909, p. 1156.

3. "Telephone Disturbances from Three-Phase Cable Systems Operated with Grounded Neutral of the Generator," by E. von Holstein-Rathlou, *E. T. Z.*, 31, 1910, pp. 637-40.

4. "Telephone Disturbances from Star-Connected Three-Phase Systems with Grounded and Ungrounded Neutral of Generators," by O. Branns, *E. T. Z.*, 34, 1913, pp. 116-20, 142-46, 175-78.

5. *The Experience of the Pacific Gas & Electric Co. with Grounded Neutral*, by Messrs. Jollyman, Downing, and Baum, A. I. E. E. TRANS., Vol. 33, 1914, p. 767.

6. *A Study of Some Three-Phase Systems*, by C. L. Fortescue, A. I. E. E. TRANS., Vol. 33, 1914, p. 753.

7. *Influence of Transformer Connections on Operation*, by L. F. Blume, A. I. E. E. TRANS., Vol. 33, 1914, p. 735.

8. *Report of the Transmission Committee*, A. I. E. E. TRANS., Vol. 35, 1916, p. 555.

9. *Grounding the Neutral of Generating and Transmission Systems*, by H. R. Woodrow, A. I. E. E. TRANS., Vol. 38, 1919, p. 827.

10. *Grounded Neutral Transmission Lines*, by W. E. Richards, A. I. E. E. TRANS., Vol. 38, 1919, p. 833.

11. *Review of Work of Subcommittee on Wave Shape Standard of the Standards Committee*, by H. S. Osborne, A. I. E. E. TRANS., Vol. 38, 1919, p. 261.

12. *A Symposium on the Subject of Grounding the Neutral of Power Systems*, will be found in A. I. E. E. TRANS., Vol. 42, 1923, pp. 405-469; see also pp. 518-526.

13. *Performance of Auto-Transformers with Tertiaries under Short Circuit Conditions*, by J. Mini, Jr., L. J. Moore, and R. Wilkins, A. I. E. E. TRANS., Vol. 42, 1923, p. 1060.

14. The following series of articles is in the *Iron and Steel Engineer*, April 1928:

a. "Effect of Grounding on Telephone Interference," J. J. Pilliod, p. 147.

b. "Theory of Grounding," F. C. Hanker, p. 155.
c. "Effect of Grounded Neutral on the Efficiency of Lightning Protection Equipment," K. B. McEachron, p. 160.
d. "Experience of a Public Utility with Grounded Neutral," G. S. Humphrey, p. 163.
e. "Effect of Grounding on Reliability of Relay Operation," E. A. Hester and B. M. Jones, p. 166.
15. "Transmission Line Engineering," by W. W. Lewis.

## Discussion

**J. O'R. Coleman:** Mr. Smith's paper presents a summary of a problem which is becoming of more and more importance in inductive coordination of power and communication lines. The practise of transmitting power at generated voltage apparently is becoming more common and in a number of these cases it is relatively simple to use the generator neutral as the grounding point of the system. There have been several cases of rather serious interference caused communication circuits by grounded neutral generators. Generators of all the principal manufacturers in this country have been involved. An examination of some of the data obtained in one of the more recent cases may be helpful in understanding the nature of this problem.

Table I shows the analysis of harmonic of the currents and voltages supplied by the generator. The analysis shown is for generator No. 2. Generator No. 1 has similar characteristics but the analyses of the harmonics were not as complete for that machine. By using the third harmonic currents and voltages shown in Table I the impedance of the system to ground can be calculated. A plot of this impedance at harmonic frequencies is shown in Fig. 1 herewith. The sign at the impedance was determined by measurements across a one-ohm reactor which was placed in the neutral of the generator.

A study of the impedance curve showed that the system had comparatively low impedance to ground and that a relatively small reactor in the neutral of the generator would materially decrease the triple harmonic currents and voltages. A pilot circuit on the telephone parallel grounded near the central office end showed 2000 noise units to ground at the far end when the generator was directly grounded. A measurement of noise made in the same fashion with the generator neutral isolated showed 300 noise units. The placing of a one-ohm reactor in the neutral of the generator reduced the noise to ground on the telephone circuits to around 700 noise units and the tuning of this reactor for approximately 1260 cycles reduced the noise on the telephone circuits to practically the same value of noise as existed with the generator isolated.

Table II shows a comparison of triple harmonic voltages and currents on the power system with the generator grounded directly, grounded through a one-ohm reactor, and grounded through a wave trap. It can be seen that the use of either the wave trap or the reactor substantially reduces the currents and voltages at all harmonic frequencies, except 540 cycles.

TABLE I
HARMONIC ANALYSIS OF CURRENTS AND VOLTAGES
GENERATOR LOADED

| Freq. | Phase volts | Residual volts | Phase amperes | Residual§ amperes | Neutral§ amperes | System ohms |
|---|---|---|---|---|---|---|
| 60 | 7600 | 14.40 | 1060 | | | |
| 180 | 103. | 269.00 | 1.510 | 1.210 | 1.610 | 55.5 |
| 300 | 97.4 | 4.74 | 26.700 | 0.685 | .. | |
| 420 | 19.7 | 0.92 | 7.620 | .. | | |
| 540 | 2.77 | 8.57 | 0.103 | 0.201 | 0.195 | 14.6 |
| 660 | 5.73 | 0.49 | 0.756 | | | |
| 780 | 2.52 | 0.39 | 0.060 | | | |
| 900 | 3.65 | 11.70 | 0.240 | 0.738 | 0.736 | 5.30 |
| 1020 | 1.37 | 0.46 | 0.072 | | | |
| 1140 | 2.10 | | 0.282 | | | |
| 1260 | 10.35 | 27.20 | 0.399 | | 1.140 | 7.96 |
| 1380 | 1.67 | | 1.108 | | | |
| 1500 | 10.70 | | 0.108 | | | |
| 1620 | 5.84 | 16.20 | 0.846 | | 2.320 | 2.32 |
| 1740 | | | | | | |
| 1860 | | | | | | |
| 1980 | 2.42 | 7.48 | 0.084 | | 0.264 | 9.43 |
| 180 | 1.350* | 261† | 0.142* | 80† | 106† | |
| 300 | 1.280 | 5 | 2.520 | 3 | | |
| 420 | 0.269 | 5 | 0.719 | | | |
| 540 | 0.036 | 310 | 0.010 | 195 | 189 | |
| 660 | 0.075 | 8 | 0.072 | | | |
| 780 | 0.033 | 15 | 0.006 | | | |
| 900 | 0.048 | 320 | 0.023 | 307 | 306 | |
| 1020 | 0.018 | 33 | 0.007 | | | |
| 1140 | 0.028 | | 0.027 | | | |
| 1260 | 0.135 | 264 | 0.038 | | 286 | |
| 1380 | 0.022 | | 0.017 | | | |
| 7500 | 0.141 | | 0.010 | | | |
| 1620 | 0.077 | 277 | 0.080 | | 274 | |
| 1740 | | | | | | |
| 1860 | | | | | | |
| 1980 | 0.032 | 309 | 0.008 | | 304 | |
| T. I. F.‡ | 19.2 | | 17.6 | | | |

Note: *Per cent of r. m. s.
†Per cent of corresponding phase value.
‡ Calculated.
§ Same quality measured in two different ways.

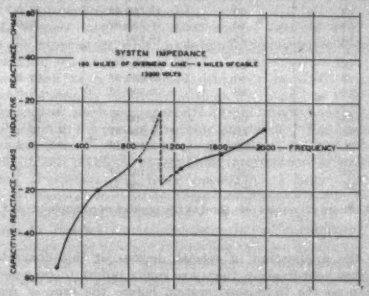


Fig. 1

CURRENT AND VOLTAGE ANALYSES

| Generator conditions | Open circuited | | Loaded | | | One-ohm reactor in neutral | | Wave trap in neutral | |
|---|---|---|---|---|---|---|---|---|---|
| Quality measured | $V_{P-N}$ | $V_{RES}$ | $V_{P-N}$ | $V_{RES}$ | $I_{RES}$ | $V_{P-N}$ | $I_{RES}$ | $V_{P-N}$ | $I_{RES}$ |
| Frequency | | | | | | | | | |
| 60 | 7600 | .. | .. | .. | .. | .. | .. | .. | .. |
| 180 | 27.6 | 77.9 | 88.6 | 227. | .. | .. | .. | .. | .. |
| 540 | 6.9 | 22.2 | 4.0 | 12.2 | 0.18 | 9.7 | 0.56 | 13.9 | 0.68 |
| 900 | 1.9 | 4.9 | 3.7 | 10.8 | 0.54 | 2.1 | 0.32 | 0.6 | 0.10 |
| 1260 | 3.1 | 8.1 | 8.4 | 22.4 | 0.74 | 5.4 | 0.51 | 0.5 | 0.05 |
| 1620 | 0.9 | 2.8 | 14.0 | 37.8 | 4.16 | 1.7 | 0.50 | 1.4 | 0.30 |
| 1980 | 5.1 | 14.4 | 2.5 | 7.8 | 0.30 | 0.9 | 0.09 | 1.0 | 0.21 |

TABLE I-A

| Ref. No. (1) | Generator rating | | | Open-delta | | *One-third of product of open-delta T. I. F. and volts per volt of line-to-neutral voltage (7) | Armature coil pitch (8) |
|---|---|---|---|---|---|---|---|
| | Cycles (2) | Kv-a. (3) | Kv. (4) | Tif. (5) | Volts (6) | | |
| 1 | 50 | 54,350 *M* | 13.2 | 750 | 230 | 7.54 | 0.61 |
| 2 | 50 | 54,350 *M* | 13.2 | 840 | 220 | 8.08 | 0.61 |
| 3 | 60 | 43,750 | 14.0 | 254 | 750 | 7.85 | 0.85 |
| 4 | 60 | 43,750 *M* | 13.2 | 690 | 305 | 9.21 | 0.73 |
| 5 | 60 | 37,500 *M* | 12.2 | 447 | 212.5 | 4.49 | 0.72 |
| 6 | 60 | 37,500 | 12.0 | 129 | 24 | 0.150 | 0.667 |
| 7 | 60 | 37,500 *M* | 11.5 | 800 | 245 | 9.84 | 0.61 |
| 8 | 60 | 35,300 *M* | 13.2 | 800 | 238.3 | 8.34 | 0.72 |
| 9 | 60 | 31,250 *M* | 12.0 | 571 | 276 | 7.58 | 0.76 |
| 10 | 60 | 25,000 *M* | 13.8 | 269 | 243 | 2.74 | 0.80 |
| 11 | 60 | 25,000 *M* | 13.2 | 488 | 341 | 7.27 | 0.76 |
| 12 | 60 | 18,750 *M* | 13.8 | 448 | 710 | 13.30 | 0.87 |
| 13 | 60 | 18,750 *M* | 12.0 | 320 | 405 | 6.23 | 0.83 |
| 14 | 60 | 18,750 *M* | 4.0 | 976 | 65 | 9.16 | 0.72 |
| 15 | 25 | 18,750 | 6.6 | 165 | 600 | 8.66 | 0.88 |
| 16 | 60 | 15,625 *M* | 2.3 | 404 | 57.5 | 5.83 | 0.83 |
| 17 | 60 | 15,625 *M* | 13.2 | 890 | 160 | 6.23 | 0.72 |
| 18 | 60 | 12,500 *M* | 6.6 | 395 | 5.6 | 0.193 | 0.667 |
| 19 | 60 | 12,500 *M* | 14.0 | 1574 | 100 | 6.49 | 0.63 |
| 20 | 60 | 6,250 *M* | 2.3 | 307 | 75 | 5.78 | 0.55 |
| 21 | 50 | 3,125 *M* | 2.3 | 616 | 70 | 10.82 | 0.54 |
| 22 | 50 | 3,125 *M* | 2.3 | 390 | 112.5 | 11.02 | 0.54 |
| 23 | 60 | 2,500 *M* | 2.3 | 1030 | 52.5 | 13.57 | 0.61 |

*Column (7) equals one-third of the product of columns (5) and (6), divided by the generator voltage from line to neutral, computed from column (4).

In the application of special devices of this character for inductive coordination there are many points to be considered relating to the individual system before the type of remedial measure to be applied can be determined. In this particular system the tuned reactor permitted a simple and readily applicable solution. In other cases with a different system impedance the same application might not have been at all practicable. This brief discussion is intended to point out some of the various factors that require consideration in a study of this character and to show that each application of this character requires careful study.

**S. L. Henderson:** Mr. Smith lists two means that can be considered in the design of the generators, which will tend to prevent trouble from the third harmonic series. Both of these are special winding combinations, which tend to eliminate the third harmonic voltages between terminal and neutral. Both of these combinations can be obtained at a cost, and I will attempt to point out what this is.

In general, machines having armature windings of two-thirds pitch cost more money. This increased cost may be due to the necessity of a larger machine, more expensive coils, or new dies and tools. Two-thirds pitch imposes restrictions on the design which involve efficiency and size. Fractional number of slots per pole is a useful means to reduce all harmonics, including thirds, but two-thirds pitch would restrict their use to those combinations which are multiples of three-halves.

One point that should not be overlooked is that a machine with two-thirds pitch has practically zero phase sequence reactance and, if paralleled with other machines which generate third harmonic voltages, may give rise to more third harmonic current in the neutral than existed previously.

A machine wound with a zig zag winding must be increased fifteen per cent in size, because the voltage is generated inefficiently. The efficiency will be reduced, first, because of the larger machine and, second, because of higher loss due to the unbalanced armature m. m. f.

**R. G. McCurdy:** Mr. Smith has called attention to what I believe is one of the outstanding problems in the coordination of power and telephone circuits from the noise standpoint. Its importance has been recognized by the Joint Subcommittee on Development and Research of the N. E. L. A. and Bell System, which is engaged in cooperative studies of inductive coordination problems. One of this subcommittee's subordinate committees, Project No. 5 on Wave Shape, has the matter under active investigation and has participated in field investigations of a number of specific cases.

I should like to offer an alternative method from the one suggested by Mr. Smith for rating the T. I. F. of electrical machines from this standpoint. As Mr. Smith points out, the relative importance of the residual and balanced components may vary over a wide range. It will depend upon the length, the configuration of the wires, and other physical features of the exposures. The relative importance may also be altered by transpositions in the power circuits. For this reason, it seems to me better to separately rate the machines as to balanced and residual T. I. F. rather than to attempt to set up a single weighted figure. As Mr. Smith states, the T. I. F. of the opened-delta is apt to be misleading. To avoid this difficulty, I suggest that instead the residual component of the line to neutral T. I. F. be used. This component may be determined by computing the ratio of the current in the meter branch of the T. I. F. network when connected to the opened corner of the delta to three times the voltage across one of the sides of the delta. The balanced component of the T. I. F. may of course be obtained across one of the sides of the delta with the corner closed, or by measuring from line to line.

I have applied this method to four of the machines listed in Mr. Smith's Table I with the following results:

| Machine No. | Weighted T. I. F. by J. S. S. method | Balanced T. I. F. component | Residual T. I. F. component |
|---|---|---|---|
| 7 | 406 | 10 | 9.9 |
| 12 | 553 | 17 | 13.3 |
| 18 | 28 | 20 | 0.19 |
| 22 | 457 | 8 | 11.1 |

It is interesting to compare these figures with the residual component of the voltage T. I. F., due to the capacitance unbalance of overhead three-phase lines. These unbalances are largely controlling in the case of isolated neutral systems and systems grounded through Y-delta transformer banks. They vary over a wide range depending upon the configuration and upon transpositions. The maximum residual voltage is around 12 per cent of the line-to-line voltage. This would correspond to a residual T. I. F. component of 0.8 for a line-to-line T. I. F. of 20.

**Bela Gati:** I have never experienced a triple harmonic previous to war, but I experienced a 13th and a 39th and often the second harmonic. This seems to be an absurdity at first, but it can be explained very easily. The insulators never have the same insulating value for the positive as they have for the negative current, thus there is a leakage current which always undergoes a rectification. If there is a rectification, and even the second half of the sine curve is cut away, a current with a double frequency, that is, the second harmonic appears in the telephone circuits by way of leakage.

I just want to say that line constants are never constant. For instance the resistance of a telephone line in a connecting test box can be 300 ohms sometimes. If the telephone exchange operator rings, she rings with 70 volts and for 70 volts this connection-resistance diminishes and the parties can speak for one or two minutes. After two minutes the resistance becomes again 300 ohms and the speaking parties become hoarse, if they speak over long distance. I have measured line coefficients of power line. The result was surprising. I have found the kilometric resistance of a line about 11 ohms and the insulation of the same power line between 10,000-100,000 ohms. The outgoing current was one milliampere at a frequency of $w = 2\pi n = 10{,}000$. We must measure all the power lines coefficients from 10 to 100 kilometers, because they are not balanced for the telephone current for such a short distance. They are balanced for the high-voltage currents, but not for the telephone currents. If we have a thousand kilometer long telephone line, it is possible that the branches have exactly the same resistances; the faults are scattered equally in the single branches, but if I measure them only in ten kilometers distance, the line is unbalanced and this creates noises in the telephone. There is always a considerable leakage, but this can be measured with telephone frequency under working conditions along with the other line coefficients of the power line of even 100,000 voltage.

I believe these measurements ought to be made and the whole balance problem ought to be studied since we have no experimental data in this respect.

**L. A. Doggett:** In Mr. J. J. Smith's article on Telephone Interference, he has listed six methods which have been used to minimize triple harmonic telephone interference. I wish to propose a seventh and submit some data illustrating the functioning of the method.

In briefest terms the proposal is that all neutrals of Y-connected induction motors or synchronous motors located within the power station be connected to ground. By this process the triple harmonic currents are provided with low impedance paths at the power station. These paths are of low impedance because both induction and synchronous motors act like practically stationary machines so far as the triple harmonics are concerned, even though they are running and doing their usual work of driving power station auxiliaries.

In the laboratories of the Pennsylvania State College apparatus has been set up to test this proposal. A harmonic alternator was connected in Y with a fundamental and a third harmonic coil in each leg. This machine is the counterpart of the power station alternator generating triple harmonics. Three wall lampboards connected in Y served as the load. The neutral of the load was then connected through an ammeter to the neutral of the harmonic alternator. With 91 volts generated per fundamental coil and 9½ volts generated per third harmonic coil, yielding an alternator terminal voltage of 151½, the current along the neutral was 3.68 amperes. The neutral of a 220-volt, 20-hp. induction motor was then tied directly to the neutral of the alternator, thus by-passing some of the third harmonic currents which previously had gone out along the line to the load. The current along the neutral which was 3.68 when the grounded neutral induction motor was not used, was now reduced to 2.565 amperes. This method offers a simple and inexpensive way of decreasing the amount of triple harmonics which get out of the power station and may be applied except where separate alternators are used to operate the power house auxiliaries.

**P. L. Alger:** Mr. Smith deals almost entirely with non-salient pole alternators, which have much smaller triple harmonic voltages than salient pole machines. If, therefore, a salient pole machine, such as a waterwheel generator or a synchronous condenser, is directly connected with an overhead line with its Y point grounded, much greater troubles from interference are to be expected than in the case of a turbine generator. The operation of machines direct connected to overhead lines, therefore, brings in some difficult problems of telephone interference, as well as of lightning protection and relay operation. I hope that the operating engineers will study these problems as a whole since they cannot be solved independently.

**Frank F. Fowle:** (communicated after adjournment) This paper presents some new and interesting data on generator wave shape, advances a novel suggestion for an interference index of generator wave shape, and touches very briefly on remedial measures for telephone interference attributable to residual voltages and currents caused by grounded generators. Mr. Smith has made it quite evident that the T. I. F. of generator voltage, from line to line, or line to neutral, as heretofore employed, is not always the index of the total inductive influence which the voltage of any generator may contribute to its connected system. The paper shows that it is necessary, furthermore, to consider the type of armature connections in the generator and the manner in which the generator is connected to the system it serves. If the generator is star-connected, with neutral grounded, and feeds direct to line, the residual voltage can then act on the external power system. In these circumstances the generator residual voltage and current may require as much consideration as the balanced voltages and currents.

The author has devised an ingenious plan to resolve the T. I. F. of the balanced voltage and the T. I. F. of the residual voltage into a single index or weighted T. I. F. If his assumptions could be depended upon as reasonably correct under a wide range of commercial conditions, the single value of composite T. I. F. would probably be helpful. However, the field conditions in actual exposures or parallels are extremely diversified, and moreover the inductive influence of the residual current is likely to complicate the problem, because it may contribute considerably to the over-all inductive effects. These considerations are rather adverse to the author's proposal, and on the whole it would seem conservative to treat the balanced voltages and the residual voltage independently.

The relative index of inductive influence of the residual voltage is the product of that voltage and its T. I. F. The paper supplies data on twenty-three generators, from which this index can be computed; these results are shown in the accompanying Table I-A. Columns (1) to (6) and column (8) are taken directly from Table I of the paper. In order to make the results directly

comparable for all generators, regardless of their line voltage, the product of residual voltage and T. I. F. has been divided by the total voltage from line to neutral, and the quotient appears in column (7). It is interesting to note that this index covers a very wide range, or from 0.15 to 13.57. Fig. 2 herewith is a graph made by plotting individual points for each pair of corresponding values in columns (7) and (8). If there were some relationship or approximate connection between this interference index and the coil pitch, it presumably would be manifested by some systematic

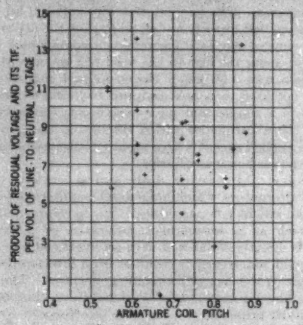


Fig. 2

grouping or arrangement of the plotted points. No such relationship is here evident, but the very low value of this index when the coil pitch is exactly two-thirds (0.667) is rather striking. Fig. 3 shows merely the instrument transformer connections for measuring this index, in case it is inconvenient or unsafe to use the open-delta connection of the armature windings.

Rather obviously there are two basic means for controlling the

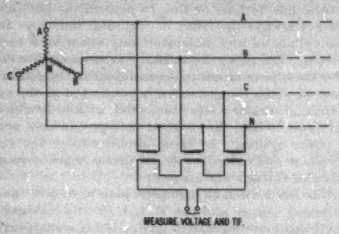


Fig. 3

inductive influence arising from residual voltage and current in this type of power system; one means is suitably to minimize or eliminate the residual voltage by control of the generator design, thus correcting the source; the other means is to interpose some suitable device or alternative grounding scheme which will provide an adequate barrier, or a by-pass, between the generator residual and the line system. In order to discuss devices or schemes of the latter class, it would be necessary to consider inductive influence as a problem involving a great many characteristics of complete power systems, whereas a discussion on generator characteristics would seem more appropriate to the title of the paper.

Star-connected armature windings have been substantially universal practise for a long period, but a coil pitch of two-thirds has been rather uncommon for many years. Looking backward, however, to a time about twenty-five years ago, when the largest a-c. generators did not exceed 2300 volts or a few thousand kilowatts in rating, the delta connection of armature windings and the two-thirds coil pitch were then in use. Although the two-thirds pitch is a very effective means of preventing triple harmonics, and thus avoiding their local circulation in a delta-connected armature, there are other means which were employed in design to secure the same result or approach it sufficiently for commercial purposes.

About twenty years ago it was pointed out that the star connection of armature windings attained the same result as the two-thirds coil pitch, and the designer would probably employ some other figure of pitch, for economic reasons, if free to do so. This was predicated no doubt on the assumption that the generator neutral would be isolated, and hence the triple harmonics, if present in star-connected armatures, would lack any path or circuit in which to circulate.

The developments which resulted in larger generators came rapidly with the introduction of the steam turbine, and with increased size came the economic need for higher voltages. This in turn made it more economical of insulation to employ star-connected armatures, with neutrals grounded for stabilizing and protective purposes. Upon the advent of larger generators and higher generator voltages, the trend in distributing energy was to deliver increasing proportions of the output to transformer banks which stepped up the voltage for transmission over extensive districts, or stepped it down for local primary distribution.

At the present time the trend of primary distribution voltages is upward, for economic reasons. The rapidly increasing mileage of electric service lines tends naturally to create more parallels with communication systems, more generally in areas where the population density is considerable. It is becoming more common to connect primary distribution networks direct to generator busses, such as 11 kv. or 13.2 kv. Grounding of the neutral for stabilizing, protective, and safety purposes is now almost universal. These facts appear to justify the use of appropriate means for controlling the residual voltage characteristics of generators installed in future.

Returning to Fig. 2, the mean of the ordinates is an index figure of 7.41, but most of the individual figures are scattered over the general range from about 4.0 to 14.0. It is interesting to note that no more than four generators have the same coil pitch, and in all there are 13 different pitches here shown. Two machines have two-thirds pitch and show very low values of the index. One machine with a pitch of 0.80 shows an index of 2.74, and another with a pitch of 0.72 shows an index of 4.49, both being very considerably below the average.

The factors which determine the magnitude of inductive effects caused by residual voltage are so numerous that it is not feasible to assign any particular value or limit of the above index which is tolerable. Experience seems to indicate that an index on the order of 8.0 or 9.0 might be high enough to require consideration in certain coordination problems, but there is little evidence as yet concerning lower values, except that so far as known there has never been any difficulty when the index is on the order of 0.2 or thereabouts. The latter conclusion is supported, at least tentatively, by the recent installations of several new generators constructed with two-thirds pitch.

It would seem to be helpful if Mr. Smith would discuss the other available means in generator design for controlling the residual voltage and T. I. F. besides the critical two-thirds pitch, and comment on the relative advantages and disadvantages of all the known means, from the standpoint of the generator and its performance.

**J. J. Smith:** I am glad to note the agreement in the discussion that the subject presented in this paper is of importance in connection with the problem of inductive coordination, particularly since transmission at high generated voltages is becoming

more common. The data given by Mr. Coleman on a situation which he has investigated recently are of interest since the analysis of the generator voltage wave shape in that case was very similar to the analysis of the generators in Tables II and III of my paper, although that machine was made by another manufacturer. It is to be hoped the work of the Joint Development and Research Subcommittee, N. E. L. A. and Bell System, will add considerably to our knowledge of the subject.

Mr. Coleman has shown how the impedance of a power system at various frequencies can be calculated from measurements of the voltages and currents of the different harmonics and how the results can be used to determine what reduction in neutral current harmonics will be produced by the insertion of a given amount of resistance or impedance in the neutral. This is an important matter since the impedance of systems varies considerably, depending upon their size and whether they consist mostly of overhead lines or underground cables, so that while a given amount of impedance might be of appreciable benefit in one location its effect in another location might be negligible. Data obtained in connection with the investigations I have described show that such system impedances vary in magnitude between fairly wide limits. I agree with Mr. Coleman that there are many points to be considered before the best solution in any given case can be determined.

Mr. Henderson has pointed out the undesirability of the special winding combinations referred to in the paper. I agree with him that these are undesirable from many points of view and will result in increased cost of machines. As suggested in the paper, there are other alternatives which can be employed to achieve the same result and these should also be given consideration.

Mr. McCurdy's and Mr. Fowle's suggestions of an alternative method of rating the T. I. F. of electrical machines from this standpoint are very similar. I believe their method of rating is a good one. My purpose in introducing the triple-harmonic weighted T. I. F. was to point out that there was an essential difference between the triple and non-triple harmonics and to arrive at a figure for the former which would give their relative effect on paralleling telephone lines as compared with the same effect for non-triple harmonics. When this is understood there appears to be no further reason for attempting to reduce the T. I. Fs. for balanced and residual components to a common base, and we may, as they suggest, simply take the product of the voltage T. I. F. across the corner of the opened delta and divide it by the phase voltage to obtain a good measure of the triple harmonics. In cases where the triple harmonics are the governing factor in the triple-harmonic weighted T. I. F. this quantity is approximately equal to 40 times that suggested by them, as may be seen by referring to the machines, which are common to all the tables—Nos. 7, 12, 22.

$$\frac{406}{40} = 10.1 \text{ which compares with } 9.9 \qquad (7)$$

$$\frac{553}{40} = 13.8 \text{ which compares with } 13.3 \qquad (12)$$

$$\frac{457}{40} = 11.4 \text{ which compares with } 11.1 \qquad (22)$$

Mr. McCurdy's reference to the residual component T. I. Fs. due to capacitance unbalance of lines is interesting and may also be compared with the figures to be expected on a perfectly balanced system grounded through a transformer bank which is one of the methods referred to in the paper for avoiding this type of interference. The residual voltage T. I. F. measured on a transformer in one test was 0.8 at very low density, 1.75 at medium density, and 4.5 at high density. You will note that the 0.8 at very low density is approximately the same as that calculated by Mr. McCurdy for the capacity unbalance.

Professor Doggett suggests that we connect the inductive motors and a-c. station to the neutral of the generator and use it to reduce the amount of the triple harmonics. While it is easy to obtain the result which he got in the Laboratory when the two machines were probably about the same size, in actual practise the station apparatus is perhaps 1/25 or so of the kv-a. of the main generator. Assuming both of them have the same per cent impedance, the maximum reduction in ordinary operation would be 1/25 = 4 per cent. On account of this small reduction I do not see much hope of using his suggestion in actual practise.

It may be well to point out that it may be difficult to use the ordinary T. I. F. meter to make the measurement suggested by Mr. Fowle in Fig. 2 if the potential transformers are rated 110 volts on the secondary side. For instance, with machine No. 1, Table I, using 100 to 1 potential transformers connected in this manner, the microamperes through the thermocouple in the network would be 750 × 230/100 = 1700 which would correspond to about 8 divisions out of 100 on the meter we use. The readings at this part of the scale would not be very accurate. Furthermore, the voltage across the open corner of the delta would be 230/100 = 2.3 volts which is too low to read on the T. I. F. meter. In general, some amplifying device would be needed to obtain the results required or a harmonic analyzer of a type already described before the Institute in which vacuum tubes are incorporated to give high sensitivity might be used. In the factory, however, the measurement can be made by connecting the machine itself delta with one corner open and using a lower ratio potential transformer.

It is difficult to add anything at the present time as to other available means for controlling the residual voltage and T. I. F. since, as pointed out by Mr. Fowle himself, no limit for a tolerable value of the index has been set. The number of factors at the disposal of the designer is considerably less than the possible number of harmonics, and the designer must use these factors to the best advantage so that all the harmonics may be of reasonably small magnitude. As a general rule if he designs so that certain harmonics will be very small, the effect will be to increase the remaining harmonics over what they would be otherwise.

Mr. Gati's suggestion that the balance of the telephone lines must also be considered is important. The Joint Development and Research Committee of the N. E. L. A. and Bell System is also studying this part of the problem.

# Inversion Currents and Voltages in Auto-Transformers

BY A. BOYAJIAN[1]

Fellow, A. I. E. E.

*Synopsis.—Line grounds on the secondary of an auto-transformer, fed from a grounded system, tend to invert the neutral of the auto-transformer. If the auto-transformer is isolated, this may lead to larger voltages, and if grounded, to larger currents than what would ordinarily be expected. The analysis of an important installation (75,000-kv-a., three-phase units at Detroit) is given below, for various possible connections and conditions of operation.*

*Features of the analysis are: (A) A novel theory and method of auto-transformer circuit representation was developed to handle some aspects of this problem that otherwise appeared elusive. The method is applicable to all networks involving auto-transformers. (B) The rather startling fact is brought out and explained that fault currents to ground on the secondary lines of an auto-transformer may be larger when stepping-up than when stepping-down. The prediction has been verified by test.*

* * * * *

## Introduction

THE use of auto-transformers in transmission circuits involves much more complicated problems than the use of straight transformers. It is very desirable to clarify the solutions of such problems so as to enable consulting and operating engineers to ascertain readily the characteristics of such circuits and the effect of various modifications. This study was undertaken in connection with some 75,000-kv-a. auto-transformers now installed in the Detroit-Edison system, and this concrete application of the theory makes the presentation the more interesting and instructive.

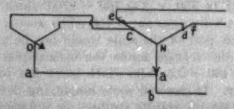


Fig. 1—Diagram of Grounded Generator Feeding an Isolated Step-Up Auto-Transformer

## Meaning of "Inversion"

Fig. 1 shows a grounded generator feeding an isolated step-up auto-transformer. Under normal conditions, the potential of $N$ is at the center of gravity of the vector diagram, and hence coincides with that of the neutral of the generator and ground.

If terminal $b$ becomes grounded (Fig. 2), the potential of $b$ is moved to ground to correspond to $o$; and, since the potential of $a$ is definitely fixed by the generator, the movement of $b$ (to where $N$ was formerly) reverses the direction of the voltage $a\,b$ as will be seen in Fig. 2. The reversal of the excitation on $a - b$ reverses the entire leg $N - b$ and throws $N$ outside of the triangle of line voltages. Hence the term "inversion." It appears that L. F. Blume first predicted this phenomenon and called it to C. P. Steinmetz's attention, whereupon the latter christened it as "inversion" of the neutral.

Besides reversal, a change in magnitude also takes place in the excitation of $a - b$ because while formerly (in Fig. 1) it was determined by the auto-transformer ratio, now it has to be equal to $o - a$ regardless of what the auto-transformer ratio may be.

## Vector Diagram of Inversion

The vector diagram of Fig. 2 is drawn as follows: The points $a$, $b$, $c$, $d$ are fixed directly by the generator; $a - N$ is drawn equal to $a - b$ times the ratio of the common turns to the series turns; $N - c$ and $N - d$ are then drawn extending to $e$ and $f$ respectively, making the ratio of $e - c$ to $c - N$ (or $f - d$ to $d - N$) that of the series to common turns. The excitation of the faulty leg in terms of normal excitation is $E_{lv}/(E_{hv} - E_{lv})$—that is, the low-voltage line voltage divided by the difference between the high- and low-line voltages.

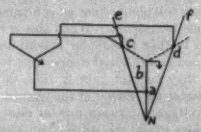


Fig. 2—Same as Fig. 1 with Terminal $b$ Grounded

Obviously, as the high- and low-line voltages approach each other, this overexcitation is increased. Thus, if the difference between high- and low line voltages is 10 per cent, the faulty leg becomes excited 10 times normal.

Considering the circuit from the standpoint of short-circuit currents, it will be seen that there will be no short-circuit currents in the ordinary sense, but the over-excitation of the auto-transformer may cause exciting current rushes comparable to short-circuit currents, depending on the degree of overexcitation.

The connection analyzed in Figs. 1 and 2 is obviously not a desirable operating connection, especially for booster auto-transformers. It was chosen merely for illustration on account of its simplicity and accentuated overvoltages. Operative connections avoid these excessive inversion voltages, but are accompanied by inver-

1. Transformer Engg. Dept., General Electric Company, Pittsfield, Mass.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

sion currents. Ten such cases are analyzed below with respect to currents and voltages, and the results are arranged in Table I.

## Discussion of Cases

The circuit connections and ground and fault locations for the ten cases are shown in the first column of Table I. The corresponding zero-sequence impedance networks are shown in the second column. The positive and negative sequence networks are not shown because they are obvious. The first four cases in which the delta tertiary winding is omitted, are of only theoretical interest for comparison, as the transformers actually have tertiary delta windings. For this same reason, these four cases have been simplified assuming that the zero sequence impedance of the auto-transformer (194 per cent for the full winding) is high enough to compel all the zero sequence current to flow through the generator. The resistances of these circuits being very small compared with the reactances, the impedances are treated as reactances.

TABLE I.
Inversion Currents and Voltages in Auto-Transformers

| System Connection (Gen. Auto.) | Equivalent Zero-Sequence Network (Only One Line Shown) | Currents: Fault-Line | Currents: Fault-Ground | Currents: Tertiary | Voltages to Ground Upper Limits: Gen. Neut. | Voltages to Ground Upper Limits: Auto. Neut. | Voltages to Ground Upper Limits: L. V. Line | Voltages to Ground Upper Limits: H. V. Line |
|---|---|---|---|---|---|---|---|---|
| 1. | $j0.1$; 7,260 / 33; 8,220 / 4.85 / Amps | 8,220 | 8,220 | 0 | 17,600 | normal | normal | normal |
| 2. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 7,100 / 4.25 / Amps | 7,100 | 8,140 | 0 | 15,300 | 7,100 | 7,100 | 14,100 |
| 3. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 6,920 / 4.1 / Amps | 6,920 | 7,870 | 0 | 14,800 | 3,700 | 0 | 14,800 |
| 4. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 6,660 / 3.94 / Amps | 6,660 | 7,570 | 0 | 14,100 | 0 | 7,570 | normal |
| 5. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 7,080 / 4.18 / Amps | 7,080 | 7,100 | [illegible] | 14,400 | 7,650 | 7,650 | 15,300 |
| 6. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 7,480 / 4.42 / Amps | 7,480 | 4,420 | [illegible] | 11,600 | 7,465 | 0 | 15,400 |
| 7. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 7,400 / 4.38 / Amps | 7,400 | 5,600 | [illegible] | 12,357 | 7,400 | 7,400 | 14,800 |
| 8. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 6,470 / 3.82 / Amps | 6,470 | 4,000 | [illegible] | 9,200 | 6,470 | 6,470 | 13,400 |
| 9. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 7,200 / 4.26 / Amps | 7,200 | 5,100 | [illegible] | 10,270 | 6,500 | 0 | 15,000 |
| 10. | $j0.1$; 7,260 / 33; 7,260 / 33.0; 6,560 / 5.06 / Amps | 6,470 | [illegible] | [illegible] | 15,000 | 0 | 6,900 | 13,600 |

By the well-known general formula, applicable to all cases of single-phase, line-to-neutral short-circuits on three-phase circuits,

$$I_{fault} = \frac{3\,E}{Z_0 + Z_1 + Z_2}, \text{ or}$$

$$= \frac{300 \times \text{base current}}{\%\,I\,Z_0 + \%\,I\,Z_1 + \%\,I\,Z_2}$$

Since the positive and negative sequence networks are obvious, the main problem is to trace and evaluate the zero-sequence networks.

Some of these cases (Cases 5-10) involve zero-sequence networks that are both conductively and inductively interlinked, and are elusive to handle. It was for this purpose that a new theory of transformer and auto-transformer equivalent circuits was developed.

## New Theory of Transformer and Auto-Transformer Circuits[2]

The conventional equivalent circuit of a transformer or auto-transformer is constructed on a one-to-one ratio basis, and therefore will not step-up or down any current or voltage. It is obvious, therefore, that a transformer in a network cannot actually be replaced by such an equivalent circuit without spoiling its fundamental function. This same observation holds true for our equivalent circuit representations of three-circuit transformers. All of these circuits are equivalent for certain purposes only, and no further. In analyzing complicated networks, however, we need an equivalent circuit which can actually completely replace the transformer or auto-transformer and perform all its functions. Such a circuit is derived by reasoning as follows:

The characteristics of a stationary outfit (which may be a transformer or auto-transformer) are completely determinable by measurements at its terminals, and therefore, such an outfit is completely replaceable by any other outfit which yields similar measurements at its terminals. Considering an auto-transformer with three terminals, $a$, $b$, and $c$, all the characteristics measurable at its terminals are that certain three impedance values $Z_{ab}$, $Z_{bc}$, and $Z_{ca}$ exist among those three terminals; and, therefore, the outfit should be replaceable by any network having similar terminal impedance characteristics. The internal connection of the equivalent network may be anything we please, but $Y$ and delta are the simplest alternatives. Accordingly, if we choose the $Y$ equivalent, the values of the leg impedances $Z_a$, $Z_b$, $Z_c$ in terms of the given

2. A thorough discussion of this theory was published in two articles in the *General Electric Review* for February, 1929. under the titles of "New Theory of Transformer and Auto-Transformer Circuits," by A. Boyajian, and "New Equivalent Circuits for Auto-Transformers and Transformers with Tapped Secondaries," by D. R. MacLeod. Through a strange coincidence, the two authors arrived at the same theory at the same time, while working on different problems, unaware of each other's work. Since the publication of these articles, Mr. W. D. Cannon called the writer's attention to an article in the *Bell System Tech. Jl.* Jan. 1925, p. 84, under the title of "Mutual Inductance in Wave Filters," in which transformer equivalent circuits, similar to those discussed here, are mentioned and credit is given in particular to Messrs. G. A. Campbell and W. L. Casper. The first foreshadowing of the idea is apparently in a paper by Campbell, *Cisoidal Oscillations*, A. I. E. E. Trans., Vol. XXX, Part II, pp. 873-909.

auto-transformer impedances $Z_{ab}$, $Z_{bc}$, $Z_{ca}$ will be:

$$Z_a = (Z_{ab} - Z_{bc} + Z_{ca})/2 \text{ vectorially.}$$
$$Z_b = (Z_{bc} - Z_{ca} + Z_{ab})/2 \text{ vectorially.}$$
$$Z_c = (Z_{ca} - Z_{ab} + Z_{bc})/2 \text{ vectorially.}$$

In appearance, these formulas are similar to those used in three-winding transformers, but there is an important difference. In three-winding transformers, the impedances are reduced to a common kv-a. basis if they are in percentage form, and reduced to the same circuit if in ohmic form; whereas in the present case the ohmic values are actual (measured) ohmic values without any reduction or transformation, while percentage values are to be based on the same amperes and volts without changing the circuit, as will be illustrated below.

It will be seen on further study, that the current and voltage transformations accomplished in the auto-transformer by magnetic coupling, are accomplished in the equivalent network by shunt and series resonance.

*Example.* To avoid beclouding the main features of the discussion by unessential incidental details, we will ignore the losses of the auto-transformer in this illustration, and consider only the reactive constants. Let Fig. 3A represent a 1000-kv-a. auto-transformer, stepping up from 1000 volts to 2000 volts, with approximately 10 per cent magnetizing current and 10 per cent leakage reactance. Such an auto-transformer can be completely replaced by the equivalent network shown in Fig. 3B. Any test applied to this network will show it to have the same characteristics as the specified auto-transformer. For instance, with a 1000-ampere unity power factor load across the secondary $H - N$, and 2000 volts maintained across it, the primary voltage will be $(1010 + j\,100)$ volts (which includes regulation), and primary current $(2000 - j\,200)$ amperes (which

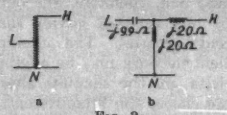


Fig. 3

a—Developed Winding Diagram
b—Complete Equivalent Circuit Representation

1000-kv-a., 1000-volt low-voltage, 2000-volt high-voltage auto-transformer with approximately 10 per cent magnetizing current and 10 per cent leakage reactance

includes magnetizing current). The primary voltage includes correctly even the regulation caused by the magnetizing current.[3]

The application of the foregoing theory and equivalent circuit to the problem of this paper is to the zero-sequence network in Cases 5-10, where the generator and auto-transformer zero-sequence paths are linked both conductively and inductively in a complicated manner, and the end sought is to replace the auto-transformer by an equivalent circuit, the branches of which have no mutual magnetic linkage, in order that the resulting network may be solved by elementary methods.

The details of all these calculations and other steps required in the preparation of Table I are given in the appendix to this paper.

## Relative Magnitude of High- and Low-Voltage Fault Currents

The fault current in a line-to-line short circuit on the secondary of an auto-transformer, is less on the high-voltage side than on the low-voltage side, being in the inverse ratio of the voltages; but this relationship does not hold true for line-to-neutral fault currents, especially when the fault current is limited entirely, or largely, by the zero-sequence impedances.

The auto-transformer steps up the voltage and also

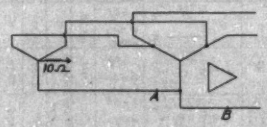


Fig. 4—Diagram of Generator Feeding Auto-Transformer With Tertiary Delta

the positive and negative sequence impedances, but not the zero-sequence impedance; and therefore, when the zero-sequence impedance is dominant, short-circuit currents may be higher on the high-voltage side than on the low-voltage side. When the zero-sequence impedance is internal, these relations may be somewhat difficult to see, but when the zero-sequence impedance is external, the principle involved can easily be made clear, and the reasonableness of the more involved cases established.

Referring to Fig. 4, a line-to-line fault current, $I_{fB}$, at $B$ will be smaller than a line-to-line fault current, $I_{fA}$, for a fault at $A$ in the ratio

$$\frac{I_{fB}}{I_{fA}} < \frac{E_{LV}}{E_{HV}},$$

that is, less than the inverse ratio of the voltages, on account of the added auto-transformer impedance for faults at $B$. This is as we would expect it to be, but consider now the line-to-neutral fault currents:

The generator is grounded through a 10-ohm resistance representing 382 per cent zero-sequence impedance, purposely chosen high so that the generator and auto-transformer impedances may be negligible in comparison, and simplify calculation.

Will a line-to-neutral fault current $(I_{fB})$ at $B$ be less than that $(I_{fA})$ for a line-to-neutral fault at $A$? Obviously,

3. Just enough discussion of the theory is here given to clarify its application to the present problem. Those who are interested in the theory beyond its present application should refer to the articles mentioned in the foregoing footnote.

$$I_{fA} = \frac{0.57\ E_{LV}}{10}$$

For a fault at $B$, the current will have to be

$$I_{fB} = \frac{0.57\ E_{HV}}{10}$$

because as the auto-transformer offers no impedance to the flow of zero-sequence currents in its series winding, there will be no stepping-up or down of these currents, and the zero-sequence impedance of the installation will be the same whether measured at $A$ or at $B$. We thus arrive at the result that

$$\frac{I_{fB}}{I_{fA}} = \frac{E_{HV}}{E_{LV}},$$

the inverse of that for line-to-line short circuits.

If the zero-sequence impedance had been within the generator windings the result could have been in no way different. If the zero-sequence impedance had been partially within the generator and partially within the auto-transformer, the result could again have been in no way different, assuming this time, however, that when the fault is at $B$ the generator is at $A$, and when the fault is at $A$ the generator is at $B$. These conclusions were verified by test.

## Appendix

### Rating and Impedance Data

*Generator Data*

1. Kv-a. rating (three-phase) ..... 75,000
2. Voltage (line) ..... 12,000 $Y$
3. Amperes (line) ..... 3,620

Reactances (to the basis of 75,000 kv-a.)

4. $Z_{g1}$ positive sequence ..... 13.5 per cent
5. $Z_{g1}$ negative sequence ..... 13.5 per cent
6. $Z_{g1}$ zero sequence ..... 5.7 per cent

*Auto-Transformer Data*

7. Kv-a. output (three-phase) ..... 75,000 as auto.
8. Low-voltage (lines) ..... 12,000 $Y$
9. High-voltage (lines) ..... 25,800 $Y$
10. Amperes L. V. (lines) ..... 3,620
11. Amperes H. V. (lines) ..... 1,692

*Series Winding*

12. Kv-a. (as trans.) ..... 40,000
13. Voltage ..... 13,600 $Y$
14. Amperes (line and coil) ..... 1,692

*Common Winding*

15. Kv-a. (as trans.) ..... 40,000
16. Voltage (line) ..... 12,000 $Y$
17. Amperes (line and coil) ..... 1,928

*Tertiary Delta*

18. Kv-a. (as trans.) ..... 18,750
19. Voltage (line and coil) ..... 6,630 delta
20. Amperes (coil) ..... 942
21. Auto. Corstio: $k = 0.532$
$(E_1 - E_0)/E_1$
22. $k^2 = 0.283$

*Impedances*

23. Auto-transformer operation (75,000-kv-a. output.) (Series common to common) ..... 9.68 per cent

*Series to Common $Z_{sc}$*

24. As transformer 40,000 kv-a. ..... 18.2 per cent
25. As transformer 75,000 kv-a. ..... 33.2 per cent

*Series to Tertiary $Z_{st}$*

26. As transformer 18,750 kv-a. ..... 12.25 per cent
27. As transformer 40,000 kv-a. ..... 26.15 per cent
28. As transformer 75,000 kv-a. ..... 49. per cent

*Common to Tertiary $Z_{ct}$*

29. As transformer 18,750 kv-a. ..... 3.59 per cent
30. As transformer 40,000 kv-a. ..... 7.63 per cent
31. As transformer 75,000 kv-a. ..... 14.3 per cent

*Series Common to Tertiary $Z_{sc-t}$*

32. As transformer 18,750 kv-a. ..... 3.96 per cent
33. As transformer 75,000 kv-a. ..... 27.4 per cent

The positive, negative, and zero-sequence impedances of the auto-transformer windings are:

34. $Z_{sc1}$ (Based on 75,000 kv-a. output) ... 9.68 per cent
35. $Z_{sc1}$ (Based on 75,000 kv-a. ouput) .... 9.68 per cent
$Z_{sc0}$ (Based on 75,000 kv-a. output)
36. Exclusive of tertiary: (delta open) ... 194 per cent
37. Inclusive of tertiary: (delta closed) .. 24 per cent
$Z_{s0}$ (As auto-transformer, 75,000 kv-a. output) .....
38. Exclusive of tertiary: (delta open) .... 44 per cent
39. Inclusive of tertiary: (delta closed) ... 11.7 per cent
$Z_{c0}$ (In terms of L. V. lines, 75,000 kv-a.)
40. Delta open ..... 201 per cent
41. Delta closed ..... 13.9 per cent

*Comments on the Zero-Sequence Impedances.* In $Y$ connected single-phase units, also in $Y$ connected three-phase shell type units, the zero-sequence impedance is a magnetizing impedance and may therefore be considered infinity (except for saturation due to

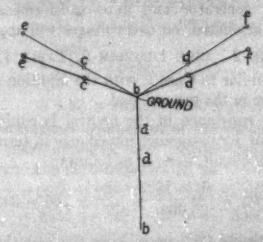


Fig. 5—Vector Diagram of Voltages

overexcitation); but in core-type three-legged three-phase units, the coupling of the magnetic circuits of the three legs acts like a high-reactance tertiary delta winding, as will be seen in the data items 36, 38, and 40. The reason why 38 is not as high as 36 and 40 is that 38 has had to be reduced to a current and voltage basis, which represents only 40,000 kv-a. in the series windings but 75,000 kv-a. in the output.

When a delta tertiary winding is provided in transformers, the reactances with respect to the tertiary are also the zero-sequence reactances (reduced to the proper basis of current and voltage); but in core-type, three-legged, three-phase units, the zero-sequence impedance is the resultant of the effects of, (a), the

interphase coupling due to the core structure, and (b) the delta winding. As the first is usually very large compared with the latter, the resultant may be taken as the two impedances in parallel, instead of attempting the equivalent of a three-circuit resolution. Thus (41) is substantially equal to (40) and (31) in parallel.

## STEPS IN THE CALCULATION OF TABLE I

### Case 1. (See Diagram 1, Table I.)

The zero-sequence currents flow through the generator and are stepped up through the auto-transformer. Hence,

$$Z_0 = j\ 5.7 + j\ 9.68 = j\ 15.4 \text{ per cent}$$
$$Z_1 = j\ 13.5 + j\ 9.68 = j\ 23.2 \text{ per cent}$$
$$Z_2 = \text{Ditto}$$
$$(Z_1 + Z_2) = j\ 46.4$$

This last quantity remains unchanged in all cases, and is therefore well to remember. Only $Z_0$ changes from case to case. In the present case,

$Z_0 + (Z_1 + Z_2) = j\ 15.4 + j\ 46.4 = j\ 61.8$ per cent

Hence:

$$I_{fault} = \frac{300 \times 1692}{61.8} = 8220 \text{ amperes}$$
$$= 4.85 \times \text{Base}$$

The maximum currents in the generator and the series and common windings of the auto-transformer will similarly be 4.85 times the base or normal current corresponding to 75,000 kv-a. three-phase.

As both generator and auto-transformer neutrals are solidly grounded, no overvoltages will appear.

### Case 2. (See Diagram 2, Table I.)

This is similar to Case I, with the addition of a one-ohm resistor in the ground lead.

One-ohm resistance in the neutral is equivalent to 34.4 per cent zero-sequence impedance in terms of the high-voltage circuit, derived as follows:

$$\%\, I\, R_0 = \frac{1 \times 1692 \times 3}{25{,}600 \times .577} \times 100 = 34.4$$

The multiplier "3" arises from the fact that if the rated 1692 amperes flow in the lines in zero sequence, the resistor current is three times that value.

The total zero-sequence impedance is therefore (see Diagram 2 in Table I):

$$Z_0 = 34.4 + j\ 15.4$$

and $Z_0 + Z_1 + Z_2 = 34.4 + j\ 15.4 + j\ 46.4$

$$= 34.4 + j\ 61.8 = 70.7 \text{ per cent}$$

Hence:

$$I_{fault} = \frac{300}{70.7} \times \text{Base}$$
$$= 4.25 \times \text{Base} = 7{,}180 \text{ amperes}$$
$$I_{series} = 4.25 \times \text{Base} = 7{,}180 \text{ amperes}$$
$$I_{common} = 4.25 \times \text{Base} = 8{,}140 \text{ amperes}$$
$$I_{gen.} = 4.25 \times \text{Base} = 15{,}300 \text{ amperes}$$

The auto-transformer neutral, being tied to that of the generator, cannot invert; but due to the drop in the resistor between the neutrals and ground, both neutrals will rise above ground $1 \times 7180$ volts.

The power factor of the fault current (with respect to the corresponding leg voltage at no load) is 34.4/70.7, or 48.7 per cent, representing approximately 60 deg. lag. This will bring the resistor drop practically in line with one of the other phases (the leading phase), so that the voltages to ground on that phase will be the arithmetic sum of the leg voltage and the resistor drop. Thus:

Max. $E_{LV}$ to ground $= (12{,}000 \times 0.577) + 7180 = 14{,}100$

Max. $E_{HV}$ to ground $= (25{,}600 \times 0.577) + 7180 = 21{,}830$

No voltage-regulation need take place in the ungrounded phases, as they will have no current except what little may be induced due to interphase induction.

### Case 3. (See Diagram 3, Table I)

Here the resistor is in the generator neutral, with a magnitude of only quarter of an ohm; but, by being in the L. V. circuit, it is equivalent to a higher per cent impedance (39.2 per cent) than the one ohm resistance of the preceding case. We have then:

$$Z_0 + Z_1 + Z_2 = 39.2 + j\ (15.4 + 46.4)$$
$$= 39.2 + j\ 61.8 = 73.2 \text{ per cent}$$
$$I_{fault} = \frac{300}{73.2} \times \text{Base}$$
$$= 4.1 \times \text{Base} = 6{,}920 \text{ amperes}$$
$$I_{series} = 4.1 \times \text{Base} = 6{,}920 \text{ amperes}$$
$$I_{common} = 4.1 \times \text{Base} = 7{,}870 \text{ amperes}$$
$$I_{gen.} = 4.1 \times \text{Base} = 14{,}820 \text{ amperes}$$
$$E_{resistor} = 0.25 \times 14{,}820 = 3{,}710 \text{ volts.}$$

The power factor and angle of lag of the fault current being substantially the same as in the preceding case, arithmetic addition of leg voltages with neutral drop is again possible. Thus:

Max. $E_{LV}$ to ground $= 6930 + 3710 = 10{,}640$ volts.

Since the auto-transformer neutral is solidly grounded this voltage ($1.54 \times$ normal) will be impressed on its corresponding phase so that the maximum high-voltage stress to ground will be 1.54 times normal, equal to 22,800. The core will also be overexcited in that leg in the same ratio.

### Case 4. (See Diagram 4, Table I)

To determine the effective zero-sequence impedance introduced by the one-ohm resistor in the generator neutral, we note that with rated current (1692 amperes) in the high-voltage lines in zero sequence, the resistor current is three times that in the common windings. That is, 5770 amperes consuming 33,200 kw., which is 44.4 per cent of the output, as indicated in the zero-sequence network (Diagram 2, Table I). This method of evaluating the effective impedance introduced by a link in any network appears to the writer as simple and

fool-proof, being a direct application of the law of conservation of energy.

$$E_0 + E_1 + E_2 = 44.4 + j\,15.4 + j\,46.4$$
$$= 44.4 + j\,61.8 = 76.1 \text{ per cent}$$

$$I_{fault} = \frac{300}{76.1} \times \text{Base}$$
$$= 3.94 \times \text{Base} = 6{,}660 \text{ amperes}$$
$$I_{series} = 3.94 \times \text{Base} = 6{,}660 \text{ amperes}$$
$$I_{common} = 3.94 \times \text{Base} = 7{,}570 \text{ amperes}$$
$$I_{gen.} = 3.94 \times \text{Base} = 14{,}200 \text{ amperes}$$
$$I_{resistor} = I_{common} = 7{,}570 \text{ amperes}$$

Obviously, the potential of the auto-transformer neutral to ground will be the resistor drop, $1 \times 7570$ volts.

The potential of the low-voltage lines to ground cannot rise above normal because the solidly grounded generator fixes it definitely.

The excitation of each leg of the auto-transformer is the resultant of the corresponding generator leg voltage and the resistor drop, and since the latter is substantially in line with one of the ungrounded phases, they may be combined arithmetically, giving

$$\text{Auto. excitation} = \frac{12{,}000 \times 0.577 + 7570}{12{,}000 \times 0.577} \times \text{normal}$$
$$= 2.1 \times \text{normal.}$$

The maximum high-voltage leg voltage will therefore be 2.1 times normal, or 31,000 volts; and the maximum line voltage to ground will be 31,000 minus the resistor drop, or 23,430 volts.

### Case 5. (See Diagram 5, Table I)

Cases 5 to 10 include a tertiary delta winding, and therefore the auto-transformer has a low zero-sequence impedance. In some of these cases the paths of the zero-sequence currents lead to a network with series and parallel branches interlinked both conductively and inductively, making it desirable to develop a suitable equivalent circuit representation for the auto-transformer without magnetic coupling. This was accomplished as described in the main body of this paper.

Thus, from item (37) in the section on data, we have

$$Z_{sc-0} = 24 \text{ per cent}$$

based on the high-voltage line current and voltage.

From item (39),

$$Z_{0-0} = 11.7 \text{ per cent}$$

based on the same high-voltage line current and voltage.

Item (41) gives $Z_{0-0}$ as 13.9 per cent to the basis of low-voltage line current and voltage, and needs conversion to the high-voltage current and voltage basis, as follows:

$$Z_{c-0} = 13.9 \times \left\{ \frac{12{,}000}{25{,}600} \right\}^2 = 3.05 \text{ per cent}$$

Indicating the low-voltage terminal by $L$, the high-voltage terminal by $H$, and the neutral end of the phase by $N$,

$$Z_{LH} = Z_{0-0} = 11.7 \text{ per cent}$$
$$Z_{HN} = Z_{sc-0} = 24 \text{ per cent}$$
$$Z_{NL} = Z_{c-0} = 3.05 \text{ per cent}$$

Hence,

$$Z_L = (11.7 - 24 + 3.05)/2 = -4.62 \text{ per cent}$$
$$Z_H = (24 - 3.05 + 11.7)/2 = 16.32 \text{ per cent}$$
$$Z_N = (3.05 - 11.7 + 24)/2 = 7.67 \text{ per cent}$$

The generator zero-sequence impedance must also be reduced to the high-voltage current and voltage basis,

$$X_{g-0} = 5.7 \times \left\{ \frac{12{,}000}{25{,}600} \right\}^2 = 1.25 \text{ per cent}$$

The equivalent zero-sequence impedance network of the bank (including generator and auto-transformer) is shown in Diagrams 5-10 in the Table, together with such other impedance as may have been put in the neutrals.

Considering Case 5 specifically, the effective resultant zero-sequence impedance of the outfit, with connections as shown with one-ohm resistance in the transformer neutral, will be

$$Z_0 = 34.4 + j\,16.32 + \frac{j\,7.67\,(j\,1.25 - j\,4.62)}{j\,7.67 + j\,1.25 - j\,4.62}$$
$$= 34.4 + j\,10.32$$
$$Z_0 + Z_1 + Z_2 = 34.4 + j\,10.32 + j\,46.4$$
$$= 34.4 + j\,56.7 = 66.3 \text{ per cent}$$

$$I_{fault} = \frac{300}{66.3} \times \text{Base}$$
$$= 4.52 \times \text{Base} = 7650 \text{ amperes}$$

The zero-sequence component of this current is one-third, or 2550 amperes, and divides between the generator and the auto-transformer, as

$$I_{0\,common\,wdg.} = 2550\,(1.25 - 4.62)/(7.67 + 1.25 - 4.62)$$
$$= 2550\,(-3.37)/4.3 = -2000 \text{ amperes}$$
$$I_{0\,generator} = 2550\,(7.67)/4.3 = 4550 \text{ amperes}$$
$$I_{0\,series\,wdg.} = 2550 \text{ amperes}$$

The resultant maximum total currents at the various points will be:

$I_{series}$ = 7650 amperes (fault current)
(faulty phase)

$I_{common}$, positive and negative sequence
(faulty phase)

$$= -7650 \times \frac{2}{3} \times \left(\frac{k}{1-k}\right)$$
$$= -5780 \text{ amperes}$$

zero-sequence $= -2000$ amperes

Total $= -7780$ amperes

$I_{tertiary}$ is entirely zero-sequence current, and is the

resultant of the zero-sequence ampere-turns in the series and common windings.

kv-$a_0$ series winding

$$= 2{,}550 \times 13600 \times 1.73 = 60{,}000$$

kv-$a_0$ common winding

$$= -2{,}000 \times 12000 \times 1.73 = -41{,}500$$

Resultant = 18,500 kv-a.
(Total of all three phases of delta) = 0.246 × Base = 0.986 × capacity

The tertiary kv-a. will be somewhat less than this, in the same ratio in which the core type construction reduces the zero-sequence impedance below that effected by the tertiary delta winding, but this refinement may be ignored.

$I_{generator}$, positive and negative sequence (faulty phase)

$$= \frac{7650}{(1-k)} \times \frac{2}{3} = 10{,}850$$

$I_{generator}$, zero-sequence (faulty phase) = 4,550

Total for the faulty phase = 15,400 amperes = 4.25 × normal.

In the other phases of the generator, the short-circuit current will be:

Resultant of positive and negative sequence currents $= \dfrac{7650}{(1-k)_3} = 5{,}425$

Zero-sequence current = − 4,550

Total = 875

This current is advanced 30 deg. with respect to one, say Phase II, and retarded 30 deg. with respect to the other, or Phase III, in addition to the power-factor angle of the short-circuit current. This can be verified by sketching the three polyphase components of the short-circuit current. The power factor of the fault current with respect to the no-load voltage is 34.4/66.3, or 52 per cent corresponding to about 60 deg. lag. Hence, the lag in one of those phases will be 90 deg., and in the other, 30 deg.

The drop due to the resultant of positive and negative sequence currents will be (13.5 × 5425/3620) = 20 per cent; that due to the zero-sequence current, 5.7 (− 4550/3620) = − 7.17 per cent; net drop 12.8 per cent. In Phase III, this will be parallel to the phase voltage and produce a 12.8 per cent regulation; while in Phase II it will subtract at a 60 deg. angle from the phase voltage and affect it only slightly.

The maximum low-voltage line potential to ground will be on Phase II, due to the neutral shift and the leg voltage adding practically arithmetically; (12,000 × .577) + 7650, equal to 14,570 volts. The high voltage line voltage to ground on the same phase, will be (25,600 × .577) + 7650, equal to 22,400 volts.

### Case 6. (See Diagram 6, Table I)

This is similar to Case 3, except for the delta; but, due to this same delta, the generator $Z_0$ entered as 5.7 per cent in Diagram 3, is entered as 1.25 per cent in Fig. 5-10; and therefore, the resistance $R_0$ entered as 39.2 per cent in Diagram 3, must be reduced in the same ratio and entered as 8.6. The zero-sequence impedance network is otherwise obvious, as shown in the diagram. Solving for the resultant impedance of this network,

$$Z_0 = \frac{j\,7.67\,(8.6 - j\,3.37)}{j\,7.67 + (8.6 - j\,3.37)} + j\,16.32$$

$$= +5.47 + j\,21.2$$

$$Z_0 + Z_1 + Z_2 = 5.47 + j\,21.2 + j\,46.4 = 5.47 + j\,67.6$$

$$= 67.9 \text{ per cent}$$

$$I_{fault} = \frac{300}{67.9} \times \text{Base} = 4.42 \times \text{Base}$$

$$= 7480 \text{ amperes}$$

The zero-sequence currents in the generator and the common winding of the auto-transformer will be out of phase from each other, on account of the presence of both resistance and reactance in the loop of the zero-sequence network. By an inspection of the diagram, it will be seen that

$$\frac{I_{0\,generator}}{I_{0\,common\ wdg.}} = \frac{j\,7.67}{8.6 - j\,3.37}$$

$$\frac{I_{0\,generator}}{I_{0\,total}} = \frac{j\,7.67}{8.6 - j\,3.37 + j\,7.67} = \frac{j\,7.67}{8.6 + j\,4.3}$$

$$= 0.357 + j\,0.71$$

$$I_{0\,generator} = \frac{7480}{3}\,(0.357 + j\,0.71) \text{ amperes}$$

$$= (891 + j\,1770) \text{ amperes}$$

$$\frac{I_{0\,common\ wdg.}}{I_{0\,total}} = \frac{8.6 - j\,3.37}{8.6 - j\,3.37 + j\,7.67}$$

$$= 0.644 - j\,0.715$$

$$I_{0\,common\ wdg.} = \frac{7480}{3}\,(0.644 - j\,0.715) \text{ amperes}$$

$$= (1608 - j\,1784) \text{ amperes}$$

The tertiary current, as the resultant of the zero-sequence currents in the series and common windings, and in terms of the base current, will be

$$I_{tert.} = \left(\frac{1608 - j\,1784}{3620} + \frac{7480}{3 \times 3195}\right) \times \text{base}$$

$$= (1.22 - j\,0.49) \times \text{base}$$

$$= 1.32 \times \text{base} = 5.3 \times \text{normal capacity.}$$

The maximum total generator current on the faulty phase, will be

$$\text{Positive and negative sequence} = 7480 \times 2/3 \times \left(\frac{1}{1-k}\right)$$

$$= 10{,}620$$

$$\text{Zero-sequence} = 891 + j\,1770$$

$$\text{Total} = 11{,}511 + j\,1770$$

$$= 11{,}600 \text{ amperes}$$

The maximum total common winding current on the faulty phase, will be

$$\text{Positive and negative sequence} = -7480 \times 2/3 \times \left(\frac{k}{1-k}\right)$$

$$= -5650$$

$$\text{Zero-sequence} = 1608 - j\,1784$$

$$\text{Total} = -4042 - j\,1784$$

$$= 4420$$

The current passing through the generator neutral resistor is 3 (891 + $j$ 1770) amperes or 5940 amperes, and the corresponding drop through the quarter ohm resistance, 1485 volts.

The upper limit of voltage stresses to ground will be, on the low-voltage side, the arithmetic sum of generator neutral shift and leg voltage. That is, 8400 volts,—in reality much less. On the high-voltage side, the stress will be practically limited to less than the normal leg voltage, because the generator neutral shift appearing as an overexcitation of the corresponding leg will be short-circuited by the delta as a zero-sequence voltage, and fail to be stepped-up properly into the series winding

### Case 7—(See Diagram 7, Table I)

The main features of the zero-sequence impedance network are that, (a), the generator neutral resistor is four times that in the preceding case, and therefore it is entered as 34.4 per cent; and (b) the auto-transformer neutral being isolated, the corresponding branch in the diagram is shown opened.

$$Z_0 = 34.4 + j\,12.95$$

$$Z_0 + Z_1 + Z_2 = 34.4 + j\,12.95 + j\,46.4$$

$$= 34.4 + j\,59.35 = 68.6 \text{ per cent}$$

$$I_{fault} = \frac{30}{68.6} \times \text{base} = 4.38 \times \text{base}$$

$$= 7400 \text{ amperes}$$

$I_{generator}$

Positive and negative sequence component

$$= 7400 \times 2/3 \times \frac{25.6}{12} = 10{,}520$$

Zero sequence component

$$= 2{,}467$$

$$\text{Total} \quad 12{,}987$$

(Note that the positive and negative sequence currents are transformed, but not the zero sequence current.)

The common winding current contains only positive and negative sequence currents (no zero sequence current), and these add arithmetically on the faulty phase, and at 120 deg. on the other phases, the latter being one-half of the former.

$$I_{common\ winding} = 7400 \times 2/3 \times \frac{13.6}{12} = 5600 \text{ amperes}$$

(faulty phase)

$$I_{tertiary} = (4.38/3)\,(13.6/25.6) \times \text{base}$$

$$= 0.776 \times \text{base} = 3.1 \times \text{normal capacity}$$

The generator neutral shift due to the resistor drop will be 7400 volts. If the regulation of the generator be ignored, the maximum low-voltage line voltage to ground will be 7400 plus the leg voltage, or, about 14,000 volts—actually, of course, considerably less.

Neutral shift is nothing but the superposition of a zero sequence voltage. What can be induced in the auto-transformer is small on account of the presence of the delta, in the present case 17 per cent. The high-voltage line voltage will be the low-voltage drop to ground plus the series winding voltage. That is, (14,000 plus 13,600 × 0.577) volts, exclusive of the voltage regulation of the low-voltage lines which tend to reduce this voltage, and exclusive of the zero sequence drop of the series windings which tend to increase it. Thus, 22,000 volts may be taken as the upper limit. Closer calculation will be illustrated in a later case.

### Case 8. (See Diagram 8, Table I)

In the light of the foregoing discussions, the zero sequence network diagram is believed to be obvious.

$$Z_0 + Z_1 + Z_2 = 34.4 + j\,24 + j\,46.4 = 34.4 + j\,70.4$$

$$I_{fault} = \frac{300}{78.5} \times \text{base} = 3.82 \times \text{base}$$

$$= 6470 \text{ amperes}$$

$$I_{generator} = 6470 \times 2/3 \times \frac{25.6}{12} = 9200 \text{ amperes}$$

(Positive and negative sequence only)

$$I_{tertiary} = 3.82/3 = 1.27 \times \text{base}$$

$$I_{common\ wdg.} = 6470\left(-\frac{2}{3} \times \frac{13.6}{12} + \frac{1}{3}\right) = -2740 \text{ amperes}$$

(faulty leg)

On the isolated legs, the resultant of the positive and negative sequence currents is in phase with the negative sequence current and *adds* to it arithmetically. Thus

$$I_{common\ winding} = 6470\left(\frac{1}{3} \times \frac{13.6}{12} + \frac{1}{3}\right) = 4600 \text{ amperes}$$

(isolated legs)

The neutral shift of the auto-transformer is due to the resistor drop, 6470 volts. Since the generator carries no zero sequence currents, its neutral may be taken as of the same order of potential as the auto-

transformer neutral, namely, 6470 volts. The limiting voltages to ground will then be, ignoring regulation, for the low-voltage lines (6470 + 6920), or 13,390 volts; and, for the high-voltage lines, (6470 + 25,600 × 0.577) or 21,200 volts.

CASE 9. (SEE DIAGRAM 9, TABLE I)

Here the zero sequence network is very simple:

$$Z_0 = j\,24 \text{ per cent}$$

$$Z_0 + Z_1 + Z_2 = j\,24 + j\,46.4 = j\,70.4$$

$$I_{fault} = \frac{300}{70.4} \times \text{base} = 4.26 \times \text{base} = 7220 \text{ amperes}$$

$$I_{tertiary} \text{ (only zero sequence)} = \frac{4.26}{3} \times \text{base} = 1.42 \times 75{,}000 \text{ kv-a.} = 5.68 \times \text{normal capacity.}$$

$$I_{generator} \text{ (Positive and negative sequence only)} = 4.26 \times \frac{2}{3} \times \text{base} = 10{,}270 \text{ amperes}$$

As in the preceding case, the resultant of the positive and negative sequence components in the common winding, subtracts from the zero sequence component in the faulty phase, and adds to it in the other phases.

$$I_{common\ winding} \text{ (faulty phase)} = 7220\left(-\frac{2}{3} \times \frac{13.6}{12} + \frac{1}{3}\right) = 3050 \text{ amperes}$$

$$I_{common\ winding} \text{ (Phases II and III)} = 7220\left(+\frac{1}{3} \times \frac{13.6}{12} + \frac{1}{3}\right) = 5130 \text{ amperes}$$

The limiting voltages to ground will be the line-to-line voltages of the respective circuits, ignoring the regulation which of course will be large, so that the indicated upper limits have a very large (may even be considered too large) margin of safety. A closer estimate may be made as illustrated in the following case.

CASE 10. (SEE DIAGRAM 10, TABLE I)

This case is of particular interest in that it brings out clearly how effectively the possible inversion voltages are prevented by the presence of the tertiary delta winding on the auto-transformer.

From a consideration of the zero-sequence impedance network,

$$Z_0 = j\ 1.25 + j\,11.7 = j\,12.95 \text{ per cent}$$

$$Z_0 + Z_1 + Z_2 = j\,12.95 + j\,46.4 = j\,59.35$$

$$I_{fault} = \frac{300}{59.35} \times \text{base} = 5.06 \times \text{base} = 8560 \text{ amperes}$$

The tertiary current is zero-sequence component only, and that flowing through the series winding.

$$I_{tertiary} = (5.06/3)\ (13.6/25.6) \times \text{base} = 0.895 \times \text{base} = 3.58 \times \text{normal capacity}$$

$$I_{generator} = 8560\left(\frac{2}{3} \times \frac{25.6}{12} + \frac{1}{3}\right) = 15{,}000 \text{ amperes (faulty phase)}$$

The currents in the common windings are only positive and negative sequence components. Their resultant in the faulty phase is double that in the other phases.

$$I_{common\ winding} = 8560 \times 0.667 \times 13.6/12 = 6470 \text{ amperes}$$

*Voltages.* The generator terminal voltages may be obtained as follows: On the faulty phase, the resultant of the positive and negative sequence currents is 5.06 ×0.667, or 3.37 times normal, and the zero sequence current is (5.06/3) (12/25.6) or 0.79 times normal.

As the power factor may be considered zero, the drop will be parallel to the faulty phase. The regulation in terms of the low-voltage circuit, will then be

Per cent regulation = 3.37 × 13.5 + 0.79 × 5.7 (Faulty phase) = 50 per cent

The drop in the other phases will also be parallel to the voltage of the faulty phase, with magnitudes as follows:

| | | |
|---|---|---|
| Positive and negative sequence | = − 1.68 × 13.5 | = − 22.7 per cent |
| Zero sequence | = + 0.79 × 5.7 | = + 4.5 per cent |
| Total reactive drop (Parallel to faulty leg) | | = − 18.2 per cent |

The vector diagram is shown in Fig. 5.

The center of gravity of the generator line voltages corresponds to a leg voltage of 54.7 per cent of normal on the faulty phase; and, as the actual leg voltage is 50 per cent, the nominal neutral of the low voltage system is only 4.7 per cent from ground in terms of normal low-voltage leg voltage, that is, 325 volts. The other leg voltages of the low voltage system will be 90.7 per cent of normal.

Considering the high-voltage side, the regulations on the three legs will be as follows:

On the faulty phase:

| | | |
|---|---|---|
| Positive and negative sequence drops | = (5.06/3) 46.4 | = 78.2 |
| Zero sequence drop | = (5.06/3) 12.95 | = 21.8 |
| Total | | 100.0 per cent |

This merely states that the line to ground voltage of the faulty line is reduced to zero, and is a check on the correctness of the computation.

On the other phases,

| | | |
|---|---|---|
| Positive and negative sequence drops | = − (5.06/3) 23.2 | = − 39.1 |
| Zero sequence drop | = + (5.06/3) 12.95 | = + 21.8 |
| Total | | − 17.3 |

The voltages to ground as determined by these regulations, are shown in Fig. 5. Comparing this with Fig. 2, the radical transformation brought about by the tertiary delta winding becomes obvious.

## Discussion

**I. H. Summers:** Equivalent circuits are usually designed to represent networks involving mutual reactance by networks not involving mutual reactance for the purpose of simplifying calculation. There are several methods of accomplishing this.

One of these is the ingenious method Mr. Boyajian uses in this paper, whereby the actual voltages and currents at the terminals are exactly the same as in the actual machinery. This method may be very valuable in certain cases.

Another basis, more commonly used, is to allow all voltage transformations to be understood but not accomplished by the equivalent circuit. In this method a single two-winding transformer without appreciable magnetizing current is represented by a single impedance, the voltage being the same on the two terminals at no load, but showing the correct per cent drop in per cent voltage at load. This method permits the use of the d-c. calculating table for a large class of complicated system problems. The other method involves a more complicated equivalent circuit.

For purposes other than those for which the equivalent circuit proposed by Mr. Boyajian is especially adapted, it may in certain cases be more desirable to represent the zero phase sequence reactances of an auto-transformer by the second method as otherwise, in complicated circuits involving loops and other transformers connected *Y-Y*., it would be necessary to represent all the simpler transformers by the more complicated equivalent network of three branches, one of which is usually a large negative value. This would often prohibit the extensive use of the d-c. calculating table which is usually possible with the other method.

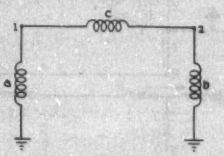


FIG. 1

The zero-phase-sequence equivalent circuit of an auto-transformer is just as simple when made up according to the second method as when made up by the first method, and has the advantage that it can be used with the ordinary known equivalent network for the other parts of the system and used with the d-c. calculating table in complicated networks. Such an equivalent circuit has already been devised and published, perhaps somewhat obscurely, in an appendix of a paper entitled *Progress in the Study of System Stability*.[1] Since this is not a place in which one would ordinarily look for the development of an equivalent circuit for the zero-phase-sequence of an auto-transformer, I take this opportunity of citing the reference for those who wish to compare the methods or make use of the second method in more complicated system analyses. In cases where both methods are applicable, they give identical results.

An interesting application of the method Mr. Boyajian uses is to make an equivalent circuit for an ordinary two-winding transformer when the ratio of transformation is not the same as the ratio of voltage bases used. This case often occurs when a transformer is provided with taps and is operated on a tap which would give a voltage other than normal at no load. A familiar case occurs when two or more transformers are operated in parallel and have different ratios of transformations. Previously it has been common practise to use cut-and-try methods to solve such a circuit.

In Fig. 1, let

$e_1$ be the rated voltage of transformer at no load on side 1 divided by the base voltage of the system connected to side 1. Let $e_2$ be a similar quantity on side 2.

$x_t$ = rated transformer reactance on its own voltage and kv-a. base.

$$x = \frac{x_t}{\text{Rated transformer kv-a. System base kv-a.}}$$

Then the following relations are evident

$$\frac{b}{b+c} = \frac{e_2}{e_1} \tag{1}$$

$$a + b + c = 0 \tag{2}$$

$$x = \frac{1}{e_2^2} \frac{bc}{b+c} \tag{3}$$

Combining (3) and (1)

$$c = e_1 e_2 x \tag{4}$$

and further combining

$$a = \frac{e_1}{e_2 - e_1} e_1 e_2 x \tag{5}$$

$$b = \frac{e_2}{e_1 - e_2} e_1 e_2 x \tag{6}$$

Thus, Equations (4), (5), and (6), determine the three branches of the equivalent circuit of Fig. 1.

Use of this equivalent circuit makes the problem of transformers with different ratios operating in parallel, a simple, straightforward circuit problem, involving no cut-and-try procedure. It makes no difference if the transformer has an "out of phase" tap.

Thus for example $e_1 = 1.0$ and $e_2 = 1.1 + j\,0.20$ means that the transformer has a 10 per cent in-phase boost and a 20 per cent quadrature boost.

In this case the equivalent circuit will contain both positive and negative resistances and reactances. However, this offers no analytic difficulty and the method leads to correct voltages, currents, and power factors by straightforward calculation.

**J. E. Clem:** Institute papers are primarily presented to give information to aid industry in solving the problems with which it is confronted. The paper by Mr. A. Boyajian was written to show the effect of an auto-transformer with a tertiary winding on line to ground faults and would be of considerably more practical use if more of the theory of the equivalent circuit of the auto-transformer for zero phase sequence currents had been included.

The equivalent network of an auto-transformer for zero phase sequence current can be easily built up from fundamental principles as follows. In Fig. 2 and Fig. 5 herewith is shown an auto-transformer with neutral grounded and a generator connected to the low-voltage lines *L* in Fig. 1, and to the high-voltage lines *H* in Fig. 4, and the fault occurs on the high-voltage lines. The zero phase sequence currents flow identically in both diagrams. The currents in flowing from the neutral *N* to the higher voltage terminal *H* must overcome impedance of the total winding between the points *N* and *H* with the tertiary winding as the secondary. This impedance is usually expressed as $Z_{sc.t}$ and for this problem must be given in ohms on the basis of total turns, that is $(n_s + n_c)$. The applied voltage is the normal voltage to ground of the faulted line.

In Fig. 3 and Fig. 6 the auto-transformer is shown with ungrounded neutral but the generator is grounded and the fault occurs on the other side of the auto-transformer from the generator. In each case the path of the zero phase sequence currents is through the series winding and the impedance to be overcome

1. I. H. Summers and J. B. McClure, A. I. E. E. Quarterly TRANS., Vol. 49, Jan. 1930, p. 132.

is the impedance of the series winding with the tertiary as secondary. This is usually expressed as $Z_{st}$ and in this case it is to be given in ohms based on the turns in the series winding, that is on $n_s$. The applied voltage is the normal voltage to ground of the faulted line.

In Fig. 4 and Fig. 7, the auto-transformer is shown as neutral grounded and the fault occurs on the low-voltage lines. In each case the path of the zero phase sequence currents is through the common winding and the impedance to be overcome is the impedance of the common winding with the tertiary as secondary. This is usually expressed as $Z_{ct}$ and for this problem is to be given in ohms on the basis of the turns in the common winding, that is $n_c$. The applied voltage is the normal voltage to ground of the faulted line.

A little consideration will show that the impedance offered by an auto-transformer to zero phase sequence currents involves no transformation from one circuit to another but is in the nature of a series reactance coil with short circuited secondary. For each of the three paths through the auto-transformer the tertiary serves as the short circuited secondary. Since these zero phase sequence impedances are series impedances the equivalent network should initially be expressed in the form of natural ohms, that is, on the basis of the turns of the winding through which the current flows. Once the network has been worked up in this manner the ohmic values should then be transferred to percentage values, basing the percentages upon the voltage of the circuit that is faulted.

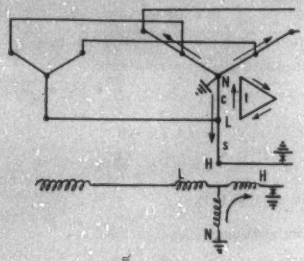


Fig. 2

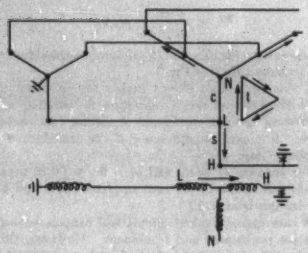


Fig. 3

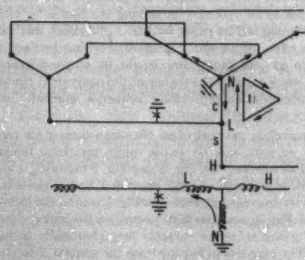


Fig. 4

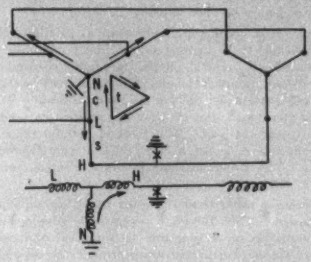


Fig. 5

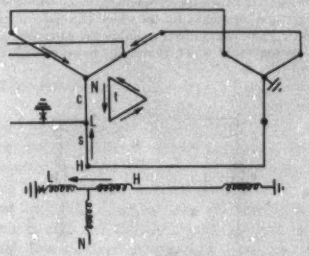


Fig. 6

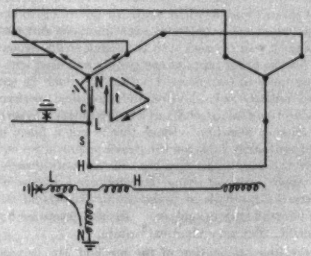


Fig. 7

An equivalent network for the zero phase sequence impedances of an auto-transformer was given in the paper by Summers and McClure.[1] This network is practically the ordinary equivalent

circuit diagram of an auto-transformer with an allowance made for an impedance between the neutral of the auto-transformer and ground. The equivalent network as worked out in Figs. 2 to 7 is shown in Fig. 8A, and the Summers and McClure network is shown in Fig. 9.

If the neutral of the auto-transformer is solidly grounded each

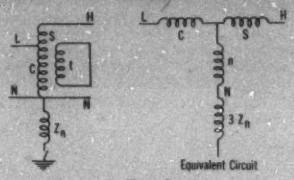


FIG. 8

$$Z_s = \frac{1}{2}(Z_{sc} - Z_{cn} + Z_{ns})$$

$$Z_c = \frac{1}{2}(Z_{cn} - Z_{ns} + Z_{sc})$$

$$Z_n = \frac{1}{2}(Z_{ns} - Z_{sc} + Z_{cn})$$

$Z_{sc} = Z_{st}$ in ohms based on $n_s$
$Z_{cn} = Z_{ct}$ in ohms based on $n_c$
$Z_{ns} = Z_{sc+t}$ in ohms based on $(n_s + n_c)$

$$Z_s = \frac{1}{2}(Z_{st} - Z_{ct} + Z_{sc+t})$$

$$Z_c = \frac{1}{2}(Z_{ct} - Z_{sc+t} + Z_{st})$$

$$Z_n = \frac{1}{2}(Z_{sc+t} - Z_{st} + Z_{ct})$$

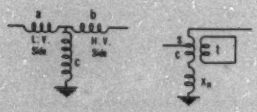


FIG. 9

"FIG. 32A—THE EQUIVALENT CIRCUIT FOR THE ZERO-PHASE IMPEDANCE OF AN AUTOTRANSFORMER

$$c = \frac{X_{sc+t} + X_{ct} - X_{sc+c}}{2} + K_c X_n \qquad (72)$$

$$b = X_{sc+t} + K_c^2 X_n - C \qquad (73)$$

$$a = X_{ct} + X_n - C \qquad (74)$$

Where $K_c$ is voltage in the common winding divided by voltage in the series plus common windings and $X_n$ is expressed on the low voltage base."

The following simplification is suggested.

$$c = \frac{1}{2}(X_{t+c} - X_{c+sc} + X_{sc+t}) + \frac{n_c}{n_t} X_n$$

$$b = \frac{1}{2}(X_{sc+t} - X_{tc} + X_{c+sc}) - \frac{n_c n_s}{n_t^2} X_n$$

$$a = \frac{1}{2}(X_{c+sc} - X_{sc+t} + X_{tc}) + \frac{n_s}{n_t} X_n$$

network gives the same impedance for the path between the neutral and the high-voltage or the low-voltage lines. For the path between the high-voltage terminal and the low-voltage terminal (neutral ungrounded) the Boyajian diagram gives the zero phase sequence impedance as the natural impedance between the series and tertiary winding while the other diagram seems to give it as the impedance between the series common and common windings, to which is added a factor which brings in the effect of the neutral grounding impedance. However, this apparent inconsistency results only if the diagram is interpreted to mean that the branch $c$ is disconnected when the neutral is

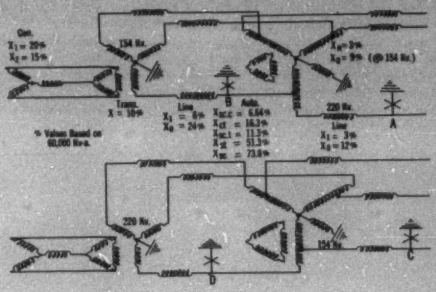


FIG. 10

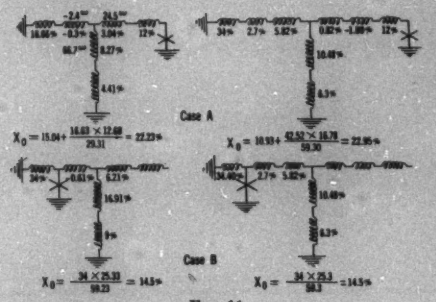


FIG. 11

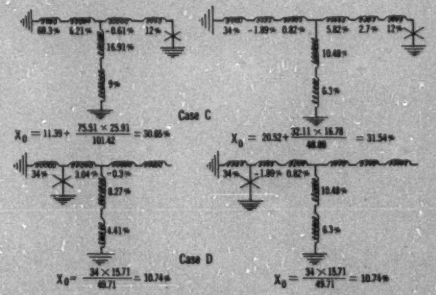


FIG. 12

ungrounded. If the neutral of the auto-transformer is ungrounded $Z_n$ becomes infinite and it seems that the impedance for the path between the high-voltage and low-voltage lines should therefore become infinite. Such is not the case, however,

as can be demonstrated from Equation (67) in the Summers and McClure paper. It is evident that when the Summers and McClure diagram is used the branch $c$ must always be considered as connected to ground regardless of whether or not the neutral is ungrounded.

To show the equivalence of the two methods the zero sequence impedance for the circuit shown in Fig. 10 has been worked out by both methods and the results given in Figs. 11 and 12.

**A. Boyajian:** A given circuit representation may not necessarily be the only possible or the most convenient one for all purposes, and the scheme presented in this paper was not so intended. Every calculator will have to choose the method which serves his particular purpose best. However, in making this choice his greater familiarity with one of the methods is likely to be the determining factor. This latter factor is very powerful, and accounts for the slowness with which the profession has been adopting such excellent methods as, for instance, the "Method of Symmetrical Components" and the "Heaviside Operational Calculus."

Mr. Clem's comment that a more complete discussion of the theory would have made the paper more useful is probably true. But authors are always faced with the unpleasant but necessary job of pruning their papers down to the ever diminishing limits set by the Institute publications committee, and in the present case advantage was taken of the fact that a very thorough discussion of the theory was published in the *General Electric Review* for Feb. 1929, pp. 110-126, reference to it being given in a footnote in the present paper.

# Controlling Power Flow with Phase-Shifting Equipment*

BY W. J. LYMAN†

Associate, A. I. E. E.

*Synopsis.—In the operation of an electric power distributing system involving various kinds of networks, a fundamental necessity is that each transforming and transmitting unit carry a reasonable share of the total load. In the case of a single system that has been developed in a coordinated manner the problem of load division has not in general been troublesome and has been solved by judicious selection of parallel circuits, use of reactors, proper system set-up, etc. The advent of inter-company connections has brought together systems of varying characteristics, changed the relation between the basic elements involved, and in some cases has made difficult the control of power flow over tie lines small in comparison to the systems which they unite.*

*It is the purpose of this paper to discuss the case of load control where closed rings or parallel path circuits are involved. After briefly reviewing the principles of voltage phase angle and power flow, a description is given of some actual tests performed on a very large interconnected system with a 250-mi. transmission loop, involving five power companies and a total generator capacity well over 1,000,000 kw. The results of these measurements are analyzed for the purpose of checking theoretical against actual values and forming a basis for the solution of problems of a similar nature.*

* * * * *

## Introduction

It is a generally recognized fact that one of the most important and sometimes the most perplexing problems encountered in the operation of inter-company connections is that of securing accurate and flexible means of regulating power flow. This is a problem which rapidly becomes more complex with the increase in the number of systems combined through interconnection into one group. Inter-company contracts, tie line capacity, and internal system limitations often require that the load exchanged at the various points be regulated within rather definite limits. Conditions have arisen where the maintenance of proper load division has been very difficult if not impossible and attention has already been directed to the solution of this important problem. Although efforts are being made to broaden interchange contract requirements it is sometimes difficult to avoid exceeding physical limitations and to secure the most efficient over-all operation.

It is the purpose of this paper to discuss experimental and analytical methods by which the fundamental problem of load control may be attacked.

At this point it may be well to mention that the problems of inter-company connection differ only in magnitude from conditions existing within most systems and cases undoubtedly exist where the same treatment might be applied to secure more flexible and economical inter-company operation.

## The Problem

When two companies are tied together at one point and have no other interconnection, the problem of load control is relatively simple. Should Company I generate say 10,000 kw. in excess of its own load, there can be but one result; the 10,000 kw. must go over the tie line to Company II. Obviously, if this exchange is to be secured without frequency variation, the increase in generator output by Company I must be carefully coordinated with a corresponding decrease in output of prime movers by Company II. The maintenance of adequate system stability, power factor control, etc., are then the chief problems. If Company II is connected in turn to a third Company III, the three not forming a closed loop, the problem of load control is very similar but somewhat more involved. Proper apportionment can be secured through governor speed adjustments for any number of series connections, the regulation becoming more difficult as the number of companies increases.

If, however, the interconnected systems form a closed loop, an entirely new element enters the problem and results in conditions which cannot be corrected by governor adjustment. In other words, if the three companies in the preceding example are connected to form a triangle, an adjustment of load on the tie between I and II would result in power flow in the other two lines. An investigation soon reveals the fact that the three exchanges cannot be independently controlled and that an analysis and solution is best facilitated by the conception of voltage-phase relations.

## Phase Angles

Considering once more the case of two interconnected companies, the conditions which exist are practically identical with those which accompany the transmission of power over any typical circuit. This is illustrated by the single-phase vector diagram of Fig. 1. It is apparent that the transmission of power from I to II results not only in a difference in magnitude between terminal voltages (in this case $V_{II}$ is less than $V_I$), but also a shift in phase angle denoted by the angle $\theta$. In actual practise the phase shift is not always apparent, but the drop in voltage magnitude is often objectionable

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†Electrical Planning Engineer, Duquesne Light Company, Pittsburgh, Pa.

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and can be readily corrected by transformer taps, voltage regulators, or power factor control.

The addition of a third system to form a loop is illustrated in Fig. 2. With the same interchange of 10,000 kw. from I to II and with the tie line 2-3 open, voltage relations will be the same as in Fig. 1. With no

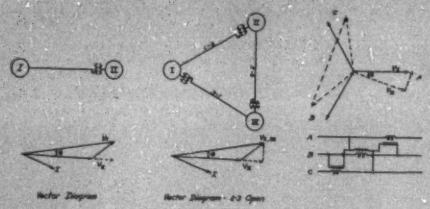


Fig. 1 Fig. 2 Fig. 3

Figs. 1, 2, 3—Voltage-Phase Displacement and Correction

Fig. 1—Two systems
Fig. 2—Three systems
Fig. 3—Phase rotator

transfer between I and III, their voltages will be practically equal and in phase. By means of regulator adjustments, it would be possible to secure voltages at the open circuit, equal in magnitude but not in the same phase position. Reference to Fig. 2 illustrates this condition and shows that there would be across the open switch a voltage about 90 deg. out of phase with the line voltage. A convenient method of attack is to consider that closing the switch will superimpose on the existing loadings around the loop a circulating power determined by the magnitude of the quadrature voltage and the total effective impedance, the direction of flow being from leading to lagging voltage.

Conditions similar to that just outlined often arise in the operation of actual systems. Sometimes the differences in phase angle at a tie point are such as to make satisfactory operation impossible. These variations are produced as a result of conditions of unsymmetrical system set-up and loading such as: difference in per cent reactance of cable and open wire lines, unequal number of transformations, location of power plants near the end of the transmission system, and non-uniform loading.

In order to prevent this circulating power which might upset exchange values, voltage conditions, and loading around the circuit, it would be necessary to introduce a quadrature voltage any place in the loop equal to the inherent displacement produced by circuit loading. A simple method of producing this correction would be to connect transformers as in Fig. 3. By connecting the secondary of a regulating transformer in one phase and the primary across the other two phases, a voltage at 90 deg. may be obtained. It can be shown that for ordinary transmission circuits, the power flow is nearly proportional to the phase displacement of the voltage. It is feasible, therefore, to obtain accurate and flexible control of power exchange by supplying some equipment which will produce the required quadrature voltage in adjustable amounts and direction.

Adding a voltage at right angles to the line voltage begins to change the magnitude as well as the direction for the larger angles. Because of this fact it may be economical to combine voltage control with phase shifting in one equipment. This can readily be achieved by one tap changing transformer and two sets of series transformers using star and delta connections. The basic principle is illustrated in Fig. 4.

By laying out the transmission ring with all impedances and given simultaneous loads it is possible to calculate the required amount of phase shift for any assumed set of conditions. In this connection it should be emphasized that the so-called "velocity of electricity" has no effect on the phase displacement even for very long lines. The "velocity" of 186,000 miles per second applies only to transients and not to steady-state conditions.

Obviously, the success of any such installation depends on the accuracy and foresight represented in the phase-angle determination. It was for the purpose

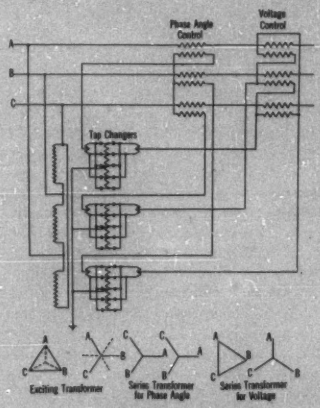


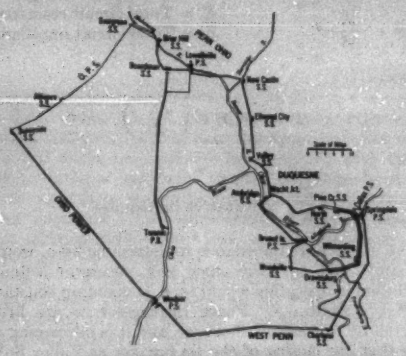

Fig. 4—Diagram of Equipment for Shifting Phase-Angle and Regulating Voltage

of establishing a workable method of making such calculations and checking theoretical and actual values that a test was performed and analyzed on a high-tension transmission ring about 250 mi. around and involving five systems.

The following discussion, it should be remembered, pertains only to cases where a closed loop or parallel path network exists.

## Description of Tests

The high-tension transmission ring which was investigated on this test is shown simplified on the diagram of Fig. 5. The systems of the West Penn Power Company, Ohio Power Company, Ohio Public Service, Pennsylvania and Ohio Power and Light Company, and the Duquesne Light Company were


Power Ohio
O.P.S.
Duquesne
Shadyside
Wilkins
Mansfield
Beaver
Valley
Mitchell
Cheat
Cabot
Conemaugh
Saxton
Bedford
Cambria
Altoona
Tyrone
Lewistown
Sunbury
Hunterstown
Gettysburg
Carlisle
Chambersburg
Hagerstown
Martinsburg
Harper
Charleroi
Cheat
Scale of Miles
Miles
Line of Power Flow
Line of Power Flow
Line of Power Flow

side of the breaker while the potential for the voltage coil was secured through a 90 deg. displacement transformer from a potential on the other side of the line breaker. Thus when the two line voltages are in phase, currents in the two elements of the wattmeter will be 90 deg. out of phase and the reading will be zero. This point can be accurately checked with the circuit breaker closed and the method is very sensitive for small angles. Fig. 6 shows the diagram of connections for the wattmeter method. An expression for determining the angles from the wattmeter, voltmeter, and ammeter readings is:

$$\text{Sin}\ \theta = \frac{W}{V\,I}$$

## Analysis of Results

*Phase Angle.* The first comparison made was between the theoretical phase angle and the measured value. Accurate descriptions were secured of transmission line lengths, conductors, and spacing and transformer capacity and percent reactance. From this information, the ohmic values of impedance were derived for each section of circuit. In this way it was possible to construct a complete vector diagram for the loop and show the various voltage relations. Fig. 7 shows the results of one of the sets of readings for which the calculations show an angle of 17 deg. as compared with a measured angle of 19.6 deg.

On Fig. 8 is a reproduction of the recording wattmeter chart of interchange power at Valley Substation. There was considerable fluctuation and it is obviously impossible to get readings taken a few minutes apart to check accurately.

*Equivalent Reactance.* Another check was secured by comparing the actual total effective impedance around the ring as determined from a physical description of the apparatus with the effective impedance calculated from the readings on the test. Thus, on this test, one of the voltmeters indicated a vector difference of 22,800 volts with the breaker opened, and the wattmeter indicated 16,300 kw. resulting power flow when the breaker was closed. These quantities result in an effective impedance of 90.5 ohms as compared with a figure of 82.7 ohms derived from transformer and line characteristics.

These values of so-called "effective" impedance may be expressed as $\frac{Z^2}{X}$ and thus vary slightly from the true impedance. The reason for this is readily apparent when we consider that although the current caused by the quadrature vector voltage difference due to the phase displacement is equal to that voltage divided by the true impedance $\left(i.\,e.,\ I = \frac{V}{Z}\right)$, this current is out of phase with the line voltage and must be multiplied by $\frac{X}{Z}$ to get the true power component.

Thus:

$$P = \sqrt{3}\,E\,I\cos\theta$$

$$I = \frac{V}{Z}$$

$$\cos\theta = \frac{X}{Z}$$

$P$ = Watts
$E$ = Line voltage
$V$ = Quadrature voltage (neutral terms)
$X$ = Total circuit reactance
$Z$ = Total circuit impedance

Hence:

$$P = \sqrt{3}\,E\,V\left(\frac{X}{Z^2}\right)$$

And:

$$\frac{Z^2}{X} = \text{Effective impedance}$$

The use of pure impedance to determine kv-a. would probably lead to error since any generator voltage regulators in operation would tend to maintain constant voltage magnitudes. Phase displacements are little affected by this action, however, and it is interesting to note that the closing of the tie breaker at Valley Substation and the resulting shifting of power flow had no effect on any of the power plant kw. outputs.

In a sense, the introduction of a quadrature voltage in a closed loop causes a circulation of power through each section, increasing or decreasing each of the previous loads by the same amount. This is illustrated in Fig. 8 where it is apparent that the same change in power appeared in the Valley-Ellwood tie, the Colfax-Springdale tie, and the Canton-Alliance circuit. In this manner it is possible to determine the voltage that must be introduced in a loop to produce any desired change in loading.

Table I was prepared as a summary of the results of the five tests showing the comparisons between calculated and actual values and other important features to be noted. Complete readings were not secured with which to calculate the phase angle for the first and last tests. The agreement between measured and calculated angles in the other three cases is quite close and the average effective impedance from test is only 7 per cent above the value derived from circuit characteristics. The variation in figures for kw. per degree is about 25 per cent above and below the average. These inconsistencies are not unreasonable when allowance is made for the fluctuating nature of the interchange power.

## Application

Where systems of the same frequency are interconnected directly or through transformers to form a closed loop, the load control would probably take the form of a special type of regulator equipped for tap changing under load and connected for quadrature

TABLE I

EXHIBIT OF RESULTS DERIVED FROM INTERCONNECTION TEST

| Test No. | Phase angle (degrees) Measured Vm. | Wm. | Average | Calculated | Total effective impedance $\frac{Z^2}{X}$, ohms Circuit characteristics | From test | Interchange at Valley S. S. Kw. | To | Kilowatts per degree (metered) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.0 | 4.3 | 4.15 | .. | 82.7 | 87.9 | 4,800 | P & O | 1157 |
| 2 | 20.3 | 18.8 | 19.65 | 17 | 82.7 | 90.5 | 16,300 | P & O | 830 |
| 3 | 8.0 | 7.5 | 7.75 | 9 | 82.7 | 80.9 | 7,200 | P & O | 930 |
| 4 | 4.3 | 3.2 | 3.75 | 5 | 82.7 | 86.0 | 3,600 | D. L. | 960 |
| 5 | 11.3 | 10.3 | 10.80 | .. | 82.7 | 96.8 | 8,400 | D. L. | 778 |
| | | | | Ave. | 82.7 | 88.4 | | | 931 |

action. Since the addition of a voltage at right angles makes a slight change in resulting magnitude, the power control could economically be combined with the ordinary voltage regulator to give complete flexibility. This apparatus would be very similar in construction and operation to the transformers which are designed for tap-changing under load and which have been developed in the last few years to a high degree of reliability. Thus the phase shifting regulator or transformer does not represent an entirely new piece of equipment but can be built and applied without extensive development work.

If voltage and reactive conditions are undesirable on either or both systems indicating the possible necessity for synchronous condensers, a motor generator set of the synchronous-synchronous frame shifting type might be used which would at the same time control power interchange. However, conditions would have to be unusual to warrant such an expense.

It is a well-known fact that a three-phase voltage regulator incidentally produces a phase shift and the application of two such devices in series will make possible the control of power and wattless kv-a. This scheme could be applied to low-voltage, medium capacity tie lines but probably is not economical in large applications. An installation of this type has been reported in operation on an extensive power system in Texas.

Where the interconnection is between systems of different frequency a motor-generator set is required, and power control can be secured by a frame shifter for the synchronous type or by use of the asynchronous machine if it is not necessary to maintain rigid phase relations.

In any event, the necessary range of phase shift can be readily determined by the method outlined and it should be remembered that this method of analyzing power flow problems and selecting equipment characteristics applies equally well to conditions within a system itself. Diversity of supply and differences in circuit characteristics may result in non-uniform loading and inefficient use of existing facilities. Conditions very likely exist where the installation of additional capacity could be obviated if inexpensive phase shifters could be applied.

## Discussion

**C. J. Sittinger:** The operating requirements of phase-shifting equipment for purposes of controlling power flow over looped parallel circuits as encountered quite generally in interconnected systems are dependent primarily on three factors, *viz:*

1. The total impedance of the circuit to be controlled and ratio of the total impedances of the parallel circuits.

2. The range and direction of power flow and closeness of control desired.

3. The geographical and seasonal distribution of load throughout that portion of the interconnected systems involved in the loop.

For purposes of illustrating the first condition, assume that the total impedance of main branch of the loop over which a definite amount of power is to be sent is $Z \angle \varphi$ expressed as a per cent of the voltage drop corresponding to the kv-a. to be transmitted, and includes the impedance of the phase-shifting equipment.

Let $m \angle (n-1)\varphi$ be the ratio total impedance of the other branch of the loop to the impedance of the main branch, so that its impedance will be $m Z \angle n\varphi$

$$\text{Parallel impedance} \quad \frac{Z \angle \varphi \times m Z \angle n\varphi}{Z \angle \varphi + m Z \angle n\varphi} = \frac{m Z \angle n\varphi}{1 + m \angle (n-1)\varphi}$$

$$\text{Series impedance} \quad Z \angle \varphi + m Z \angle n\varphi = Z \angle \varphi (1 + m \angle (n-1)\varphi)$$

Without adjustment of the phase-shifter, the transmission of the given base load at a given power factor, cos $\theta$, will cause a voltage drop between the two ends of the loop of

$$1.00 \sqrt{\theta} \, \frac{m Z \angle n\varphi}{1 + m \angle (n-1)\varphi} \text{ per cent}$$

The amount of power diverted from the main branch to the other branch of the loop would then be

$$\frac{1.00 \sqrt{\theta}}{m Z \angle n\varphi} \times \frac{m Z \angle n\varphi}{1 + m \angle (n-1)\varphi} = \frac{1.00 \sqrt{\theta}}{1 + m \angle (n-1)\varphi}$$

The voltage which must be inserted in the series circuit of the loop in order to neutralize this power flow would be

$$\frac{1.00 \sqrt{\theta}}{1 + m \angle (n-1)\varphi} \times Z \angle \varphi (1 + m \angle (n-1)\varphi) = 1.00 \sqrt{\theta} \times Z \angle \varphi$$

This voltage is just equal and opposite to the drop in the main branch due to the entire load, and results in equal voltages at both ends of the loop, which, of course, is the condition necessary for no diversion of power, or zero flow in the other branch. The only factors, therefore, which need be taken into account in a simple loop of fixed impedance without intermediate loads, are the amount of load, the power factor, and the total impedance of the main branch.

Assuming a specific case of load at unity power factor, 10 per cent impedance and a line angle of 75°, which would not be

uncommon if transformers were included in the circuit, the percent corrective voltage would be 10 $\underline{/75^\circ}$ and the phase angle shift would be $\tan^{-1} \dfrac{10 \sin 75^\circ}{100 + 10 \cos 75^\circ} = \tan^{-1} \; 0.0922 = 5^\circ - 16'$

For power transmitted in the opposite direction, the same corrective voltage would be necessary, but the phase angle shift would be $\tan^{-1} \dfrac{10 \sin 75^\circ}{100 - 10 \cos 75^\circ} = \tan^{-1} 0.0982 = 5^\circ - 36'$

For half the power flow the per cent corrective voltage would be 5 $\underline{/75^\circ}$ and the phase-shift $\tan^{-1} 0.0469$ or $2^\circ - 41'$.

It is evident that, aside from other considerations, the total phase-shift for a reasonable power flow is relatively small and if this were the only factor, the specification of phase-shifting equipment would be a simple matter.

Referring to the amount of power diverted when operating without phase-shift control, which was found to be $\dfrac{1.00 \sqrt{\theta}}{1 + m \underline{/(n-1)\varphi}}$, it will be seen that the amount of diversion is dependent only upon the ratios of the impedances of the branches and the total power flow. If $\varphi = 75$ deg. as in the preceding example and the impedance in the diverting branch is twice that of the main branch with a line angle of 60 deg., so that $m = 2$ and $n = 0.8$, then for a unity power factor load, the power diversion will be

$$\frac{1.00 \sqrt{\theta}}{1 + 2 \underline{/0.2 \times 75^\circ}} = 1.00/2.93 + j\,0.52 = 0.330 - j\,0.059$$
$$= 0.335 \underline{/10^\circ - 9'}$$

Similarly if the impedance in the diverting branch is one-half that of the main branch with a line angle of $82^\circ - 30'$ so that $m = 1/2$ and $n = 1.1$ then for unity power factor load the diversion will be

$$1.00/1 + 1/2 \underline{/-0.1 \times 75^\circ} = 1.00/1.496 - j\,0.065$$
$$= 0.676 + j\,0.029 = 0.677 \underline{/2^\circ - 27'}$$

With a 17-tap phase-shifter of the type outlined by Mr. Lyman, employing reactors in the tap changing equipment, a change of one position with a 50,000 kw. load would cause an average shift of 1030 kw. in the first case and 2110 kw. in the second case. For other total loads, the amount of load shift would be proportionate. It is obvious that fine control with this type of equipment is not possible and must be supplemented by some readjustment of voltages throughout the system if no power is to be diverted from the main branch. It is also evident that the impedance ratio of the two branches of the load and the amount of power to be delivered have a marked effect on the closeness of control possible.

As pointed out, the discussion up to now has been confined to a simple loop without intermediate loads. The more usual case consists of a continuous line of one or more circuits between two points, with or without one or more transformations in voltage, and numerous points along the line where power is supplied to the system or loads are taken off. From each end of this line there may be other lines running toward each other over another route and which could form the nucleus of a second connection between the two points in question. Due to distribution of loads and generating stations, the open ends of the lines will as a rule have considerable inherent phase displacement as well as differing in voltage. If the interconnection between the two points joins a hydroelectric district with a steam generating district, the inherent phase displacement will vary considerably from season to season depending upon the amount of water available for hydroelectric generation.

To complete the loop by closing the open ends of these lines and subsequently control the flow of power over this loop by means of phase-shifting equipment, there would be required, in addition to the phase-shift necessary for load control, a further phase-shift to take care of system differences. In other words, it must supply additional voltage at the proper angle so that the open ends of the lines will match, thus permitting closing of the loop without disturbing the system balance. This phase-shift may, and usually will be of greater magnitude than the phase-shift necessary for load control and it may be positive or negative with respect to the latter. Fig. 7 of Mr. Lyman's paper illustrates this condition very clearly, and further indicates that lengthy and laborious computations may be required in order to determine the probable necessary range of operation of phase-shifting equipment. The difference between the calculated and the actual phase displacement is due primarily to the fact that the various impedances cannot be determined accurately. The reactance of a conductor is affected by proximity to conductors of another circuit. The reactance of a transformer depends upon the particular taps used. This latter reactance is especially subject to wide variation on different taps in the case of auto-transformers and phase-shifters. On a particular case which the writer has been studying, the reactance of the phase-shifting equipment varied from 3.4 per cent to 5.5 per cent.

Referring again to the question of closeness of control it was pointed out that the angular shift necessary to obtain proper power control is ordinarily quite small,—on the order of 3 deg. to 5 deg. The phase-shifting equipment must, however, supply the necessary voltage component to permit the connected systems to match. With an inherent difference of 15 deg., a total phase-shift of 20 deg. may be necessary in one direction, and possibly 10 deg. in the opposite direction when seasonal load change reverses the inherent phase difference. If the tap changing equipment is connected to take the full range of the phase-shifter or 30°, then control of load will be six times as great. For the typical cases given previously a change of one position on the tap changer would cause average load shifts of 6200 kw. and 12,70 kw. respectively for a 50,000 kw. load, compared to 1030 kw. and 2110 kw. in the case of the simple loop without intermediate loads.

It is hoped that this discussion will give a clearer picture of the conditions under which phase-shifting equipment must operate. Two induction regulators in series will give excellent control inasmuch as an infinite number of steps is possible. However, if large changes of in-phase voltage are necessary the capacity for phase-shift is appreciably reduced. Indicators would be necessary in order to show the position of the moving coils, otherwise it would be difficult to determine what changes have been made. The cost of such equipment, especially for higher voltages, is usually prohibitive. The regulating transformer type of phase-shifter is mechanically a much simpler piece of equipment, having no moving parts except the tap changer. The ability to shift phase is only affected in a small way for wide changes of in-phase voltage and the cost of such equipment is relatively small, since it consists essentially of transformers and their appurtenances. For interconnections involving appreciable inherent phase differences, however, this equipment is open to the objection that close control of load is not possible with the designs thus far offered.

It appears that three methods of overcoming this difficulty are possible. The first would be to provide the exciting transformer with from fifty to a hundred or more taps, or three to six times that now offered, but only the phase-shift tap changers would be involved. These should be brought to the stationary member of some contact making device such as a drum controller. The seventeen taps of the tap changer and the neutral point would be brought to the moving member so as to permit manual selection of any seventeen successive taps, their range being selected to allow sufficiently close control of the load.

Instead of a multiplicity of taps, the standard seventeen taps could be provided except at the center where fourteen more taps would be added, which, together with the three

standard center taps would span the proper portion of the regulating transformer to give the fineness of control desired. The load tap changer would then be permanently connected to the fine taps. To take care of the wider inherent phase displacements due to system differences, the neutral or zero point would be connected to the movable arm of a manual tap changer to which the standard taps would be connected. A combination of this scheme with the first would make possible double the phase shift with a given regulating transformer.

As another alternative scheme, a second phase shifting series transformer with tap changer equipment is suggested supplementing the main transformer, but of such a ratio that its voltage would be one-third to one-sixth (or perhaps even as low as the voltage obtained in the main phase-shifting transformer when spanning three taps). This would require three sets of tap changers all working on the same taps of the exciting transformer; but this does not seem to involve any serious complication or much added expense, and would certainly add much to the flexibility required of such equipment in order to make it of practical use.

**C. A. Powel:** Mr. Lyman shows in his paper that if the voltage and power readings are carefully made, the power flow around a loop can be readily calculated and the results depended upon. Now that a-c. calculating boards are available, the large amount of arithmetical work involved in such calculations can be eliminated.

Mr. Lyman also shows that 17 deg. phase displacement existed across the breaker at Valley substation, and that when the breaker was closed, this same angle existed internally in the loop, causing a circulating current largely in phase with the voltage. This can perhaps be likened to a short-circuited synchronous generator where the terminal voltage disappears and is replaced by the short-circuit current. As Mr. Lyman points out, if the circulating current, in seeking the path of least impedance, leads to undesirable results, such as overloading cables or upsetting contractual exchange values, the situation can be easily remedied by phase angle control equipment.

**W. J. Lyman:** One thing which was not mentioned in presenting the paper is the possible combination of this scheme of phase angle control with voltage control as is being used to a very large extent at the present time. In other words, the equipment necessary to get this power control as described is not radically new. It is simply an alteration in the apparatus which is already quite standard. This is probably one of the main elements of value in the scheme.

Another important fact is that only one device of this nature is required for any one loop. In the system shown in the paper, although there are three companies and three tie lines, only one regulator is necessary.

The last thing I want to mention is that the increments of angular displacement provided for by the equipment must be in accordance with the total impedances involved in the loop.

# Electrically Welded Structures
## Under Dynamic Stress

BY MORRIS STONE* and J. G. RITTER†
Non-member Non-member

*Synopsis.—In the general application of welding to various types of constructions, those structures carrying variable stress have been least adapted to fabricated construction. In the present paper it is shown that by properly considering such factors as maximum working stress, residual welding stresses, and stress concentration, it is indeed possible to weld any type of structure without fear of trouble. Many various cases of such structures are described as to their method of fabrication and success of operation.*

THE general application of arc welding to all types of construction has extended rapidly during the past few years, but not in the field where dynamic stresses were imposed because of the lack of information on the fatigue resistance characteristics of such welded structures. Even as far back as 1911, Stanton[1] and Abell[2] after making a series of Wohler tests of welded material, advised against welds for variable stress applications. However, recent investigations such as those described in this paper, justify a more general increase in the use of welding under these conditions.

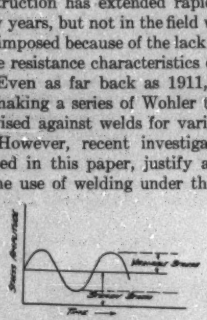


FIG. 1—DIAGRAM ILLUSTRATING COMBINED STEADY AND VARIABLE STRESS

The general nature of the action of weld metal under fatigue is much the same as for virgin metal, except that lower test values are obtained, and less consistency of results. If we consider, first, the pure weld metal, we find endurance limit values varying from ± 9000 lb. per sq. in. to ± 22,000 lb. per sq. in., depending on the care in making the weld, its porosity, size of weld, etc. Dustin,[3] commenting on the fatigue of welds, states the difficulty in obtaining consistent values, due to blow holes, slag inclusion, etc. This aspect of testing has forced the use of large size test pieces for obtaining fatigue values on weld material.[4] The reason for such a necessity can be appreciated when one considers the very nature of a weld, which is porous and non-homogeneous. The effect of a small surface hole will be much more serious on a small specimen than on a large—so that in general, one should expect higher and more consistent results from large size fatigue specimens.

An active comparison of endurance limits as determined for varying sizes of welds is the object of a present research, and we need not be surprised to find the larger size welds showing lower endurance limits. Such an effect can be explained by the injurious influence of residual stresses in the larger welds, which do not occur in the smaller welds, where they can be relieved by the heat of subsequent welding. Such results would indicate opposite tendencies to those published[5] for tensile strengths, yield points, etc.

From the widely differing values of endurance limit, it is entirely feasible to count on the value of ± 15,000 lb/in². This, it will be realized, must be compared with endurance limits of ± 25,000 lb. per sq. in. for mild carbon steel to as high as ± 60,000 lb. per sq. in. for some alloy steels.

Most structures are rarely subjected to purely variable stress—alternating between equal values of tension and compression—but rather combinations of steady and variable components as illustrated in Fig. 1. The failure of metals under such conditions is still a matter of investigation, and is only now becoming clarified from the point of view of design utility.

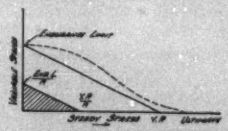


FIG. 2—CURVES SHOWING RELATION BETWEEN VARIABLE AND STEADY STRESSES

One of the most common stress conditions, and probably the most elementary for a material study, is that of simple tension or compression superimposed by a variable stress of smaller magnitude. Experiments, investigating failure under various ratios of steady to variable stress, have been carried out for many years, with certain characteristic relationships becoming evident. If we plot steady stress as abscissas versus variable stress as ordinates,[6] the experimental curve of

*Mechanical Engineer, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

†Welding Engineer, Westinghouse, Elec. & Mfg. Co., East Pittsburgh, Pa.

1. T. E. Stanton and J. R. Pannell, I. C. E., Dec. 1911.
2. W. S. Abell, I. C. E., March 1919, in an investigation for Lloyd's.
3. H. Dustin, *Revue Universelle des Mines*, Dec. 1926.
4. R. E. Peterson, "Fatigue Tests of Large Specimens." A. S. T. M., June 1929.
5. G. Lobo, "Strength of Butt Welds," *Journal of Amer. Welding Society*, April 1929.
6. *Recent Improvements in Turbine Generators*, S. L. Henderson and C. R. Soderberg, A. I. E. E. Quarterly TRANS., Vol. 47, April 1928, p. 549.

"Stress Analysis in Electrical Rotating Machinery," *A. S. M. E. Trans.*, 1928, M. Stone.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

failure follows somewhat that shown by the dotted line in Fig. 2. This has been approximated to by Gerber as a parabola, and by Goodman as a straight line connecting endurance limit and ultimate stress, but it is more conservative and easier of application to use the straight line approximation shown connecting endurance limit and yield point.

The relation between allowable variable stress, $S_v$, and corresponding steady stress, $S_s$, as defined by the straight line is, where

$S_e$ = Endurance limit

$S_y$ = Yield point

$$\frac{S_v}{S_e} + \frac{S_s}{S_y} = 1$$

Now in the actual applications of arc welded structures, we do not permit ourselves to operate close to failure stresses; therefore the idea of factor of safety must be introduced.

Due to the very many exigencies that may occur in welding, such as poor fusion, impurities, porosity, etc., we, in our design practise, have set a factor of safety of 3 to be used both on the yield point in steady stress applications and on the endurance limit for fatigue. This confines our stresses to the shaded area shown in Fig. 2 and our stress relation now is expressed by

$$\frac{S_v}{S_e} + \frac{S_s}{S_y} = \frac{1}{n}\left(n = \text{factor of safety}\right)$$

For welds, this relation takes on the quantitative aspect of

$$\frac{S_v}{15{,}000} + \frac{S_s}{30{,}000} = \frac{1}{3}$$

The endurance limit and yield point values being taken here are average figures.

To illustrate its use: Suppose we have a pure variable stress, then $S_s = o$, and the allowable $S_v$ is given by

$$S_v = \frac{15{,}000}{3} = 5000 \text{ lb. per sq. in.}$$

On the other hand, suppose we consider a static application, where $S_v = o$, then the allowable stress, $S_s$ is

$$S_s = \frac{30{,}000}{3} = 10{,}000 \text{ lb. per sq. in.}$$

These are the values adhered to in all designs where welds have to withstand live stress. An intermediate case may be: If $S_s = 5000$ lb. per sq. in., what is the allowable variable stress that may be superimposed? Thus

$$\text{Allowable } S_v = \left(\frac{1}{3} - \frac{5000}{30{,}000}\right) 15{,}000 = 2500 \text{ lb.}$$

per sq. in.

The design situation becomes more complex where welds are to withstand combined shear and direct stress,[7] or direct stress on planes at right angles to each other. These fields have not as yet been fully investigated experimentally even in the realm of metals themselves, and even less for welds. This leaves us with the necessity of relying on the well established rules for stress combinations as calculated from the ordinary theory of elasticity, and interpreted as we have discussed above.

At this point, we must inject an idea extraneous to fatigue considerations for pure metals, but one which occurs when heat treated alloy steels are welded together or to ordinary steels. Tests that have recently been made consisted of welding a ring of metal around a heat treated ni-chrome steel (0.56 per cent Cr, 1.17 per cent Ni.) test bar, and then after machining off the bead, subjecting the bar to an alternating stress. The endurance limit dropped from 66,000 lb./in.$^2$ (for the alloy steel) to 16,200 lb./in.$^2$ Like reductions were noted in ductility and impact resistance. This important result emphasizes the point that the fatigue strength of welded joints cannot be increased by using high grade parent metal—the effect of welding is to reduce the endurance limit to only average values for mild carbon steel. This fact is important, particularly, where joints are designed to fail in the parent metal and not in the weld. This result, however, is not to be interpreted to apply in the case of static stress, where tensile properties do not appreciably change.

As soon as we begin to extend our ideas to welded joints, much of our knowledge becomes inapplicable.

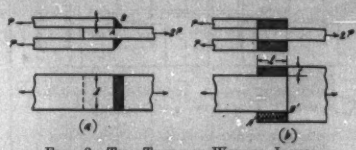



Fig. 3—Two Types of Welded Joints

To interpret our informaion on weld and parent metal for use in welded joints is to assume that the stress distribution is known. This unfortunately is the stumbling block in most cases.

Even in the simplest of welds—fillets, butt, side, or end welds—actual tests must be carried out to determine the upper limit for stress application. And for the great majority of joints, which are made up of combinations of the above, there exists little chance of being able to predict stress distribution.

To examine the simplest of joints, let us compare the two types of joints shown in Fig. 3, the first, a joint of front welds and the second, a joint of longitudinal or side welds, as to their suitability to withstand dynamic stress.

From tests that have been made in the past, notably by Dustin,[8] the strength of joint (a) is best predicted by considering the section $A\ B$ to be subjected to pure tension and we must associate the stress given by

7. F. C. Lea, *Engineering*, Aug. 20, 1926.

8. H. Dustin, Congres International pour l'Essai des Materiaux, Amsterdam, 1927.

$$f = \frac{\sqrt{2}\,P}{t\,l} \text{ with failure.}$$

Failure usually takes place at this critical section. For type (*b*) welds, the breaking stress can be written as

FIG. 4—ARC WELDED A-C. GENERATOR

$f = (\alpha\sqrt{2}\,P)/(t\,l)$ where $\alpha$ has the value of approximately 2/3. This factor has this low value due to the stress concentration at the ends of the weld, causing the break to progress from $A^1$ and $B^1$ inward.[9] Despite

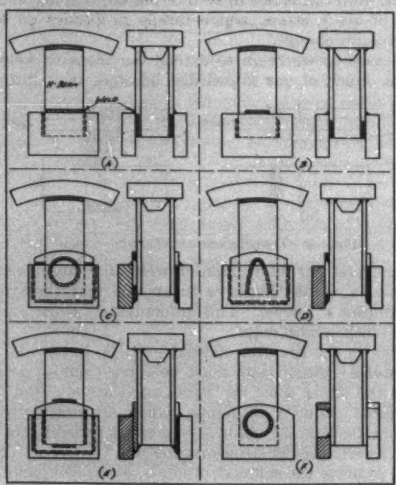



FIG. 5—SPECIMENS TESTED ON VIBRATION MACHINE

the lower allowable stress for joint (*b*) (where stress must always be compared with shear stress failure, while in (*a*) the much higher value of tension failure can be approached), it must be noted that the energy of rupture of joint (*b*), is much larger than that for (*a*), and Dustin even goes so far as to favor (*b*) over (*a*) for dynamic loading. A conclusion like this, however, is clearly a case of balance of ductility of break against allowable stress.

The design of machines to be constructed of structural shapes welded together involves a great many factors in addition to the direct stresses in the welds. Fig. 4 shows the type of construction widely used for a-c. generators and motors, the rotors of which are direct connected to geared machines or combustion engines. These machines are subjected to large torque variations of both high and low frequencies and a considerable amount of experimenting has been carried out to determine the best arrangement of the structural members and welded connections.

It was quite easy to make the welds themselves efficient in these structures, but the stress concentration in the structural members was a serious problem. It will be noted that the H-beams of the rotor are placed so that the smallest moment of inertia is utilized for

FIG. 6—VIBRATING TEST MACHINE WITH A-C. ROTOR TEST ARMS

torque loads. This arrangement calls for larger beams but gives the most economical design to keep stress concentration at a minimum.

Fig. 5 shows several methods of fixing the H-beams into the hub of the rotor which were tested on the machine shown in Fig. 6. This machine subjected the specimens to a very violent oscillating vertical motion corresponding to torque oscillations in the actual rotor. Specimen (*c*) proved to be the best, but specimen (*b*) has proved satisfactory for normal application. Further tests are being conducted on a machine which will give actual as well as relative values of the stresses encountered and will also permit the superimposing of initial stresses in the structure which are independent of the varying stresses.

The initial stresses which are encountered in welded structures proved to be very harmful when the structure is subjected to varying stresses as discussed earlier in the paper. These initial strains are caused by the actual shrinkage of the weld metal itself and by the unequal heating of the various parts of the structure while being welded. Bending and twisting strains are set up while cooling to room temperature. Many complete rotors were built to determine if it was possible

9. Stress distributions of this type have been qualitatively studied by J. H. Smith, "Stress-Strain Characteristics of Welded Joints," *Journal of Amer. Welding Society*, Sept. 1929.

to obtain a structure free from initial strains. The method used in determining the residual strains was to drill small gage holes in the pieces before being assembled and recording the variations in the distances between them after being welded. After the rotor was completed, additional strain gages were clamped to the structure at various places and the individual members cut loose from the structure by hack saws. Various

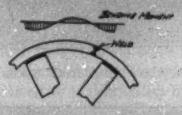


Fig. 7—Weld in Rotor Rim Located at Point where Bending is Absent

welding sequences, peening of welds, artificial cooling of members, and jigs were used, but it was found to be commercially impracticable to obtain a complete rotor free from high residual strains.

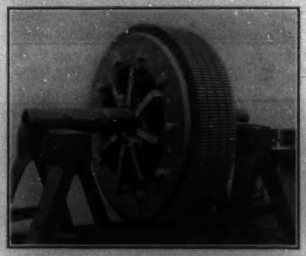


Fig. 8—1000-Kw. Arc Welded D-c. Rotor

Annealing was then adopted in order to remove the strains and tests were made at various temperatures by our Research Dept. It was found that practically all residual strain was removed at 1000 deg. fahr. and this

Fig. 9—Arc Welded Single-phase Stator

temperature was adopted for all welded apparatus where a strain free condition is necessary. Several complete rotors were annealed at 1000 deg. fahr. and the residual stresses found to be under 1500 lb. per sq. in.

Annealing at higher temperatures was found to be undesirable because of the greater liability of warping and cracking the welds. All of the physical properties of the weld itself are decreased by high temperatures and because of this it is not considered practicable to obtain refinement of the grain structure of the parent metal adjacent to the weld at the expense of the weld

Fig. 10—25000-Kv-a. Lower Waterwheel Bracket

itself. These results concur with previous conclusions of other investigators.[9, 10]

It is of interest to note the design consideration necessary in the use of butt welds for the rims of the above mentioned rotors. These rims are made of bar stock rolled up and butt welded. It was at first thought desirable to locate the welds of one of the rotor arms across the butt weld in order to reenforce it but the bending and tension stresses were above our allowable limit. The location of the weld as shown in Fig. 7 at a

Fig. 11—Two Waterwheel Brackets under Test

point where the bending in the rim is zero and only the centrifugal tension exists, made it possible to use a welded construction.

In Fig. 8 we have a typical arc welded d-c. rotor, 1000-kw., 300-rev. per min. for steel mill application. The construction here is characteristically different from the a-c. rotors in that there is no welded connection between the spokes and rim, thus eliminating the condition where locked up stresses are serious. This

10. J. B. Rose, *Journal of American Welding Society*, Sept. 1929.

permits the use of welding without strain annealing and has been applied with complete success to Diesel driven generators, steel mill drives, ship drives, etc., all of a dynamic stress type. All machines of this type have

Fig. 12—300-Hp. Blower Propeller

been tested at repeated short circuit and maximum overspeed, and are designed to withstand a torque load of ten times normal.

Fig. 13—Arc-Welded Lashing for Turbine Blades

Fig. 9 shows a welded single-phase machine in which the varying stresses imposed have as serious an effect on the stator as on the rotor. This type is subjected to

Fig. 14—Under Frame for Diesel Electric Locomotive

200 per cent torque pulsations at twice the impressed line frequency.

Fig. 10 shows an arc welded bracket for supporting the rotor of a 25,000-kv-a. waterwheel generator. This type of bracket must be designed to permit a very small deflection and must withstand varying and shock loads. The waterwheel sets up considerable vertical vibrations and under certain operating conditions water surge im-

Fig. 15—Crank Case for High-Speed Diesel Engine

Fig. 16—7000-Hp. Marine Reduction Gear Unit

Fig. 17—175-Ft. Arc Welded Railroad Bridge

Fig. 18—Corner of Fabricating Shop
Rolling A-c Rotor Rims

pacts can be so severe that the rotor is actually lifted from its thrust bearing. Fig. 11 shows two brackets being tested for deflection by pulling them together with a through bolt. The tests showed that the

deflection of the welded brackets is comparable with the corresponding cast design and can be predetermined with accuracy. The purpose of the bolted joints shown is to permit the dismantling for shipment. A considerable number of brackets of this general type have been in use for some time.

Fig. 12 shows the propeller[11] of a large volume high-pressure blower which is directly driven by a 300-hp., 3250-rev. per min. induction motor. It is constructed by arc welding the two blades into a slot out in the hub. Various strength and fatigue tests were made on this design and it has withstood severe service conditions. The entire blower housing is fabricated by arc welding and in some applications the propeller is driven by an all welded steam turbine.

Fig. 13 shows the application of arc welding for turbine blade lashing which must withstand unusually severe vibration stresses. This construction has been successfully used for several years.

Fig. 14 shows a welded cab underframe for a Diesel electric locomotive. It has successfully withstood the severe bumping and twisting strains imposed by yard switching service.

Our company has also used arc welded designs successfully in the following applications which are subjected to dynamic stress conditions:

Crane structures.

Marine reduction gear units of several thousand hp.

Trolley pole bases for street cars.

Various ventilating fans.

Lifting lugs on various apparatus. Elevator cages and equipment.

Railway motor housing and gear cases.

Locomotive equipment supports.

Railway bridges.

Crank cases for high speed railway Diesel engines.

We have emphasized, in this paper, the degree to which electric welding may be relied upon in applications where the structure is subjected to dynamic stress. Such applications can be successfully made by giving due consideration to the factors of maximum working stress, residual welding stresses, and stress concentration. The pessimism of the past few years regarding dynamic applications is slowly disappearing and it is only by the careful consideration of all factors that arc welding will be extended to all types of fabrication without restriction.

## Discussion

**B. L. Barnes:** First, it is, I believe, generally agreed that it is possible to deposit welds by hand which will have less initial stress in the deposited metal than would be present in welds that are made by a continuous machine process. Would the authors consider it necessary to anneal all welded machine parts such as rotor spiders shown in the illustrations regardless of whether they are welded by hand or machine?

Second, the paper mentions some limits of allowable working stresses in the deposited metal. I wish to ask whether the allowable stress in the weld is dependent upon the size of the weld. For instance, it is, I believe, considered that metal deposited by a single operation is more uniform and stronger per unit area than that in a larger weld requiring two or more operations. Would the same working unit stress be allowed in a large weld requiring two operations as in a small weld requiring but one operation?

**C. H. Jennings:** Messrs. Stone and Ritter are to be commended on the very valuable and interesting information presented in their paper *Electrically Welded Structures Under Dynamic Stress*. It has been the aim throughout the paper to show how electric welding has been successfully applied to dynamically stressed structures and to discuss the application of a very useful and convenient method for taking into consideration the dynamic and static stresses when designing welded structures.

This paper is of particular interest to those who are investigating the properties of welds and promoting the use of welding in industry, for it shows how welding has been successfully applied in cases where it was at one time thought unsafe and impossible. This development of welding has only been made possible by the extensive research investigations that have been and are being conducted on the physical properties of welds.

Unfortunately, relatively little work has been done by investigators on the fatigue of welds, a test which is of prime importance for obtaining information on welds subject to dynamic stresses. The company with which the writer is connected has gone deeply into this phase of welded joint investigation and is obtaining some very interesting and valuable information.

It is mentioned in the paper that the use of large specimens has been resorted to in an effort to minimize the effect of stress concentration due to pits and holes, and that in doing so lower endurance values are obtained. This is quite true but the writer feels that this low endurance limit cannot be entirely explained by the injurious effects of residual stresses in large welds. An additional factor that probably aids in producing this low endurance limit is the possibility of some physical change in the structure of large welds as compared with small ones. As yet, however, no definite explanation is available.

The low fatigue results obtained on large specimens are not in disagreement with results published for tensile properties of welded joints,[1] where it was found that the strength of butt welds increased with the thickness of the welded plates, as at first might be expected. The increase in the tensile properties of butt welds as the thickness of the welded plates is increased to at least one inch, is possibly explained to a certain extent, other factors being constant, by the manner in which the plate is welded. In the tests made by Mr. G. Lobo, Jr.,[1] who first published the fact that the tensile properties of butt welds increase with the thickness of the welded plates, up to plate thicknesses of at least one inch, the specimens were welded by weaving the electrode back and forth across the V, when advancing it along the joint. For thin plates and at the bottom of a V, where the crosswise movement of the electrode is small, this gives in effect a bead laid perpendicular to the axis of stress when the plate is tested. When the width of the groove to be welded became larger, as at the top of the V in a large plate, the weld became in effect a number of small beads laid nearly parallel to the direction of stress when the specimen is tested. Also from tests made from pads of weld metal it is known that the tensile properties of weld metal stressed parallel to the direction of deposition are much greater than those obtained by stressing the weld metal perpendicular to the direction of deposition.

This may partly account for the higher tensile values obtained from large plates, where the weld is, in effect, laid nearly parallel to the direction of stress rather than perpendicular to the direction of stress as on thin plates. Also, in large welds the possi-

11. Detailed Description, *Power*, July 23, 1929.

1. G. Lobo, Jr., "Strength of Butt Welds," *Jour. of American Welding Society*, April 1929.

bilities of better fusion and operating conditions are provalent. Even though the residual stresses are higher in large specimens, they have little effect on the strength obtained from static tests and it is possible that the advantages obtained from the above items more than overcome them and any other inherent weakness that might be found in large welds.

In fatigue tests on large specimens, the directional effect produced by the manner in which the weld metal is deposited and the possibilities of better fusion and operating conditions also have a beneficial effect on the endurance limit, but the high residual stresses and possible structural changes become of great importance and probably more than counteract this beneficial effect.

Another series of fatigue tests which is mentioned and is of importance is that on the different methods of fixing H-beams into the hubs of rotors. Tests on joints similar to those illustrated in the paper are being continued in order to obtain numerical values for comparing the different types. The importance of these tests is quite evident for such joints can be applied to all types of structures and bridges as well as to electrical machinery.

In these tests, a slight digression was made from the conventional fatigue tests (complete reversal of stress) for joints of this type would not be subjected to such conditions when in service. The method being employed in making the tests is to subject the test specimens to varying initial bending loads upon which is superimposed a constant cyclic load. Thus by varying the initial bending loads on the specimens, a critical initial bending load for each type of joint can be obtained. By this is meant an initial static bending load of such a value that greater static bending loads will produce fatigue failure and static bending loads equal to or less than this will not produce fatigue failure when subjected to a superimposed cyclic load of the value used in the test.

With this information, it is possible to obtain actual values of comparison between the various types of joints by comparing the initial bending loads that can be applied without producing fatigue failure.

These few facts are mentioned as they are directly connected with the work mentioned in Mr. Stone's and Mr. Ritter's paper and show the kind of work that has been and is being done in order that welded designs such as they have mentioned are possible.

**J. C. Lincoln:** (communicated after adjournment) This paper is of considerable interest from an academic point of view, and while the conclusions do not entirely coincide with those of other noted experts, the information given is of undoubted value.

As a matter of commercial application, however, in general the design is determined not from the fatigue limitation but from the amount of metal which must be used in order to make the part machinable rapidly without undue trouble from bending. As a rule, if stiffness and strength sufficient for this are present, they are in excess of the quantities needed for commercial operation.

The authors' recommendation regarding annealing brings up a moot point. Their success with this treatment is not universally conceded. Many other manufacturers with a longer experience state with equal fervor that annealing is of no commercial benefit. As a matter of fact, very few structures which are fabricated by arc welding are now annealed.

The application of any process of this kind is carefully considered by the engineer. It is customary to build the first few structures in the light of this engineering, but after the design has become common commercial necessity or practise, very often the design is changed materially, and in spite of the objections of the engineer it frequently develops that many of the troubles which he predicted failed to materialize.

Arc welded structures in many cases have already gone through this period and the tens of thousands of manufacturers who are using this manufacturing tool, frequently without any engineering, generally with only the faintest conception of the stresses involved, have been able to produce commercially satisfactory results. In doing this they use only the rule of thumb method of making the new design half the section of the previous cast structure.

**J. G. Ritter:** Mr. Lincoln states that intensive design is unnecessary in making welded structures; in our own plant and in many other large plants the design of welded apparatus has passed the stage of converting from castings. It would be very impracticable in designing a new machine to first make it cast and then make the welded structure half as heavy, as Mr. Lincoln suggests.

It would be ridiculous and unnecessary to anneal all stuctures, but the experience of "most large manufacturers" has proved that annealing is essential in certain rigid structures subjected to dynamic stress conditions.

Mr. Jennings discussion of the relation of fatigue to size of welds is well taken. Most of the data on fatigue of welds have been obtained from built up structures rather than simple welds and much more work should be carried out in testing of the fundamental welds.

# Tap Changing Under Load
## for Voltage and Phase-Angle Control

BY HOMER B. WEST[1]
Associate, A. I. E. E.

***Synopsis.***—*One of the most important, and sometimes most involved, problems brought about by the many interconnections of electrical systems, is a means of accurate and flexible regulation of power flow. The adjustment of voltage and the control of wattless current by means of tap-changing-under-load equipment has become quite extensive. The regulation of power flow by means of phase-angle control has been put into practise on a limited scale. One means of accomplishing this, which has been used in a few cases and which is being considered on a larger scale, is the adaptation of tap-changing-under-load equipment with properly connected static transformers.*

*The purpose of this paper is to discuss briefly the connections employed and the equipment used in connection with static transformers for the purpose of voltage and phase-angle control.*

### Introduction

THE rapidly increasing number of interconnections between power systems is making possible the shifting of loads from one system to another in either direction in response to the diversity of system loads, and is resulting in improvements in the quality of service and in economies due to savings in plant capacity. The extent of interconnections can be appreciated when one realizes that the aggregate transformer capacity now installed with adjustable voltage ratio under load amounts to more than five million kv-a. A large percentage of this equipment is used for system interconnections.

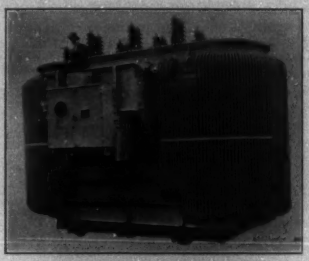


FIG. 1—SEPARATE REGULATING TRANSFORMER COMPLETE WITH TAP-CHANGING-UNDER-LOAD EQUIPMENT FOR 11 PER CENT VOLTAGE REGULATION ON A 50,000-KV-A., THREE-PHASE, 24,000-VOLT CIRCUIT

These interconnections are presenting the problems of interchange of wattless kv-a., which involve voltage control, and the problems of controlling the power flow in definite paths through networks, which involve both voltage and phase-angle control. The purpose of this paper is to show the connections employed and to describe the equipment used for this purpose.

### Voltage Control

When two systems are tied together at one point and have no other interconnections, a difference between the two system voltages at the point of interconnection will cause wattless kv-a. to flow from the system with higher voltage to the system with lower voltage. Transformers with equipment for changing the voltage ratio under load are used to compensate for the difference between system voltages and control the interchange of wattless kv-a.

Fig. 1 is an interesting example of tap changing under load equipment for this application. In addition to system interconnections, many other applications for tap-changing-under-load equipment for voltage control have been found. Examples of such applications exist where the equipment is used to compensate for line and transformer drop in transmission circuits, to maintain the voltage at secondary distribution busses, between predetermined limits, and in the supplying of power to synchronous converters and furnace transformers. An example of the latter application is the use of an 8120-kv-a., 25-cycle, single-phase, 12,000-volt furnace transformer with a low voltage range of 60 to 30 volts in 64 steps of less than one-half volt each, obtained by the "UB" equipment later described in this paper.

The needs of many users of voltage ratio adjusting equipment are usually met with a range of 10 per cent adjustment above and below normal voltage. Now and then a greater range is needed, but equipment for more than 10 per cent regulation up and down is becoming more rare. The manufacturer's practise with tap changing equipment seems to be resolving itself into the building of a standardized equipment, giving a total voltage range of 20 per cent, with 10 per cent regulation above normal in four steps, and 10 per cent below normal in four steps. If a greater ratio adjustment than 10 per cent is needed, and it can be used in four steps up and down, the standardized equipment may be used by providing suitable taps in the transformer winding.

There are three fundamental methods of changing the voltage ratio of transformers under load: (1) by induction regulators or step induction regulators; (2) by

1. Transformer Engineering Department, Westinghouse Electric & Manufacturing Company, Sharon, Pa.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

the parallel-winding method; and (3) by the single-winding method.[2]

1. Induction regulators are generally used on low-voltage distribution circuits of small capacity. Step induction regulators, Fig. 2, are used to obtain small increments of voltage between taps, but since expensive equipment is involved, they are seldom used except for special applications.

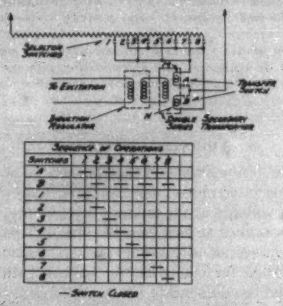



Fig. 2—Development of Transformer Winding and Sequence Chart for Step Induction Regulator Equipment

2. Fig. 3 is a development of the parallel winding method. This method is now obsolete because, (a) it is not economical from the design point of view; (b) the multiplicity of taps usually makes it necessary to place part of the mechanism inside the case; (c) it requires a complicated sequence of operations; and (d) part of the winding is overloaded during transition periods.

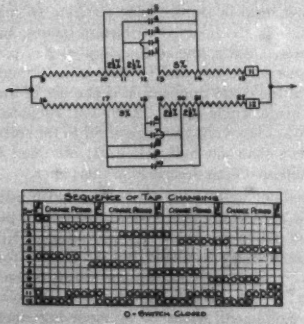



Fig. 3—Development of Transformer Winding and Sequence Chart for the Parallel Winding Method of Changing Transformer Taps under Load.

3. One single-winding method, known as the multiple circuit method, which is an outgrowth of the parallel-winding method, is shown schematically in Fig. 4. The principal difference between this and the parallel-winding method is that, instead of two parallel windings, a multiplicity of double taps on a single winding is used. Also, a separate auto-transformer is used during the transition period to control the circulating current, whereas in the parallel-winding method the inherent impedance between the two windings served this purpose.[3]

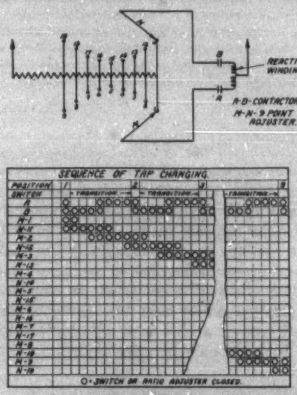



Fig. 4—Development of Transformer Winding and Sequence Chart for the Multiple Circuit Method of Changing Transformer Taps under Load

A simpler single-winding method which is later described, is shown schematically in Fig. 5.

The single-winding method has outlived the parallel-winding method and is now being used by all leading

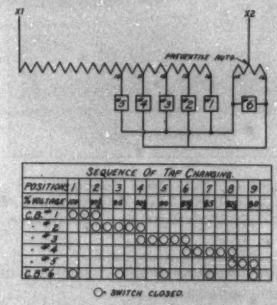



Fig. 5—Development of Transformer Winding Showing Taps, Arrangement of Switches, Bridging Auto-transmer, and Sequence Chart for the Simple Single-Winding Method of Tap-Changing-Under-Load Equipment

2. L. H. Hill, A. I. E. E. Trans., Vol. XLVI, 1927 p. 582.

3. L. F. Blume, *General Elec. Rev.*, March, 1928, p. 123.

manufacturers. As a consequence, this paper deals principally with the single-winding method of tap changing and describes the equipment involved, in which every opportunity for simplicity in design has been used.

The simplest method of changing the voltage ratio of a transformer is to provide taps in the transformer

Fig. 6—Front Elevation View of Transformer with the Type "UB" Tap-Changing Equipment

winding and a bridging auto-transformer to be switched along the taps as is shown in Fig. 5. A range of 10 per cent voltage above and below normal, each in four steps, is obtained with this simple arrangement.

To obtain the full winding of the transformer in the

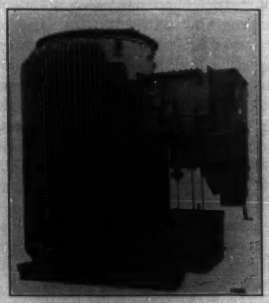


Fig. 7—Side Elevation View of Transformer with the Type "U B" Tap Changing Equipment

circuit, Fig. 5, switches 1 and 6 are closed. The circuit is then through the full transformer winding and divides through the preventive auto-transformer, one-half being through one side of the auto-transformer and one-half being through the other side in the opposite direction. The voltage of the transformer is therefore the voltage induced in the entire winding. To change taps one step, switch 6 is opened and 2 is closed. This connects the auto-transformer across the two taps, and, since the line lead is attached to the center of the preventive auto-transformer, the line voltage comes the same as it would have been had the line lead been attached to a tap midway between the two actually brought out.

Similarly, to change taps still further, the process is completed in the same manner as indicated in sequence

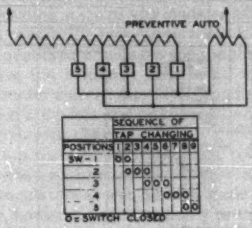



Fig. 8—Development of Transformer Winding and Sequence Chart for Single-winding Method of Tap-Changing-Under-Load Equipment in its Simplest Form

of tap changing in Fig. 5. This method of switching produces the whole range of nine voltage ratios with only five tap leads and six switches. Each operating position is equivalent to an exact tap position. Figs.

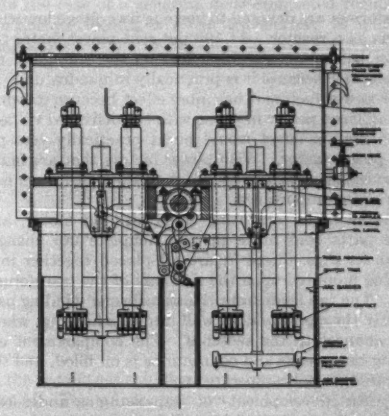


Fig. 9—Cross-section Elevation of the Type "UB" Tap-Changing Equipment

6 and 7 show front and side elevation views of a transformer with this single winding method of tap-changing-under-load equipment.

Fig. 8 is a schematic diagram of a further simplification of the single winding method of tap changing under load with a bridging auto specially designed to meet two different operating conditions. When it bridges across

two taps, it operates simply as an auto-transformer. On the alternate tap positions half its winding is connected in series with a tap from the transformer winding and it functions as a reactor. Under the latter condition, it introduces into the circuit a small out-of-phase voltage vector. The special design features of the auto-

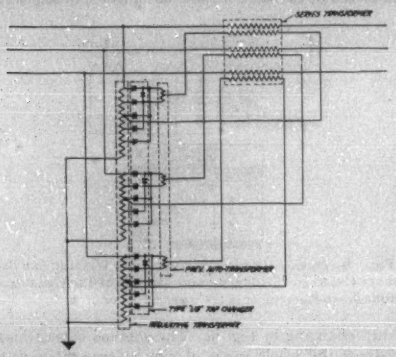



Fig. 10—Separate Regulating Auto-transformer with "UB" Tap Changing Equipment for Changing Taps under Load for Voltage Control

transformer are devoted to keeping its voltage low when it acts as a reactor. At 100 per cent power factor this vector has no measurable effect on the voltage of the transformer because it is practically in quadrature. At lower power factors it has more effect because it swings around more nearly in phase with the delivered voltage. Its maximum effect would be at practically zero per cent power factor. With power factors that are found in service, the reactor effect of the auto-transformer is of no practical importance.

The switches, operating cams, driving motor, and other parts that make up the complete tap changer shown in Figs. 6 and 7, are all placed together in a housing mounted upon the side wall of the transformer case. The tap leads from the transformer winding pass directly through the tank wall into this housing, where they connect to the switches. The compartment enclosing these leads and connections is oil filled, and the switches themselves operate in oil.

In the development of tap-changing-under-load equipment, it was found much better, as a means of simplifying the scheme of connections and operation, to place all parts of it outside the transformer case. Power transformers, as they are built at present, are at best rather complicated affairs, and keeping mechanisms and moving parts out of the main transformer case helps considerably in the effort to keep them as free from complications as possible. With the type shown, only a few leads need be carried through the tank wall. The net result of the combination of transformer and tap changer is one that represents the utmost simplicity and reliability. A cross-section drawing, illustrating the arrangement of the switches and the mechanism that operates them from the cam shaft, is shown in Fig. 9.

Like most tap changing equipments operative under load, the equipment is designed to be operated by motor from a distance, but it can also be operated by hand when desired. The remote control is accomplished at the switchboard with a single switch used either to raise or lower the voltage. As soon as the mechanism starts to move in response to the switch, the control is taken away from the operator and the mechanism automatically completes the change of taps. Indicating lamps and position indicators at the switchboard complete the equipment.

When the tap changer operates directly in the winding to be regulated, the switches used for changing taps must be insulated for the voltage of the particular part of the winding in which they operate and be capable of carrying the winding current. Sometimes it is cheaper to use a regulating transformer connected as shown in Figs. 10 and 11, with a rating of only the kv-a. of the control required. The voltage and current may be jointly adjusted to give the minimum switchgear cost. For transformers already installed, it is customary to

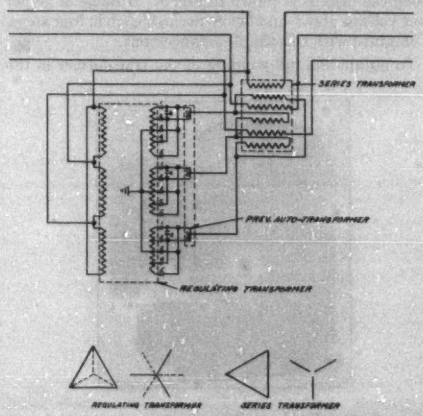



Fig. 11—Separate Two-Winding Regulating Transformer with "UB" Tap-Changing Equipment for Changing Taps under Load for Voltage Control

use a tap changing equipment to vary the voltage of a separate regulating transformer in this manner. The regulating transformer may take the form of an auto as shown in Fig. 10, or of a two-winding transformer as shown in Fig. 11. The adjustable voltage is applied to a series transformer connected in the line whose voltage is to be regulated. The principle of changing taps and

the equipment are the same as used for new transformers built for the purpose.

### Phase-Angle Control

If one of two interconnected power systems is in turn connected to a third power system without forming a closed loop, the problem is still one of voltage control because the division of actual load is controlled through governor speed adjustments.

If two or more interconnected systems or parts of one

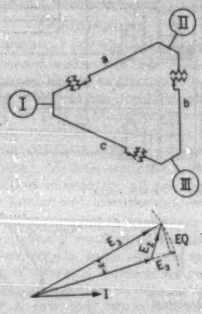



Fig. 12—Three Power Systems Interconnected to Form a Power Loop and Vector Diagram Showing the Conditions which Exist when the Line is Opened between Systems II and III

system form a closed loop, Fig. 12, conditions arise which cannot be corrected simply by voltage control and by governor adjustments. The governors in each generating station can be adjusted to control the power output from that particular station. The closed power loop, however, forms two paths between a generating station and the load at points around the loop. The tap-changing-under-load voltage control equipment can be adjusted to obtain voltages of equal magnitude at a particular location in the power loop, but these voltages may not necessarily be in phase. For example, if the line is opened between stations II and III, Fig. 12, and the voltage $E_2$ is measured on the station III side and the voltage $E_3$ is measured on the station II side, there may be a voltage $E_x$ between $E_2$ and $E_3$ across the open breakers. The dotted extension of $E_2$ indicates how the voltages can be adjusted to equal magnitude by means of tap-changing-under-load equipment for voltage control only, but a quadrature voltage $E_Q$ still exists across the breaker, because $E_2$ and $E_3$ are not in phase. If the tie line be connected to form a closed ring, current would flow from $E_2$, the line with leading voltage, to $E_3$, the line with lagging voltage.

If a voltage in quadrature with one of these delivered voltages, $E_2$ for example, is added in the line to compensate for $E_Q$, the two voltages $E_2$ and $E_3$ can be brought into phase with each other. The division of load can be adjusted between the two parallel paths of the loop by adding in-phase components and quadrature components of voltage to compensate for the impedance voltage in one of the parallel paths of the loop.

The voltage relations, of course, would change with a change of load. The added quadrature voltage should, therefore, be available in adjustable form.

This is a simple illustration of the possibilities of phase-angle control. With a ring system involving several generating stations and loads supplied at various points, the problem is more involved. However, if in-phase and quadrature voltages are supplied to the ring to neutralize the resultant impedance voltage of the entire system for a given set of load conditions, the way is cleared for a flexible and an economic distribution of current throughout the ring.

Quadrature corrective currents and voltages may be obtained with synchronous condensers and polyphase induction regulators as well as with static transformers. This paper, however, is devoted only to the use of static transformers for the purpose.

A quadrature voltage may easily be obtained in a three-phase system with transformers. If voltages from phases $B$ and $C$ of the star-connected regulating winding in Fig. 13 are connected in series, the resultant voltage, $a$, will be displaced 90 deg. from the voltage of phase $A$. With suitable transformer connections it can be superimposed upon the voltage of phase $A$.

In the case of a separate delta-connected regulating transformer feeding a series transformer to add the quadrature voltage to the line, the secondary winding

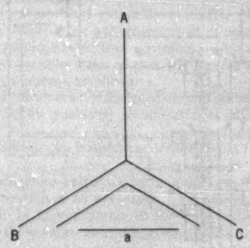



Fig. 13

of the regulating transformer is connected in star as in Fig. 14. The voltage from neutral to $C$ of this winding, for instance, is displaced 90 deg. from phase $A$ to neutral of the main system.

Equipment which has been developed for adjusting the voltage ratio of power transformers without interrupting the load may be adapted to the control of phase angle without any modifications in the mechanism; it may be used for this purpose also without disturbing the continuous flow of power.

For phase-angle control, a quadrature voltage of

10 per cent will cause a shift of phase angle of approximately 6 deg. Twenty per cent voltage in quadrature will shift the phase about 11 deg., and 36 per cent is required for a phase shift of 20 deg.

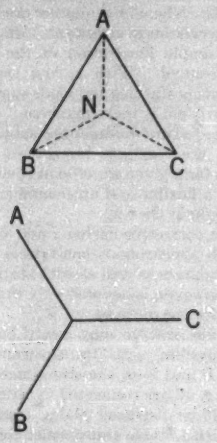



Fig 14.

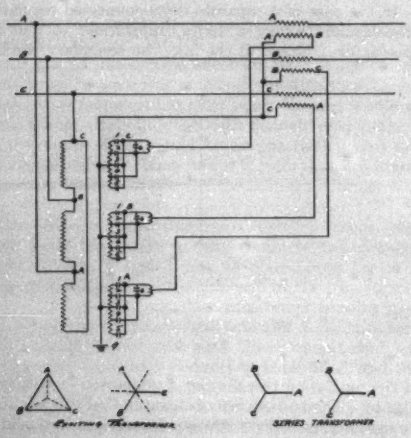



Fig. 15—Separate Two-Winding Regulating Transformer with "UB" Tap Changing Equipment for Phase-Angle Control

Voltage adjustment and phase-angle control may be combined in the same transformer. Separate switching mechanisms and separate series transformers are, of course, required in order to get the separate adjustments. Figs. 15, 16, and 17 show typical schemes of connections for phase-angle control and for combined ratio and phase-angle control.

The greatest problem in connection with phase-angle

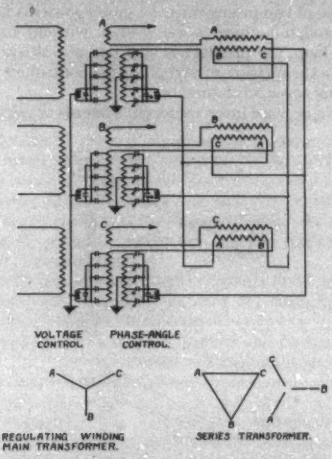



Fig. 16—Transformer Bank with Regulating Winding and Two "UB" Tap Changing Equipments for Combined Voltage and Phase-angle Control

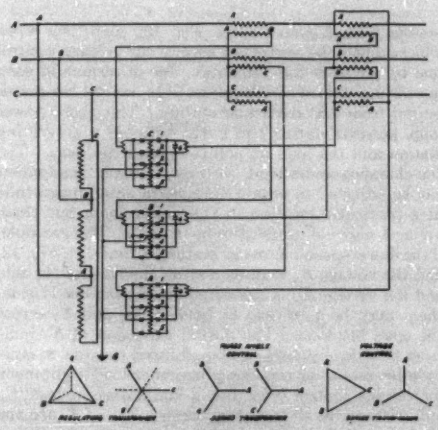


Fig. 17—Separate Two Winding Regulating Transformer with Two "UB" Tap Changing Equipments for Combined Voltage and Phase-angle Control

control with static transformers is not the equipment, for it is available in simple and reliable form. It lies rather in the calculation of the amount of phase shift

required to get the operation that is wanted for the varying conditions under which load is delivered. In the case of complicated interconnections with several generating stations and various load centers with variable distributions of load, it is not altogether a simple matter to determine just what shift of phase will produce the best net results.

It would seem that the static transformer with phase-angle control equipment will eventually occupy an important place in the progress of interconnections.

## Discussion

**J. S. Lennox:** Previous to 1922, equipment for controlling the ratio of transformers under load was rather limited in its application and confined largely to the method shown in Fig. 8 of the paper. Since that time the development has been rapid as evidenced by the first part of the paper showing the evolution in methods used by one manufacturing company.

Probably the most outstanding improvements have been in the mechanical design. Modern equipments are mechanically driven throughout, thus eliminating all necessity for electrical interlocks and other similar protective devices.

The mechanical equipments fall naturally into two classes, one in which the tap connections are changed and the current in the reactor circuit broken by the same contacts and the other in which the functions of changing connections and rupturing the current are handled by separate devices developed for each purpose. In the latter case, only two switches are required, one at each end of the reactor.

The first of these types of equipment is only suited for use with electrical circuits which permit bringing all the tap connections out of the transformer, as obviously no switching operations can be permitted in the transformer oil.

The second type is more flexible in its applications but advantage of it is usually taken to place the ratio changing device in the clean transformer oil adjacent to the windings.

In this connection, Mr. West says "in the development of tap changing under load it was found much better to place all parts of it outside the transformer case." I should like to ask Mr. West what operating experiences forced him to this conclusion. So far as I am aware experience covering seven years on a rapidly increasing number of equipments totaling well over two hundred to date has not resulted in a single failure of the parts placed inside the transformer. What few failures have occurred have been confined to bushings or equipment outside of the transformer though damage to the transformer windings may in some cases have resulted.

Most of the electrical circuits shown in the paper can be used with either type of mechanical equipment though some such applications would be quite costly. Fig. 8, for instance, lends itself most readily to the use of the first type of equipment because of the small number of switches required whereas either type can be applied economically to Fig. 5. On the other hand, the second type with ratio changing and current interruption performed by separate devices is best suited to Fig. 4.

I should like to mention one winding arrangement not illustrated in the paper that has come into extensive use in the last three or four years. Electrically it is similar to Fig. 5 of the paper if operation is confined to positions 1, 3, 5, 7, and 9, wherein switch No. 6 is closed, thus short-circuiting the preventive reactor. To obtain nine operating positions it is necessary to have nine taps as the bridging positions are not used.

Considering the sequence chart of Fig. 8, it will be seen that the preventive reactor is either in series or in parallel with the system on every position. In Fig. 5 it is in parallel on alternate positions but never in series. The arrangement referred to is a still further refinement in which the reactor is short-circuited on all positions.

Due to the increased number of taps, this method can be used economically only with the first type of mechanical equipment up to five or possibly seven ratios. For nine or more ratios it is necessary to use the second type of equipment with the ratio changing and the switching functions separated. The additional cost involved in such an application is to a considerable extent overcome by the possibility of quantity production of the various elements and by the fact that the preventive reactor is only one half the size called for in Fig. 5.

### Phase Angle Control

As shown by Blume (A. I. E. E. May 1927) if the relation $X$ to $R$ is alike for all portions of the loop the currents will divide to give minimum losses. Where this is not the case it may prove more desirable to readjust the lines by the use of reactors than to employ phase angle control. Certainly it would be difficult, if not impossible, for an operator to control the currents in a loop of any complexity to obtain minimum line losses.

Assuming properly balanced lines, complete flexibility of loop operation, at minimum line losses and including local distribution at fixed voltage from each station bus, can be obtained by installing power factor control on the transformers connected to the loop.

In such a case, however, the power factor or in-phase control would be located between the stations and the loop rather than in series with the loop as shown in Fig. 12.

Operation at minimum losses, however, may result from overloading transformers or cables where such are in series with the loop. Phase-angle control, possibly accompanied by power-factor control, may in such cases offer a more satisfactory solution than adjustments by means of series reactors.

A recent interesting shipment of ratio control covered two large series regulating transformers with the windings so arranged that by a simple change in connections they can be converted from phase angle control to power factor control, thus permitting their use in any manner required by future conditions at the point of application.

**F. W. Gay:** One would gather from reading Mr. West's paper that the effect of the auto-transformer or reactor is not important. I should like to take exception to this statement. There are three possible types of auto-transformer equipment for tap changing purposes, as follows:

1. The auto-transformer is designed with a saturating magnetic circuit. When operating as an auto-transformer with power supplied to the start and finish of the winding and power taken off the mid tap, the transformer is operated at the knee of the saturation curve. During tap changing there is a brief period during which one-half of the turns of the auto-transformer are in circuit functioning as a reactor. The voltage across the active turns will be approximately 50 per cent greater than the voltage across these same turns when functioning as an auto-transformer. It is therefore evident, if the power factor is low and it is desired to raise the voltage, say 2½ per cent from a tap on the main transformer, that when one-half of the auto-transformer is cut into circuit as a reactor, the voltage will drop 2½ per cent, or more, depending upon whether the power factor is moderately low or very low and the voltage will jump approximately 5 per cent as the winding turns are switched from reactor functioning to auto-transformer functioning. If a purchaser is going to use a tap changing transformer on a low power factor load and is determining on the size of the tap changing steps on the basis of permissible flicker voltage, he should note that the incremental jump in voltage actually obtained on this type of equipment will be approximately twice that of the tap change.

2. In the second type of tap changing auto-transformer an air core auto-transformer is used, having a very high magnetizing current. This auto-transformer when functioning as an auto-transformer is generally designed to take approximately 100 per

cent magnetizing current. If the transformer taps are spaced at 5 per cent intervals, the magnetizing current of the main transformer will be increased approximately 5 per cent when the auto-transformer is functioning as such. The voltage across half the turns of the air core auto-transformer, when it is functioning as a reactor, will generally be less than half the voltage across the saturated iron core reactor just discussed.

3. The third type of tap changing equipment uses auto-transformer with closely interlaced windings having a very low magnetizing current. This auto-transformer is normally shunted by a reactor, having a circuit breaker in series. The circuit breaker is closed at all times except when the auto-transformer is functioning as an auto-transformer across the main transformer taps. In this scheme the magnetizing current drawn by the auto-transformer, when it is functioning as an auto-transformer, is substantially negligible, generally being less than one-tenth the magnetizing current drawn by method one and only two or three per cent of the magnetizing current under method two. The reactance that such an arrangement inserts in the circuit when operating on a main transformer tap should not exceed a quarter of one per cent. However, during the instant of change from full tap to half tap the magnetizing current drawn by the reactor in shunt with the auto-transformer will be approximately five times as great as that drawn by method two.

To sum up, the operating man will do well to remember that no matter what method is used in changing from tap to tap, the effect of the auto-transformer is by no means negligible unless the power factor closely approximates 100 per cent. That method of tap changing should be chosen which best suits the system.

I should like to suggest a possible winding connection for transformers which may be found very convenient for use in conjunction with phase changing equipment.

It is well known that a phase changing equipment to care for much more than fifteen electrical degrees becomes very expensive. I would suggest that each phase of one of the transformer windings be provided with two coils for series multiple connection with 86 per cent taps in each coil. Such a winding may be connected parallel star or series delta. This special winding should be provided on the side not equipped with voltage taps. With such an arrangement on a transformer interconnecting two systems, any phase relationship may be obtained in steps of thirty electrical degrees; in other words, it is possible to meet the requirements of any system with which interconnection is to be made within fifteen electrical degrees.

**E. K. Huntington:** I should like to discuss Mr. West's paper from the standpoint of its application to systems connected with transformers which are largely for supplying power between these systems; in other words, a superpower connection. Oftentimes these connections normally carry very little power and therefore they may be operating at quite a low power factor. Under these conditions the operation of tap changing equipment at low power factors is quite important.

In considering the purchase of a tap-changing equipment on our system in Rochester, we already had installed a 20,000 kv-a. transformer bank connecting our system with the Niagara 110-kv. system. In applying tap-changing equipment to this transformer, we found that it would be necessary apparatus which would give us a variation of possibly 10 per cent in voltage range. This was determined by shifting the present taps on the high side of the transformer. A shift of 2½ per cent in voltage taps gave us a change of about 3000 reactive kv-a. in the tie between the two systems. This ratio of course varies with different kinds of load on the system but a fair average is 1000 reactive kv-a. for each per cent of voltage tap change.

It is possible, of course, to limit the size of the regulating transformer required by the use of the taps on existing transformers for seasonal changes.

In regard to the dip in voltage which occurs during tap change, it is quite essential that this be determined in advance, so that every time a tap is changed on the transformer a surge will not be created on the system which will be reflected in the system voltage. The amount of this surge is of course entirely dependent upon the design of the preventative auto-transformer connected between transformer taps. The design of this auto-transformer should be one that is adapted to the particular application of the tap changing equipment. This is something that is quite essential if we are going to avoid voltage dips during tap changing, particularly if such changing is made automatic and occurs at frequent intervals.

**M. S. Schneider:** (communicated after adjournment) The Cincinnati electrical load is supplied partially from Columbia Power Station, which is located approximately twenty miles from the city. The energy from this station is transmitted to the Cincinnati district over four 66-kv. circuits which are connected to the district's 13.2-kv. network by means of suitable transformer substations.

In addition to the four 66-kv. circuits, a 33-kv. circuit connects the Columbia Power Station with the Cincinnati district. This 33-kv. circuit supplies load to consumers located between the station and the city. To provide flexible voltage control on this circuit a three-phase voltage regulating transformer is connected

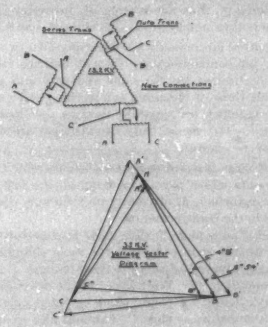



Fig. 1

*A, B, C,* input voltages
*A′ B, B′ C, C′ A,* full boost voltages
*A″ B, B″ C, C″ A,* full buck voltages

on the 13.2-kv. side of a 15,000-kv-a., 13.2/33-kv. transformer bank at the Columbia station. This transformer bank supplies the 33-kv. circuit.

During 1928 and 1929, when plans were made for increasing the capacity of the Columbia Power Station from 90,000 to 126,000 kw., it was realized that the division of load between the four 66-kv. circuits and the 33-kv. circuit would be such as to seriously overload the latter. It was necessary, due to load conditions, to keep this circuit energized from the Columbia Power Station and also from the Cincinnati 13.2-kv. network. In order to limit the current flow over the 33-kv. circuit the regulating transformer was installed as previously explained.

This three-phase regulating transformer was designed for insertion in the delta of the 13.2-kv. circuit of a 15,000-kv-a., 13.2/33-kv. transformer bank. It was used to regulate the voltage of the 33-kv. output of this bank under load giving four 2½ per cent steps above and below normal.

The connections between the regulator and main bank were later changed so as to obtain a combined regulation of voltage and phase angle. With the new connections the 33-kv. output of the main bank could be increased 5.44 per cent in voltage and

at the same time retarded 5 deg. 54 min. in phase, or the voltage could be reduced 4.61 per cent and the phase advanced 4 deg. 9 min.

Figs. 1 and 2 herewith show original and final general connections and also 33-kv. delta voltages before and after the change. The change in connections was easily made and subsequent tests showed that the kv-a. load was reduced 31 per cent. This was the result desired. Before the transformer was installed the 33-kv. circuit was opened frequently each day at a consumer's plant located at approximately the mid point of the circuit. These oil circuit operations were due to the excessive current being supplied over this circuit from the Columbia Power Station to the Cincinnati district, and they became so frequent that it was necessary to open the circuit at the Cincinnati end at certain times of the day, whenever the load attained certain values, in order to prevent their occurrence. After the regulating transformer was installed, the load was reduced sufficiently so that the oil circuit-breaker operations due to load transfer were eliminated. The customers along the route of this circuit were not affected in any manner.

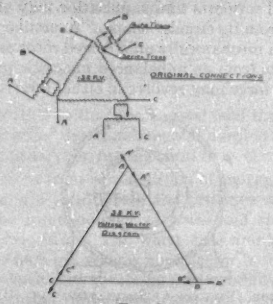



Fig. 2

*A, B, C,* input voltages
*A B′, B C′, C A′,* full boost voltages
*A B″, B C″, C A″,* full buck voltages

After the connections of the regulating transformer had been changed the kv-a. load supplied over this circuit could be regulated within the limits of the transformer. The regulation of voltage causes a variation in the reactive load and at the same time the varying of the phase angle changed the power load. The original connections permitted voltage regulation only, and consequently variation only of reactive load.

**H. B. West:** I shall refer first to comments by Mr. Lennox.

Tap changing under load, as applied to power transformers, is comparatively new, being only six or eight years old. Some of the earlier equipments used parallel winding schemes, as shown in Fig. 3 of my paper. However, experience has shown that the single winding method is much simpler. Therefore, the use of schemes shown in Fig. 5 and Fig. 8 has followed the use of the parallel winding scheme, and they are being used today after the evolution in methods as pointed out by Mr. Lennox. The scheme shown in Fig. 4 is an outgrowth of the parallel-winding method, and while it is a single-winding method, it does not take advantage of all the possible simplicity of the single-winding method.

Mr. Lennox states that only two switches are required for such a scheme as that shown in Fig. 4, but if one refers to the sequence of operation, he will readily see the extra complication over and above that involved in the use of schemes as shown in Figs. 5 and 8.

Power transformers today, even at their best, are somewhat complicated because of high voltages and multiplicity of windings, sometimes three and sometimes four. The designer, therefore, does not care to complicate the design any further, and because of the simplicity in design and operation, all parts of tap changing under load equipment have been kept outside of the transformer tank.

Mr. Lennox referred to two figures in my paper, stating that the number of steps was limited somewhat either to nine or eleven positions, depending upon whether the scheme shown in Fig. 5 or that shown in Fig. 8 was used. This is correct. In making a survey of the range required of the equipments now in service, we have found that a 10 per cent range plus and minus will serve the needs of practically all cases. We have, therefore, standardized on equipment to give this range in voltage in 2½ per cent steps. There have, of course, been some special cases where we have supplied tap changers to give more positions, but in such cases, as well as in those cases where a smaller number of taps is required, we always keep all parts of the tap changing equipment outside of the transformer tank.

In the scheme shown either in Fig. 5 or in Fig. 8, fewer taps are required in the transformer winding than in the scheme discussed by Mr. Lennox, and the operation of the tap-changing equipment is simpler.

It is realized that other methods may be used in phase-angle control, but this paper has been devoted to transformers and tap changing equipment used for that purpose, because it would seem that they will eventually occupy an important place in such applications, because of their simplicity, reliability, and flexibility.

Referring to Mr. Gay's comments, I would estimate that approximately half of the equipments supplied by one manufacturer has been with the scheme shown in Fig. 5, and half has been with the scheme shown in Fig. 8. At 80 per cent power factor, if the voltage between taps in the transformer winding is 5 per cent the steps in voltage using the scheme shown in Fig. 5, would be 2½ per cent, and the steps using the scheme shown in Fig. 8 may be of the order of 1½ per cent and 3½ per cent for alternate steps instead of each step being 2½ per cent.

It may be well to point out that it will take only two seconds to complete the operation in going from one tap position to another, and this means that any dip in voltage that occurs in the transition period would be of a smaller duration. It would seem that voltage dips of the order actually obtained, in a period of such short duration, would not be of much consequence.

# Quiet Induction Motors

BY L. E. HILDEBRAND[1]

Member, A. I. E. E.

*Synopsis.—Magnetic noise in induction motors is caused by the vibration of magnetic parts produced by the varying forces associated with the changing flux density in the adjacent air parts of the magnetic circuit. Torsional vibration of the motor is caused by unbalanced windings or applied voltages. Vibration of the rotor simulating a mechanically unbalanced rotor is caused by two fields differing by two poles and not of the same frequency or direction of rotation. Vibration of the stator by distortion from a circular shape results from the presence of other simple combinations of fields. Teeth tend to vibrate axially at double applied frequency.*

*The magnetic noise produced by a motor can be predicted from a qualitative analysis of the air-gap field supplemented by an approximate quantitative analysis and consideration of the stiffness of the parts.*

## Introduction

DUE probably to the previous lack of engineering importance, there is very little information on the subject of noise in electrical machines readily available in our technical literature. When mentioned at all, it is usually covered by a few general, superficial, and, frequently, inaccurate statements. It has been found that these general statements can be made precise by building up an exact theory from elementary fundamental principles.

A motor is a source of sound because some part is moved periodically by a periodically varying force. This axiomatic statement is made to emphasize the fact that the study of noise is a detailed exact study of the parts which can vibrate and the forces which move them.

Magnetic noise (so called) is that in which the forces are those associated with the varying magnetic flux density. We can limit the study to the vibration of magnetic parts produced by the flux in the adjacent air parts of the magnetic circuit. The conductors themselves can usually be neglected as a noise source as the forces on them, being situated in the relatively weak leakage field, are small. Likewise we can neglect whatever internal stress may exist in the magnetic parts as the rigid parts are not deformed appreciably.

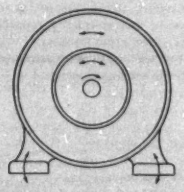


Fig. 1—Torsional Vibration Produced by Two Fields with Like Number of Poles but Different Angular Velocities

The noise producing parts can vibrate in several ways. A torsional vibration of the stator and rotor as a whole results from periodic torque pulsation. Such a vibration may be particularly objectionable as it is transmitted directly through the motor feet to the supporting structure. (See Fig. 1.) Due to the reaction of unsymmetrical supports torque pulsation may also distort the stator from its circular shape. A circular vibration simulating a mechanically unbalanced rotor as shown in Fig. 2 results from an unbalanced magnetic pull. This unbalanced force may revolve in either direction and at other than synchronous or rotor speeds or it may even be stationary. If due to the use of skewed members the phase of the force is not the same for all axial positions it will tend to shake the rotor as well as to bend the shaft, *i. e.*, it simulates two unbalanced weights with different axial and angular positions. The stator may be deflected, as shown in Fig. 3, into a rotating elliptical shape. Similarly, the forces may be balanced on more than two radii resulting in a tendency toward a rotating polygon. The laminations and particularly the teeth may vibrate axially. Experience indicates that teeth seldom if ever vibrate tangentially. The rotor may vibrate axially as a whole, causing noise by striking the bearings.

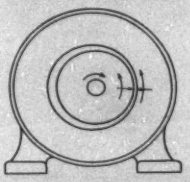


Fig. 2—Rotor Vibration Simulating an Unbalanced Rotor

Most vibrations are forced; *i. e.*, their frequency is not near a critical frequency. In this case the vibration is proportional to the force and inversely proportional to the rigidity of the parts. However, since there are several causes for flux density variation and hence several frequencies of applied forces, there is considerable chance of encountering a critical vibration in which a small force produces a large deflection.

1. Electrical Engineer, General Electric Company, Lynn, Mass.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

### Magnetic Forces

At every point on the air-gap surface there is a directed varying force proportional to the flux density squared. The summation of the tangential components of force is the total torque. The radial components according to their configuration tend to distort the parts.

As is well known and contrary to elementary text book theory, the air-gap field is at no instant distributed according to a simple sinusoid and the distribution changes as it rotates. This is equivalent to saying

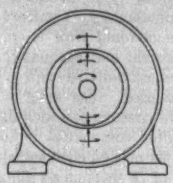


Fig. 3—Elliptical Vibration of Stator

that in addition to the fundamental field there are other fields with other than fundamental number of poles and some with other than fundamental frequency.

It is evident from consideration of energy that torque pulsations will result from the presence of two fields having the same number of poles and rotating with different velocities. The worst case and possibly the only one which is a serious noise factor is that in which there is a backward revolving field produced by single-phase operation, unbalanced applied voltages, or unbalanced windings.

It has been shown by Fritze[2] and also by Chapman[3] that two fields differing by two poles produce an unbalanced magnetic pull as illustrated in Fig. 2. In Fig. 4 instantaneous values of the radial forces are plotted for a field having a two-pole and a lesser four-pole component to show the superposition of this unbalanced radial pull on the high harmonic force components. The shape of this force curve changes as the fields rotate but there is always present the same radial unbalanced component which may be stationary but which usually rotates. The noise produced is like that of a motor with an unbalanced rotor revolving at the speed of rotation of the unbalanced component.

It can also be shown (see Appendix A) that the combination of two fields differing by four poles or a single two-pole field tends to distort the parts into a rotating ellipse. In general the combination of two fields having poles whose sum or difference equals any given number $g$, or a single $g/2$ pole field tends to distort the stator or rotor into a polygon having $g/2$ sides and usually rotating.

2. *Archiv fur Elektrotecnik*, Vol. 10, pp. 73-95, July 23, 1922.
3. *I. E. E. Jl.*, Vol. 61, No. 313, pp. 39-48, Dec. 1922.

There is always present a double line frequency axial vibration of teeth and punchings best corrected by tight clamping and impregnation. Frequency is double because the forces are proportional to the flux density squared.

The method of determining the noise tendency of a motor is to tabulate qualitatively all of the possibly existing fields and examine for two fields differing by two poles, four poles, etc., or two fields with the same number of poles revolving at different speeds. The disturbing pairs of fields are examined more critically and roughly quantitatively with regard to magnitude, frequency, and rigidity of parts. With these data the quality of the finished design becomes dependent upon the skill of the designer in combining parts to obtain results which can be predicted rather than the chance results of applying less fundamental rules.

It is beyond the scope of this paper to make a thorough study of the air-gap fields except perhaps to enumerate the order of the fields probably existing and the factors upon which their magnitude depends in order to point out how the several design features are

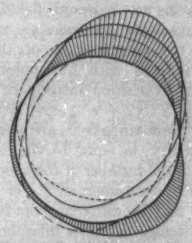


Fig. 4—Radial Face Produced by the Combination of a Two- or Four-Pole Field

Heavy circle is reference zero line
Dotted curve is $\sin x$
Dash curve is $\frac{1}{2} \sin (2x - 15 \text{ deg.})$
Full line curve is flux density, $\sin x + \frac{1}{2} \sin (2x - 15 \text{ deg.})$
Radially shaded area represents radial force, $[\sin x + \frac{1}{2} \sin(2x - 15 \text{ deg.})]^2$

related to magnetic noise. The fields existing in an induction motor air-gap may be roughly classified with regard to source as follows.

1. Fundamental for which motor is designed.
2. Stator magnetomotive force harmonics.
3. Stator magnetomotive force sub-harmonics.
4. Rotor magnetomotive force harmonics.
5. Rotor magnetomotive force sub-harmonics.
6. Gap eccentricity permeance variation.
7. Stator slot permeance variation.
8. Rotor slot permeance variation.
9. Permeance variation due to saturation.
10. Slot pattern permeance variation.

As is well known with a symmetrical winding, the magnetomotive force in addition to the fundamental contains harmonics of order, $N = (\pm)\,(2\,\phi\,g \pm 1)$

where $N$ = order of harmonic, $\phi$ = number of phases, and $g$ = any positive integer. The sign indicates the direction of rotation. In a squirrel-cage winding the number of phases equals the number of bars per pair of poles and produces the corresponding harmonic magnetomotive force. A non-symmetrical winding produces other fields having fewer than fundamental number of poles. The magnitude of the magnetomotive force waves is inversely proportional to the order, is proportional to the current in the winding, and is dependent upon the well known pitch and distribution constants. The flux field produced is approximately proportional to the magnetomotive force and inversely proportional to the air-gap unless there is a closed secondary circuit to such a field in either winding. It should be recognized that while the fundamental flux is proportional to the magnetizing current the harmonic flux is proportional to the total current if there is no suitable closed low impedance secondary circuit. In the latter case the flux is greatly reduced.

In addition to these so-called harmonic fields, the presence of slot openings, and other irregularities in the air-gap introduce other disturbances in the flux equivalent to introducing new harmonic fields. These may be called permeance fields. If there are $m$ equally spaced irregularities, the combination of the fundamental magnetomotive force with $2N_s$ poles and the $m$'th order permeance variation introduces new fields, the largest having $2(N_s + m)$ and $2(N_s - m)$ poles. The important permeance fields are given by $m$ equal to one for eccentricity, $m$ equal to the number of stator slots, $m$ equal to the number of rotor slots, and $m$ equal to the difference in numbers of stator and rotor slots. The frequency may be different from fundamental and the fields may rotate in either direction. The magnitude of the field is approximately equal to the magnitude of the disturbance in the even gap permeance; *i. e.*, the amount of eccentricity or the effective slot opening.

## Tests

Some 1500 motors of about 200 distinctly different designs have been tested with regard to noise. These are assorted over a range of ¼ to 15 hp., 25 to 60 cycles, two- and three-phase, different types of squirrel-cage rotors including single and double windings, slip-ring motors, all overhung slot riveted frame construction. In many cases a motor of a particular rating has been made and tested changing pertinent factors one at a time. As the volume of test results is entirely too large for adequate presentation the following general digest is offered.

No case has yet been found entirely inconsistent with this theory. Only a few cases have been observed noticeably inconsistent. With few exceptions the observed noise has agreed very closely and in detail with that predicted by the methods here presented. The agreement has been particularly good in those cases where a design has been modified to correct an existing noise tendency and in those cases where the design has been changed one factor at a time.

Before presenting any illustrative examples, a description of the method used for measuring noise is in order. It has been found that the human ear and judgment is adequate to measure the disagreeableness of noise if assisted by a standard for comparison. With this standard at one end and the motor being tested at the other end of a room designed with such absorption characteristics as to simulate the absence of walls an observer midway between the two noise sources is impressed equally by them if they are of the same degree of disagreeableness. This method is essentially analogous to the photometer. Contrary to the general impression, the personal error is small and measurements are consistent and adequately precise. In the absence of a commercially recognized unit an arbitrary scale has been used. The scale is an arithmetical progression of disagreeableness such that the noise of the quietest individual commercial motor is recorded as one and that of the noisiest commercial motor about five.

The average of 28 tests on six different sizes of four-pole, three-phase, squirrel-cage motors with 36 stator slots, 7/9 winding pitch and 45 rotor bars, gives a noise reading 1.7 at no-load and 2.4 at full load. The increase in noise with load less rapidly than the primary current is increased would suggest as a cause the combination of primary harmonic fields and permeance fields except that some of the individual motors presumably with even gaps test 1 at no-load and 3 at full load which clearly points to a secondary harmonic field for at least one of the principal noise producing fields. The 23rd stator harmonic with 96 poles and only slightly damped by a 45-bar rotor winding, cooperating with the 94-pole rotor harmonic, the two differing by two poles, constitute the required condition for rotor vibration. The unbalanced pull is proportional to the product of the magnitudes of the two fields. As at no load the rotor harmonic field is zero, the motor is quiet. Under loaded condition both disturbing fields increase and hence the noise rapidly increases.

The use of a 44-bar rotor changes the 94-pole rotor field into one with 92 poles differing by four poles from the 23rd stator harmonic. This constitutes the condition for a rotating elliptical vibration of the stator. However, as the four-pole yoke section is for other reasons quite rigid there should be a distinct improvement. Tests have been made on 17 motors using this 44-bar rotor covering the same range in ratings but averaging 30 per cent larger in horsepower. The average no load noise is 1.3 and the average full load noise is 2. Also, the distinct difference between no load and full load noise in individual machines has disappeared.

A similar case relates to a group of small eight-pole, three-phase, squirrel-cage motors with 48 stator slots, 5/6 winding pitch, and 57 rotor bars. The average of tests on 74 motors gives a noise rating 1.9 at no-load and 2.5 at full load. In this case the noise is

caused by the combination of the 104-pole primary harmonic and the 106-pole secondary harmonic. Changing to 68 rotor bars decreases the noise to 1.2 at no-load and 1.5 at full load as the average of 20 somewhat larger motors.

A group of six-pole, three-phase, squirrel-cage motors with 54 stator slots, 7/9 winding pitch, and 68 rotor bars test consistently 2 at no load and 3 to 4 at full load. The noise is caused by the combination of the 138-pole primary harmonic and the 142-pole secondary harmonic, which differing by four poles, constitutes the condition for elliptical vibration of the stator yoke. Changing to 66 rotor bars gives 1½ to 2 at both no-load and full load.

A group of small eight-pole phase-wound secondary motors with 54 stator slots, 8/9 winding pitch, and 48 rotor slots, 5/6 winding pitch, both wound for three phase, was tested with a poor unsymmetrical primary grouping such as to introduce a backward revolving fundamental field and both two- and four-pole sub harmonic fields with their harmonics. The combination of sub harmonic fields differing by two poles caused very bad rotor vibration. The use of a larger shaft reduced the noise. The arrangement of primary groups was next changed to eliminate the backward fundamental and the two-pole sub-harmonic fields but leaving the four-pole sub-harmonic field. Using the original small shaft, the noise was reduced to 4. In this case the disturbing factors are closely associated with the fundamental field and its harmonics differing by four poles from the four-pole sub-harmonic field and its harmonics. The rotor vibration was practically eliminated but the stator vibration was still present. The stator was next made with a symmetrical winding in a 72-slot stator with a reduction in noise to 2.

Several summarized general statements can be made based on this method of noise prediction and confirmed by tests.

An eccentric air-gap is always a serious noise source as it introduces two new fields with two more and two less than the fundamental number of poles and thus tends to cause rotor vibration. In squirrel-cage motors with few poles these fields are partially damped by secondary currents. An increased air-gap usually decreases noise at the expense of power factor as the permeance variations are decreased and also harmonic fields are less since if undamped they are proportional to the total current in the winding and inversely proportional to the gap.

With otherwise equivalent design a motor with a phase wound rotor is usually more noisy than a similar squirrel-cage machine. The slip ring motor generally has fewer rotor slots with wider slot openings and hence the permeance variations are greater and of a lower order. In a slip-ring motor choice of number of rotor slots is more restricted. A squirrel-cage winding damps many more fields than a polar winding. In a slip-ring machine secondary harmonic and sub harmonic fields are frequently more serious.

Noise is reduced by lower flux density if it is caused by fundamental or permeance fields. In this case the forces are proportional to the square of the fundamental flux density. Other fields depend upon primary or secondary ampere turns and may be decreased or increased by changed fundamental flux density.

The use of skewed rotor slots is an effective means for correcting noise due to high order fields. It can be shown that the skew should be equal to an even number of poles as referred to one field of the pair which is the most serious noise producer. A skew of two poles is reasonably effective although four poles is very much better. This desirable skew is usually equal to the pitch of one or preferably two rotor slots.

As until recently more than ordinary quiet operation has been a secondary consideration and as standard parts must be satisfactory for many ratings, there exists in every manufacturer's line a variation in quietness of particular ratings and a lesser variation in individual machines. This will always be the case as the features which make the quietest machine are frequently incompatible with other desirable features.

### Summary

As a general rule subject to the usual imperfections of generalized statements, the avoidance of a backward fundamental field and pairs of fields of appreciable magnitude differing by two or four poles is conducive to quiet operation. Gaps must be even and concentric. Parts must be rigid and punchings tightly clamped. As a rule subject to imposing unnecessary design restrictions and possible introduction of undesirable torque characteristics a motor will be quieter if the numbers of poles, stator slots, rotor slots, difference of stator and rotor slots, and winding repetitions bear simple multiple relationship and the motor is quieter the larger the greatest common divisor of these factors.

## Appendix A

The radial component of air-gap flux density may be expressed in wave equation form as a series of trigonometric functions of angular position and time.

$$\beta = \Sigma \beta_k \cos (k x - l t + \theta)$$

The summation is made for the several necessary values of $k$ and $l$. $2k$ is the number of poles of a given sinusoidal component, $l/2\pi$ is the equivalent frequency, and $\theta$ is a general phase difference angle.

Assuming that the radial force is proportional to the square of the radial component of flux density,

$$F = (1/8\pi) [\Sigma \beta_k \cos (k x - l t + \theta)]^2$$

This force is a function of angular position and time and can be expanded into a series of sinusoids. Let $F_{M_k}$ be the coefficient of the $M$'th space order cosine term in the expansion of $F$.

$$F_{M_k} = (1/8\pi^2) \int_0^{2\pi} [\Sigma \beta_k \cos(k x - l t + \theta)]^2 \cos M x \, d x$$

Expanding the integrand, the general term is
$\beta_1 \beta_2 \cos (k_1 x - l_1 t + \theta_1) \cos (k_2 x - l_2 t + \theta_2) \cos M x$
in which $k_1$ and $k_2$ may be the same or different.

$F_{M'} = 0$ unless $k_1 \pm k_2 \pm M = 0$ in which case

$$F_{M'} \alpha \beta_1 \beta_2 \cos [ (l_1 \pm l_2) t + \theta]$$

The sign of $l_2$ is the same as that of $k_2$ which makes $k_1 \pm k_2 \pm M = 0$

Likewise, if $F_{M'}$ is the coefficient of the $M'$th space order sine term in the expansion of $F$,

$$F_{M'} \alpha \beta_1 \beta_2 \sin [ (l_1 \pm l_2) t + \theta]$$

Thus $\quad F_M \alpha \beta_1 \beta_2 \cos ]M x - (l_1 \pm l_2) t + \theta]$

For $M = 1$, *i. e.*, with two fields differing by two poles there is a force simulating a mechanically unbalanced rotor revolving with speed $l_1 - l_2$ tending to displace the rotor or stator as a whole. For $M = 2$, *i. e.*, with two fields differing by four poles there are forces balanced across any diameter, rotating with speed $\frac{1}{2} (l_1 - l_2)$ tending to distort the rotor and stator into a rotating ellipse. Also a single two-pole field produces the same kind of force rotating at speed $l$. Carrying out the suggested mathematical deduction in detail shows that in this case the proportionality constant is one-half that in the case of two fields with unlike numbers of poles. Similarly, with two fields differing by any number of poles or a single field of half that number of poles the rotating forces tend to deform the stator and rotor into a rotating polygon of like number of sides. Forces are proportional to the product of the absolute values of the offending fields.

When the vibration is produced by a single field the noise frequency is twice the frequency of the field. When the force is produced by two fields their frequencies or direction of rotation must be different to cause noise producing vibrations. With two fields revolving in the same direction the noise frequency is the difference in frequencies of the two fields. If the fields revolve in opposite directions $l_2$ is inherently negative and the noise frequency is the sum of that of the two fields. Since most fields are either exactly or nearly fundamental frequency the most common noise frequency is exactly or nearly double applied line frequency.

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### Noises in Electrical Machinery

#### Books

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Eason, A. B., "Prevention of Vibration and Noise," Bibliography, p. 2.

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## Discussion

**H. C. Specht:** The problem of building induction motors with a minimum of noise has caused the engineer a great deal of worry. In spite of all the theory that is known to us, keeping the undesirable noise out of the motor still remains a difficult art. I agree with Mr. Hildebrand that the unbalanced forces caused by harmonic fields are about the most troublesome factors. Already Dr. Stiel, H. Fritze, and F. T. Chapman have shown this by a very detailed analysis and Mr. Hildebrand by his analysis, arrives at the same results. If this were the only cause of magnetic noise, it would seem to be a rather simple problem to design quiet motors. For ordinary service where the quietness of operation is not of so great importance, this rule alone may be sufficient. However, in recent years there have come up applications, particularly for small motors, where an almost dead silent operation is demanded. For such motors we must take into consideration many other factors that enter into the problem of noise.

One factor, and a very important one, is the skew of either the stationary or rotating member. In order to minimize noise and to obtain uniform starting torque in all rotor positions, most small induction motors are built with a skew. Unfortunately there seems to be no exact theory available as to what degree the rotor should be skewed. Mr. Hildebrand makes a statement in his paper that the skew should be equal to an even number of poles of those harmonics which are the most serious noise producers. I wonder if this can be accurately proved by an analytical theory. So far, all the theory on harmonics is based on straight cores.

I do not quite agree with the author that the teeth vibrate only axially and seldom tangentially. In my opinion this depends very much on the width and length of the teeth. It has been my experience that short, wide teeth give less noise than long, narrow ones. Since the laminations were of the same thickness the axial vibration would not change materially; therefore I assume it can be only the tangential and radial vibration. No

doubt the zigzag leakage in induction motors has a great bearing on the noise. The vibration of the teeth as well as the tooth tips may be tangential as well as radial. I have tried motors without dipping them in varnish or bakelite so that the laminations in axial direction could move fairly freely. However I have noticed only a slight difference compared with motors that were dipped and baked having a more rigid body. This seems to me also somewhat of a proof that the axial vibration of the teeth is bothering only a little, if at all. However, axial vibration of the rotor may be of a serious character if the laminations are not built up accurately at right angles to the axis or if the core is skewed considerably. Furthermore, we assume in our theory that the air-gap is always uniform; as a matter of fact, this is seldom true and particularly not when the surface is not ground to size. It should be remembered that the air-gap in induction motors is very small, varying in size from 0.010 in. upwards, depending on the size and speed of the motor. As a rule, manufacturing tolerances of 0.002 of an inch or more have to be allowed; this is certainly a great percentage of the specified air-gap. On motors with a larger number of poles this is not so serious but, for example, on a four-pole motor, which is about the most common case, the unbalanced pull due to this irregularity would be quite considerable.

Another important factor in the problem of noise is the mechanical construction as a whole and the mounting of the motor. If there are periods of natural frequencies that are in resonance with any frequency of the magnetic vibrations, the noise may be amplified to a very objectionable degree. For example, a thin cast iron housing, round in shape, with end brackets of a bell shape, will have periods of natural frequency which very often happen to be in the order of the magnetic noise frequencies. If this is the case, the original noise may be amplified many times. On the other hand, if the motor is to be mounted on a construction which has a natural frequency somewhere near the various frequencies of the vibrations in the motor, the noise may be increased terrifically. As an example, we may take this case of a blower motor for an oil furnace; in this case the motor is usually connected directly to the oil burner structure. It is surprising how noisy a motor, which on the test bench in a noise-proof room was found to be very quiet, would sound running mounted on an oil burner. The same difficulty was experienced with motors for household refrigerators and therefore most of the manufacturers have adopted flexible mounting, using springs or material of a flexible nature. For such quiet operation it will also be necessary to keep the flux density in the gap and iron parts very moderate.

There are many more factors that have to be considered in order to obtain real quiet motors but the few points I have brought out may be sufficient to show that the problem of noise will remain a very difficult one. Nevertheless, this should not discourage us, for by carrying on the study we may succeed some day in predetermining the quietness of a motor. Also, it seems to be very desirable to have more papers on the subject of noise brought before the Institute in the future for discussion.

**R. E. Hellmund:** A careful study of Mr. Hildebrand's paper reveals that the paper covers in terse statements, either directly or by inference, a very large percentage of all the causes of noise in motors as well as the factors entering into the problem. For this reason, the paper is a very valuable contribution to the art.

Somewhat contrary to Mr. Hildebrand's opinion, I am rather inclined to believe that the scarcity of papers on this subject is not so much due to the fact that the matter has not been held of sufficient importance in the past, but rather to the fact that this problem of noise is a very difficult one as far as correct analytical determinations are concerned. It is true that the requirements for quiet operation of machinery are becoming more rigid right along; nevertheless, noisy motors have been a problem with the designers of motors for a great many years. In addition to the many factors referred to in the paper, others can be mentioned, an example being the great influence of the weight and mass of the parts, a point scarcely touched upon in the paper. The principal difficulty is that many of the factors covered in the paper by one or two sentences would require for their complete analysis calculations and explanations filling several pages.

One fact that makes the analytical study of noise in the induction motor particularly difficult is that the fundamental fluxes, as well as certain of the harmonic fluxes and their influence upon noise, are considerably affected by the damping actions of the secondary, while certain other harmonic fields, especially those caused by zigzag leakage, are not subject to any damping effects. This makes it necessary to study very carefully not only the causes and characteristics of the various fields but also the damping effect to which they are subjected. This may be readily demonstrated by discussing a few simple examples.

Let us consider first the simple case of a two-pole motor and assume that it has a squirrel-cage secondary with very low resistance. In this case, with the motor running, all harmonic fields caused by improper chording of polyphase windings or im-

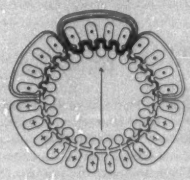


Fig. 1

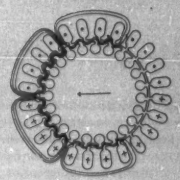


Fig. 2

Plate A

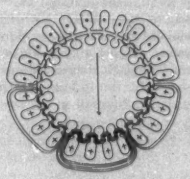


Fig. 3

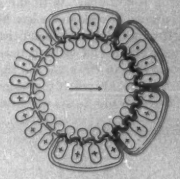


Fig. 4

Plate A

proper distribution of single-phase windings, that is, all differential leakage fluxes, are damped out. Furthermore, the secondary will damp out any irregularities in the fluxes which might be caused by irregularities of the air-gap. As a consequence, there will be no unbalanced magnetic forces on the rotor from such causes, and therefore no noise from these causes. This is, of course, under the assumption that the main flux is not able to distort the rotor elliptically, an assumption which is usually correct with the very deep and therefore stiff punchings of two-pole motors. The main flux while rotating can, of course, also elliptically distort the stator punchings and thus cause noise. However, here again the relatively deep and stiff punchings of the stator are of considerable assistance in eliminating noise. I do not know of many cases where noise has been traced to the elliptical distortion of two-pole stators in induction motors by the main flux, but I have run across a number of cases where elliptical stator distortion has been responsible for noise in some two-pole induction regulators.

As previously mentioned, the damping effect of the rotor does not influence the zigzag leakage fluxes. Figs. 1, 2, 3, and 4,

Plate *A*, show these zigzag leakage fluxes for the case of a two-pole motor with one slot less in the rotor than in the stator for four different relative-tooth positions. The four figures show the differences caused by moving the rotor one tooth pitch. It can be readily seen from these figures that the zigzag leakage fluxes are very much unbalanced and that the unbalancing rotates 360 deg. around the circumference and fluctuates in amplitude while the motor moves one tooth pitch. I have found quite a number of cases where this or similar unbalance has caused vibrations and noise in fractional horsepower motors

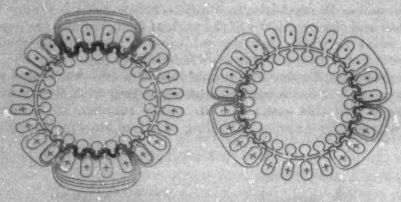


Fig. 1 Plate B Fig. 2

either by a deflection of the shaft or by looseness of the bearing. This condition is especially likely to result in noise with frictionless bearings having slight clearances. A difference of one slot between the stator and rotor has been chosen here as an extreme case. Such a condition is not likely to occur in practise, but similar conditions, although less extreme, may exist with any odd number of slots in the rotor, a construction which has been frequently employed in the past in order to avoid dead points under starting conditions. With the greater masses in large motors, this condition is of course less likely to cause noise. Nevertheless, it is nearly always safer, especially in small motors, to use an even number of slots in the rotor. Figs. 1 and 2, Plate *B*, indicate that in this case the zigzag leakage is always balanced. With uniform air-gap it is of course possible that in both Plates *A* and *B* the zigzag fluxes will bring about distortion in the stator

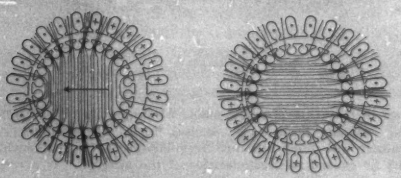


Fig. 1 Plate C Fig. 2

and, especially in Plate *B*, an elliptical distortion would seem possible, assuming that the stiffness and mass of the stator are not sufficient to counteract such tendencies.

So far, low secondary resistance has been assumed. As soon as rotors with high secondary resistance are used, certain main flux unbalanced conditions are possible, as well as the existence of winding harmonics or differential leakage fields. Not only will such conditions be influenced by the total secondary resistance, but a certain influence upon the various fields will even be caused by the distribution of the total squirrel-cage resistance between the bars and the resistance rings. It is therefore evident that with partially damped main flux irregularities, partially damped differential leakage fields, and undamped zigzag leakage fields, the final outcome is rather difficult of correct analysis.

As indicated in the paper, with wound secondary the damping effects are again different from and generally not as good as in squirrel-cage motors. On the other hand, certain favorable balancing effects, especially with regard to the main flux, can be obtained by connecting oppositely located stator or rotor winding groups in parallel, and the existence of differential leakage fields can of course be greatly minimized by proper chording and winding distribution.

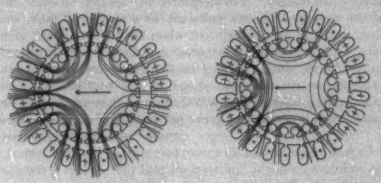


Fig. 1 Plate D Fig. 2

So far, we have essentially considered a two-pole motor, but several of the statements apply to motors of four poles as well. On the other hand, there are certain differences which must be taken into account. Plate *C*, for instance, shows a two-pole motor with eccentric rotor and no damping effect upon the main flux. It is evident that, no matter how unbalanced the air-gap may be in a two-pole motor, the total flux leaving and entering the rotor on two opposite sides thereof must be the same if the center of the flux is as shown in Plate *C*, Fig. 2. However, with the center of the flux as shown in Fig. 1, certain unbalances are possible. This means that with the eccentric and varying pull on the rotor bearings, there is again the possibility of rotor vibration and noise. In Plate *D*, an equivalent four-pole motor

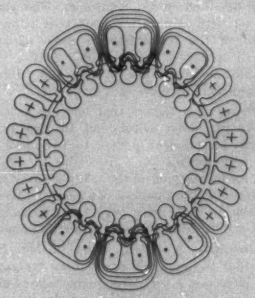


Plate E

is shown, and in this case the eccentric pull on the rotor is always present and reasonably uniform in the same direction, which therefore means that with a four-pole motor less noise might be expected from this cause.

The main flux distorting effect on the stator of motors having four or more poles should, of course, be less if we assume the same stiffness, because such distortion is no longer elliptical. On the other hand, the distortion caused by zigzag leakage fluxes may be elliptical, as shown in Plate *E*, for an even number of rotor slots.

As in the case of the two-pole motor, the zigzag fluxes, however, are balanced with regard to the rotor and therefore should not cause any rotor vibrations. Plate *F* shows a four-pole motor with one less slot in the rotor than in the stator, and here the conditions are much the same as with the two-pole motor having the same number of slots, indicating the possibility of rotor vibration in small motors.

Examples of the different possibilities can be multiplied indefinitely, but it is believed that the few examples given will indicate the great many possible varieties and give a somewhat clearer picture of some of the conditions to those not familiar with the superimposition of various harmonic fields of different types.

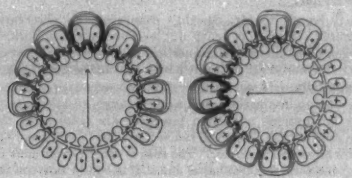


Plate F

Fig. 1 Fig. 2

While, as pointed out, there are distinct difficulties in completely analyzing noise tendencies, it nevertheless seems desirable to devote a good deal of further attention to this subject and to work up various additional papers and calculating methods. Even data collected relating to the predominating causes of noises in different types and sizes of motors should prove of value as they would reduce the analytical work necessary for the various ranges of size in individual types of motors.

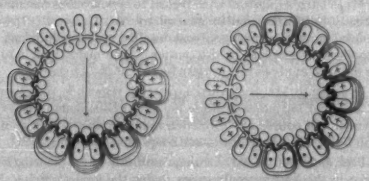


Plate F

Fig. 3 Fig. 4

**R. L. Young:** We have been following motor noise characteristics closely for the past 20 years or more. It seems obvious that when a number of machines ranging perhaps up to 75 hp. are to be put in an office near where a wire chief's staff must carry on telephone testing, they must be reasonably quiet. Further, it is often desirable to run these machines all night and some central offices are located in residential districts where a very small noise is noticeable while people are trying to sleep. A great deal of work, therefore, was done in cooperation with the manufacturer during 1911 and 1912 involving trials of skewed slots, reduction of windage, low magnetic saturation, prime rotor slots, and other features. Finally, a very satisfactory line of induction motors was evolved, although there were as many as a dozen different designs of a single size, for example 20 hp., built up before the desired results were obtained. It might be mentioned that these highly satisfactory results were obtained at that time largely through the work of Mr. F. J. Rudd and others in the same engineering organization to which the author belongs.

The difficulty mentioned by the author in securing a suitable method of noise measurement was experienced and finally two or three representative motors were picked out, which were run under specified conditions, as standards of maximum noise. They were polyphase motors run single-phase to make a fair amount of noise, and test inspectors were told that all the motors accepted must sound at least as quiet as these. If the work were being done now, however, I believe we should consider the audiometer recently developed by the Bell Telephone Laboratories which has been used with success in measuring certain mechanical noises. If desired it would appear practicable to make a phonograph record from a typical motor and use this as a standard of comparison in terms of which other motors could be rated, without the necessity of operating the standard motor during tests.

At present the noise situation isn't so acute. With the coming of the dial central offices, which require considerably more power, it is usually desirable to have a separate machine room which is now seldom located in the part of the building where the wire chief has to test or where the commercial department may have offices. Another complication, however, has arisen, resulting from the practise of power companies in gradually putting into effect requirements for higher power factor. Induction motors are likely to draw penalties, since they don't have very high power factors, particularly if run at light load for parts of the day. It is then necessary, in general, to use some synchronous motors to bring the average up to perhaps 85 or 90 per cent.

The synchronous motors have been found to be very much noisier than the specially quiet induction motors formerly used. This is to be expected, since, to mention a single feature, they have salient poles which make a considerable whistle as they pass the ventilating openings, and the design has apparently not received much attention to secure quiet operation. The large increase in noise has led to some unfavorable comment.

This brings me to the question that I should like to ask the author, assuming that the synchronous motor is nearly enough like the induction motor to benefit in some degree by the studies of quiet operation made for the latter. I should like to know what the possibilities are of obtaining quiet synchronous motors in sizes from 25 to 100 hp.

**O. Graham:** The methods employed by Mr. Hildebrand in the study of induction motor noise are applicable to other types of machines. I have been interested in similar noise problems in synchronous motors and generators and have found the study of various harmonic fields to be fruitful. In large synchronous machines using fractional slot windings the sub harmonics are particularly troublesome unless care is taken in the selection of the number of stator slots.

As pointed out in the paper a table of the orders of the existing harmonics will show very quickly whether or not the possibility of trouble exists, although a quantitative examination of these harmonic fields is necessary before one can be sure that trouble will occur. It sometimes happens that two sets of forces exist, each of which alone is capable of producing elliptical vibration, although their phase positions may be such that they nearly cancel one another, and a quiet machine results. I have in mind a case in which a two pole sub-harmonic field was present, but the machine was noticeably quiet. Further analysis showed that there was also a pair of fields differing by four poles, whose sum almost completely cancelled the effect of the two pole field. The outcome is less fortunate if the two kinds of fields happen to be in phase instead of being out of phase.

It has been found that the question of *resonance* is important in large machines. Calculations and measurements of the vibrating periods of stator structures have shown that it is quite possible to get natural frequencies in the range of 120 cycles per second, which is the frequency of the major flux pulsations in 60-cycle machines.

Another point of difference between the large diameter multipole class of machines and the smaller motors with few poles and relatively rigid stators is that in the former a force distributed in four poles or even more may give trouble. Mr. Hildebrand points out the source of such forces in his statement covering the force polygon with $g/2$ sides.

One further difference which I believe exists between the synchronous machine and the induction motor noise problem is the absence, in synchronous machines, of the case in which the offending fields differ by two poles. It seems to me that this type of unbalance requires primary and secondary members with different numbers of phases. The synchronous machine, in addition, has another type of magnetic noise not dependent upon stator current which produces sounds in the range of slot frequency.

**C. A. M. Weber:** The noise problem which is covered in part by Mr. Hildebrand is not a new problem but rather a problem which is receiving more consideration today than formerly because the public is rapidly becoming more noise-minded. Designers have always considered noise problems in connection with their designs but in view of the increasing demand for quieter motors, designers have had, during the past few years, a greater incentive to investigate the question of noise in rotating electrical machinery.

As an illustration of the importance of this matter I wish to mention that the National Electrical Manufacturers Association, at its last annual meeting, appointed a committee to investigate the question of noise in rotating electrical machinery particularly from the point of view of the various instruments and devices available for the purpose of measuring such complex noises as occur in rotating electrical machinery.

Such contributions as the author's paper and the ensuing discussion and future papers on this subject will be of considerable assistance to this committee of the National Electrical Manufacturers Association. As a member of this committee I feel that designers familiar with the noise problem in rotating electrical machinery should be encouraged by the Institute and others to write papers on this subject and to enter freely into discussions of the various phases of noise so that this committee and others may benefit by the many years of experience of designers in reducing the noise in rotating electrical machinery.

**C. J. Fechheimer:** In the analysis of noise problems of electrical machinery, we must consider three sources:

1. The noise due to windage;
2. The noise due to the main magnetic flux;
3. The noise due to the leakage fluxes.

These can be readily separated in machine. To determine whether it is windage noise, the machine can be run at normal speed without any excitation. For the induction motor it means that the machine is run up to normal speed without any load and then disconnected from the circuit. For the synchronous and other machines, of course, the method is obvious.

The noise due to the main magnetic flux can be determined by exciting the machine without any load. Then, as the load comes on, we can determine whether the noise is increased and if so it would be due to the leakage fluxes.

**L. E. Hildebrand:** The discussion has indicated that some parts of this paper are too brief. As Mr. Hellmund has pointed out the last three paragraphs of that part of my paper under the general subject of magnetic forces contains either by terse statement or inference a skeleton for the analysis of the air-gap flux which leads to an understanding of the magnetic forces. My method is to use the approximate so-called magnetic Ohm's law to express the magnetomotive force and the permeance each as trigonometric series in wave equation form. The product of these two series gives an indication of the number of poles and equivalent frequency of the principle harmonic fields together with an indication of the magnitude. Of course as has been pointed out both in my paper and by Mr. Hellmund, damping must be considered. Mr. Hellmund's diagrams show pictorially and physically rather than mathematically what these harmonic fields are like.

With regard to Mr. Specht's discussion, his observation of tangential vibration of teeth will lead me to watch more closely for such phenomena. His question with regard to skewed slots may be answered generally by a reference to the force equation in the appendix. If we consider that this equation expresses the force on one lamination, add a phase angle to take care of the other laminations and then integrate the expression axially, the result indicates that the radial force has been broken up into a main force and a couple. The case is exactly analogous to two unbalanced weights instead of one. If the rotor slots are skewed exactly two poles as referred to one of the offending fields, the main force is eliminated but there still exists a couple tending to shake the rotor. If the rotor is skewed four poles both the main force and the couple are eliminated, *i. e.*, the case is analogous to three rotating weights.

A statement has been made with regard to the avoidance of an odd number of slots with which I cannot agree. We may consider a case in which the poles, stator slots, and rotor slots are all divisible by three. Whatever is happening on one radius at one instant is also happening on two other radii spaced exactly 120 degrees at the same instant and the forces are balanced as a "Y" connected system. In this case the number of slots can be odd.

Mr. Young's question with regard to synchronous machines has already been answered in general by Mr. Graham. The same general methods of analysis and detailed study will make a quiet synchronous machine or d-c. motor. The main thing is to do it by detailed analysis rather than by rule of thumb methods.

In reply to Mr. Bela Gati's question regarding the generation of a second harmonic voltage no such phenomenon has been observed. Of course any vibration must produce a voltage distortion but of what magnitude and frequency I do not know.

I am indebted to Mr. Graham and others for pointing out an error in the first example given under the subject of test. The 23rd harmonic is 92, not 96 poles. But the general reasoning is not materially changed. The 23rd harmonic with 92 poles differs by two poles from the 94 pole rotor harmonic field and constitutes a cause for rotor vibration. Changing to 44 rotor slots changes the 94 pole rotor harmonic to a 92 pole field which by cooperation with the 23rd harmonic constitutes a cause for torque pulsation which according to test results certainly is not very serious.

# SYMPOSIUM ON LIGHTNING

## Lightning on Transmission Lines

### Cathode Ray Oscillograph Studies

BY J. H. COX* and EDWARD BECK*

Associate, A. I. E. E. Member, A. I. E. E.

*Synopsis.—This paper is a review of the work done and results obtained in Norinder-type cathode ray oscillograph studies of lightning on transmission lines during 1929. The various installations and methods of test are described. The wave shapes recorded are illustrated and their meaning discussed. The paper also contains a preliminary description of an artificial lightning investigation, using a portable 1,000,000-volt surge generator and a portable cathode ray oscillograph. The methods used and some of the preliminary results are discussed.*

* * * * *

THE summer of 1928 saw the first concerted effort, likely to bring results, to determine the exact characteristics of lightning disturbances on high-voltage transmission lines.[1,2] This was made possible by the development of the cathode ray oscillograph, the only available device for making complete records of voltage transients of the speed of lightning surges, to the automatic stage so that it will respond to and record transients whose time of occurrence cannot be foretold. An outstanding contribution in this application of the cathode ray oscillograph was made by Dr. Norinder, whose development permits the oscillograph to be energized prior to the time of an expected transient and which acts as its own relay to record any chance lightning surge in its entirety. This instrument was briefly described at the Winter Convention of 1928.[1] During the lightning season of 1928 the Westinghouse Company, in cooperation with the Aluminum Company of America, set up and operated two stations with such oscillographs on the 154-kv. Cheoah-Alcoa transmission line in Tennessee. One oscillographic record of a natural lightning transient was secured in this preliminary investigation. This first year's work proved the adequacy of this type of recording apparatus and laid the foundation for further effort in 1929.

In 1927 preliminary work had also been done in the investigation of the behavior of transients on a transmission line using a surge generator, cathode ray oscillograph and a five-mile, 22-kv. idle line loaned by the Duquesne Light Company.[3] This work also has been continued on a much greater scale on a 220-kv. idle line with a one million-volt portable surge generator and a portable cathode ray oscillograph of the Norinder type.

The complete lightning problem on transmission lines may be divided into three phases. The first is the nature of natural lightning surges as they occur on lines, and this must be determined by collecting data on the characteristics of this phenomenon by means of automatic cathode ray oscillographs connected to lines during storms. The second is the behavior of such transients on transmission lines and is to be determined by applying controlled surges to a line from a surge generator and measuring them under various circuit conditions with cathode ray oscillographs. This method of studying the second phase of the problem is made necessary by the infrequent occurrence of natural lightning transients. The third phase of the problem is the impulse characteristics of insulation, apparatus, and protective devices used on transmission systems. This, of course, is best determined by laboratory studies with a high-voltage surge generator and a cathode ray oscillograph.

#### 1929 Lightning Program

Laboratory investigations with surge voltages have been in progress for several years, as has been the study of lightning on transmission lines by means of the klydonograph. In 1927 and 1928 the field studies of lightning and controlled surges was given greater impetus by the use of the cathode ray oscillograph. To complement the laboratory work with adequate field activity on the problem, the following program of field lightning investigations during the season of 1929 was entered into with the cooperation of the operating utilities mentioned below:

1. Aluminum Company of America. The two stations on the 154-kv. Cheoah-Alcoa transmission line in Tennessee to study natural lightning, and operated in 1928, were continued.

2. Public Service Company of Northern Illinois. A third field laboratory similar to those in Tennessee and to study natural lightning, was installed on the 132-kv. Joliet-Chicago Heights line in Illinois.

3. American Gas & Electric Company. A fourth field laboratory similar to those in Tennessee, and to study natural lightning, was installed on the Turner-Logan section of the 132-kv. system of the Appalachian Electric Power Company in West Virginia.

4. Public Service Electric & Gas Company. A fifth laboratory was installed on the 220-kv. Bushkill-Roseland line in New Jersey, for the purpose of studying both natural lightning and controlled surges.

Experience in Tennessee during 1928 with the first design of Norinder type oscillograph suggested certain modifications in design which would further improve

*Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

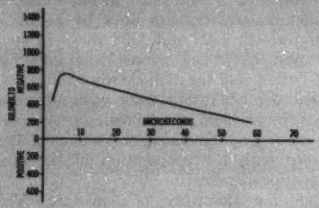
1. For references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

the quality of the records, make the instrument more convenient and flexible in operation and simplify the construction. The new oscillograph was designed by Mr. O. Ackermann and is described by him in a companion paper presented at this Convention.[4] In the 1929 program the three original instruments, with certain refinements, were used in the two Tennessee stations and the Chicago station. Instruments of the new design were used in the West Virginia and New Jersey stations.

The stations, with the exception of that in New Jersey, were essentially the same as described in the Fortescue, Atherton, and Cox paper in that they consisted of a cathode ray oscillograph connected through

a




b

Fig. 1—(a) 750-Kv. Lightning Surges Recorded at Chilhowee, Tennessee, in 1928

(b) Surges shown in (a) Replotted to an Extended Time Scale

a potentiometer to the most exposed line conductor, supported by klydonographs connected to all three conductors at the cathode ray oscillograph station and at a short distance on either side, and other accessories. The line on which the test in New Jersey is being conducted, being in the state of construction and therefore without load, presented a rare opportunity for the pursuit of the second phase of the lightning problem, that of the study of controlled surges, in addition to permitting the recording of natural lightning transients on the highest insulated line in existence in this country. For this reason the oscillograph with all accessories at this location was made entirely mobile by mounting in an automobile trailer and in addition a mobile surge generator good for one million volts and built on a second automobile trailer was provided. Both of these equipments were made entirely self-sustaining by the provision of independent power supply units consisting of mobile gasoline engine generator sets. Either equipment could be moved to various

Fig. 2—Stationary Lightning Laboratory

Tower 89, Joliet-Chicago Heights Line, Illinois

points along the line for the generating or recording of controlled surges with the oscillograph always available for the recording of natural lightning.

## Potentiometers

In the stations erected in 1928 a parallel pipe type of potentiometer was used consisting of three 3-in. iron pipes 10 ft. long mounted with suspension and apparatus

Fig. 3—Cathode Ray Oscillographic Equipment of Lightning Laboratory

Interior of station shown in Fig. 2

type insulators as in Fig. 2. In those stations erected in 1929 a potentiometer consisting of iron rings suspended entirely with suspension insulators was found to be more convenient. These potentiometers are illustrated in Figs. 4a and 5. It has been found by experience both in the field and in the laboratory, that a potentiometer suitable for this sort of work should have as high a capacity as possible without exerting appreciable influence on the transients being studied. At best leakage currents under rain conditions, corona under high-voltage conditions, and changes in surrounding

objects, somewhat modify the potentiometer multiplying ratio. The error involved is not considered to be sufficient to justify elaborate precautions for use in klydonograph tests, but in cathode ray oscillograph tests where the greatest accuracy possible is justified, the rings were made quite large and the upper ring on the potentiometer was made out of 4-in. pipe to keep down the influence of corona at high voltages. The most accurate type of potentiometer has been found to be a non-inductive resistance; therefore, this type

Fig. 4—Lightning Laboratory at Stillwater, New Jersey

(a) Mobile cathode ray oscillograph laboratory
(b) Interior of oscillograph laboratory
(c) Lightning station showing oscillograph laboratory, potentiometers, and living quarters
(d) Mobile surge generator extended for use

has been used in the tests on the idle 220-kv. line. Of course this type of potentiometer is not feasible on energized lines.

## Time Scales

The first Norinder oscillograph used in these field investigations was equipped with a moving film, a high speed being secured by revolving the film on a drum spinning at between 6000 and 8000 rev. per min. This permitted a time scale of about 400 microseconds to the inch and provided a simple method of timing. In the earlier work this had some advantages as the length of the lightning transients expected was not known and the scheme had been used successfully by Norinder. The revolving film drum has proved useful in the measurement of switching surges of long duration. However, the moving film has proved to be too slow for detailed study of lightning or artificially generated transients. Consequently, in the 1929 investigation the film was left stationary and the timing axis was provided by a high-frequency oscillator according to the method of Harrington and Opsahl.[4] This permits great flexibility in timing with possible speeds much faster than have been found necessary for any type of work, thereby securing detail; it also has the advantage of combining this fast timing with long duration due to the fact that the time scale can double back upon itself repeatedly, thus recording the entire transient and any subsequent reflections that may occur. It has one disadvantage in that the records, if they are long, may become complicated because of the repeated crossing of the film but this is overshadowed by its advantages, particularly as it is a simple matter to replot the records to Cartesian coordinates, as has been done in Fig. 7, assuming the frequency of the timing oscillator is properly chosen. It has been found that for the recording of natural lightning disturbances a sweep across the film in 10 microseconds is satisfactory in that it gives detail and records the entire transient without an objectionable number of crossings of the film.

Another method of timing is by the use of a circuit which will sweep the beam across the film only once, thereby providing a linear time scale. This method has a disadvantage in that the record embraces only such phenomena as occur during one passage of the beam across the film. Moreover, to secure a complete record it is necessary to initiate the timing sweep without delay when the transient occurs, otherwise the beginning

Fig. 5—Gradient Station near Chilhowee, Tennessee, showing Klydonograph and Potentiometers

of the disturbance may be lost. However, where the order of duration of the expected transient is known, and provided a system can be secured which produces the sweeping movement with negligible time delay, the inconvenience of replotting each record may be avoided by the use of this time scale. A relay of the Norinder type because it acts with zero time delay lends itself very well to such a timing method as is described in the contemporary Ackermann paper. This has been found very useful in studying controlled transients where the test can be repeated at will, and the time scale adjusted

to the best advantage. Furthermore, now that the approximate duration of lightning transients is known, it is probable that our future investigations of natural lightning will be conducted with this method.

### Gradient Stations

In addition to the equipment connected to the line in Tennessee, four antennas were erected and connected to klydonographs through potentiometers for the purpose of gaining additional information on cloud field gradients. Two of these were 10 ft. above the earth and

Fig. 6—Oscillograms of Lightning Surges Taken on 220-Kv. Line

the other two were 20 ft. above the earth. One of each height was installed on the mountain top and one of each in the valley. Because of the relatively less importance of gradient data the installation of cathode ray oscillographs at these stations was not considered justified and only klydonographs were installed. Although there was a large number of storms there were not many records. The maximum gradient recorded was 20 kv. per ft. and this appeared uniform as the gradient indicated by the high and the low antennas was the same.

### Lightning Surge Records

Considering the fact that in 1928 only one surge was obtained with the two stations in Tennessee, remarkable progress was made in 1929. A large number of records of transients of various magnitudes has been obtained. A striking feature of the season's work was the absence of lightning surges during the spring and early summer at the locations of the stations. All the records obtained were recorded after July 15. Typical examples of the surges recorded are shown in Figs. 6 and 7. Of particular interest is the surge shown in Fig. 6a and replotted in Fig. 7a. In this case the wave front increased at the rate of 143 kv. per microsecond. The voltage rose considerably beyond the range of the film at the particular setting used and at approximately 12 microseconds a flashover occurred on an adjacent conductor reducing the voltage on the conductor to which the oscillograph was connected to one million volts, after which it decayed to 600 kv. at 55 microseconds. At this point the reflected wave arrived from the far end of the line where it had flashed over a non-inductive resistance located at that point, thereby modifying the original tail of the wave. It appears from this record that the voltage on the conductor studied rose to the order of 2,000,000 volts before the flashover on the adjacent conductor took place and did so in the order of 12 microseconds. After this, had not the reflection modified the surge, it would have remained above half value for the order of 75 microseconds. This is one of the longer waves recorded but is typical of most of the surges measured as is apparent from Fig. 9, which shows a group of typical records replotted to the same linear scale. The principal characteristics of these surges are

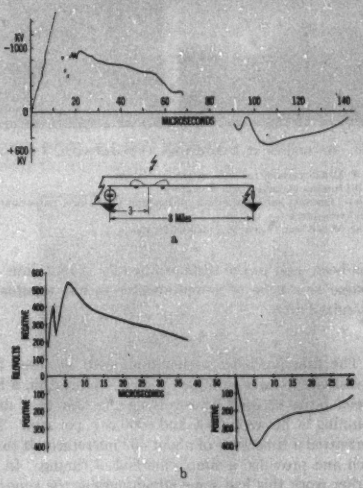


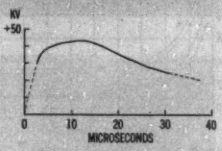

Fig. 7—(a) Surge shown in Fig. 6a Redrawn
(b) Surge shown in Fig. 6b Redrawn

presented in tabular form below the figure. It should be noted that the slopes of both fronts and tails are very much alike for the surges shown in Fig. 9, and this is also true for those which have been recorded but which are not included in this figure. Furthermore, the surge recorded at Wallenpaupack in 1928 and presented at the 1929 Winter Convention[3] had the same general shape. The surges recorded indicate that the lower valued surges are shorter in duration than those

of the higher voltages. Of the waves recorded the fronts have varied from two to ten microseconds, the durations above half value from 10 to 75 microseconds, and voltages from just above line voltage to beyond the range of the instrument at the calibration used.

The field experience of 1929 further substantiates the statement made at the last Winter Convention[1]

a




b

Fig. 8—(a) 45-Kv. Lightning Surge on 220-Kv. Line (b) Surge Replotted to Linear Time Scale

that those surges which have voltages and durations high enough to be dangerous on high-voltage lines are caused by direct strokes, and that induced strokes are innocuous, except perhaps on the lower voltage circuits such as distribution lines. This is indicated by visual observation of many severe strokes close to the line and station which did not cause surges and by the small number of surges per storm. It is also indicated by instances of surges recorded which were known to be caused by direct strokes. These particular records conform in characteristics to the general type of surge recorded and from theoretical considerations it is not logical that direct stroke and induced stroke surges should be similar. It is unlikely that induced transients would have the steepness of front, magnitude, and duration of the higher voltage records. The authors believe that some of the smaller surges, which were shorter in duration, may have been induced by strokes near the line.

The conclusions that all important surges on high-voltage lines are caused by direct strokes somewhat modifies the point of view formerly held regarding lightning on transmission lines. Instead of there being two entirely different types of important surges, the induced stroke amenable to control and the direct stroke entirely beyond control, it now appears that there is no pronounced demarcation and that protection is a matter of degree. This being the case it seems hopeful that protection methods may soon be extended to include those occasional severe strokes which now go beyond control.

## Switching Surge Records

Although previous klydonograph tests have shown that switching surges are not of sufficient magnitude to be important on properly insulated transmission systems, tests were also made to determine the characteristics of such surges. The first records showed that the time scale frequency used for lightning was entirely too fast and the records obtained crossed the film so many times that they were difficult to analyze. Examples of such records are shown in Fig. 10. Subsequent tests were made using the rotating film drum as discussed above and oscillograms taken in this manner are shown in Fig. 11. The striking feature about these records is their duration, which is extremely long

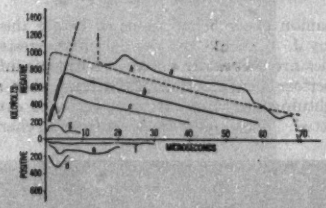



Fig. 9—Typical Lightning Surges Recorded with Cathode Ray Oscillographs

| Surge No. | Oscillogram No. | Polarity | Rate of rise kv. per μ-sec. | Crest kv. | Time: To crest μ-sec. | Time: To ½ max. E μ-sec. | Where taken |
|---|---|---|---|---|---|---|---|
| a | C-6018-C | Neg. | 143 | Unknown 1000 recorded | 7 m-sec. to 1000 kv. | | New Jersey |
| b | | Neg. | 183 | 750 | 5 | 33 | Tenn. |
| c | C-6018-B | Neg. | 270 | 550 | 6 | 26 | N. J. |
| d | C-6018-D | Pos. | 137 | 325 | 3 | 4 | N. J. |
| e | C-5017-I | Pos. | 30 | 180 | 5 | 15 | W. Va. |
| f | 6039-E | Pos. | | 45 | | 30 | N. J. |
| g | 5015-B | Neg. | 167 | 160 | 2.5 | 8 | W. Va. |
| h | | Pos. | 500 | 1000 | 2 | 43 | Trafford Test |

compared to that of lightning surges. It is interesting to note the step-like form of these surges, due to successive reflections from the line ends, showing the typical surge charging or discharging of a line. Further, the low value of these surges confirms the conclusion based on klydonograph tests that switching surges are not of dangerous magnitude, the normal crest voltage to neutral on this line being 108 kv.

### Application of Lightning Data

The particular significance of the lightning data thus far obtained is their relationship to transmission line insulation and protective apparatus. The impulse flashover characteristics of line insulation, as well as the operating characteristics of lightning arresters, have been quite accurately determined by laboratory studies. The work on insulation characteristics is described in a

Fig. 10—Switching Surge Oscillograms—Oscillating Time Scale

companion paper being presented before this convention by J. J. Torok[4] and the lightning arrester characteristics are accurately known. With this information the performance of transmission lines when subjected to lightning surges of the types recorded can now be predicted. The impulse flashover time lag characteristic

Fig. 11—Switching Surge Oscillogram, Linear Time Scale

of insulation as determined at the Trafford High-Voltage Laboratory has been studied with the use of the wave as shown by the dotted curve in Fig. 9h. This wave has a front of the order of one microsecond, which is considerably shorter and therefore more severe than any of the surges thus far recorded, and is steeper than the steepest lightning surge which is likely to occur. It also conforms in shape to the severe observed transients.

An example of the flashover—time lag characteristics of insulation is shown in Fig. 12, reproduced from Torok's paper[4] for purpose of illustration, and shows the impulse ratio curves for standard suspension insulators in strings from 2 to 16, and needle-gaps in air. The significant feature of these curves is that they flatten out at a low impulse ratio in the order of six microseconds. This means that when this type of structure is subjected to lightning surges having the durations secured in the tests thus far, the maximum surge which can be impressed without flashover is very little above the 60-cycle crest flashover of the structure in question. They also show that for a very high, steep surge which reaches the flashover of the insulation in the order of one microsecond, the actual flashover may occur at a voltage of the order of 1.8 times the 60-cycle crest flashover. This latter, of course, determines the magnitude of the chopped wave which passes on and may be impressed upon a piece of apparatus unless it is reduced by lightning arresters, but it should be emphasized that it is impossible for a wave of this magnitude to be impressed upon the line insulation without causing a flashover if the surge has a duration of the

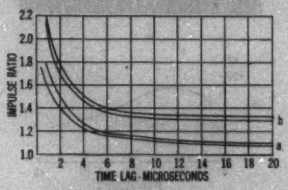



Fig. 12—Impulse Ratio-Time Lag Curves of Insulation

(a) Suspension insulators
(b) Needle-gaps in air

order of lightning surges. These impulse flashover curves, together with the knowledge of the types of surges experienced, permit the intelligent coordination of the various types of insulation in a transmission system. The records secured of natural lightning also furnish data on the amounts of energy that lightning arresters have been called upon to handle and provide valuable information for use in the development of new types of arresters.

### Controlled Surge Study

In the second phase of the work, that of the study of controlled transients, a great amount of valuable information has been and is being obtained. However, these data are not sufficiently analyzed or complete at this time for adequate presentation but will be reported in a subsequent paper. As stated above, the idle 220-kv. line with open ends and sectionalized at one point presented a rare opportunity for the pursuit of this program. Such factors as surge impedance, mutual surge impedance, reflections, and so forth, have been rather completely defined on a theoretical basis but certain quantities in the calculations such as distance of the ground return, size of wire under corona condi-

tions, and so forth, need further investigation. These are being studied. In addition such factors as attenuation due to corona at high voltages and the influence of ground resistance in various connections are relatively unknown. These also are being studied and determined completely with considerable accuracy.

The line on which this work was performed proved particularly convenient for this type of study. With the wide spacing, the mutual coupling was great enough

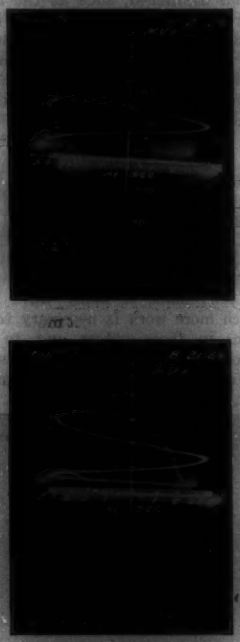


Fig. 13—Oscillograms of Mobile Surge Generator Wave using Oscillating Time Scale

to give induced waves amply large for measurement, and yet not so great that the reverse reaction appreciably modified the original wave. In this way by making various cross connections, such as connecting the outside conductors at the far end and impressing a surge on one conductor with oscillographic measurement on the return of the wave on the other conductor, a great variety of set-ups and tests could be made with all the equipment and the entire force working at one location. However, although the tests require somewhat more time to perform when the surge generator and oscillograph are located at different points, this does not involve great difficulty and operation under such conditions is quite satisfactory.

Furthermore, as mentioned above, the necessity of replotting surges when taken with an oscillating time scale is somewhat inconvenient and this inconvenience is particularly prominent in controlled surge tests where a great number of records are taken in a short time. Therefore, in these tests the circuits were modified to provide a linear time scale. In controlled surge tests this scale has no disadvantage since the length of the surge expected is definitely known and its time of arrival can be chosen at will within the desired limits. The circuit used was a modification of the timing circuit used at the Trafford High-Voltage Laboratory, and described by Torok and Fielder[7] in the *Electric Journal* of July 1929, adapted to use with the Norinder type of relay.

Fig. 13 shows oscillograms generated by the one million-volt mobile surge generator taken with the use of the oscillating time scale. It is noted that this gives

Fig. 14—Oscillograms of Mobile Surge Generator Wave showing Attenuation

(a) Original surge, ½ microsecond front, 940 kv.
(b) Attenuated surge after 2.65 miles of line, 3.5 microsecond front, 350 kv.

a sharp record with a long time scale but requires replotting to be easily readable. Only a small amount of the surge within the target band is missing. Figs. 14, 15, and 16 show oscillograms taken with the linear time scale. These are directly readable and also with this system the entire wave down to zero voltage is obtained.

The waves shown in Figs. 14, 15, and 16 are typical of the work being done. Fig. 14 shows a typical example of records showing attenuation. The upper

oscillogram (*a*) shows an original surge having a front of about ½ microsecond and a magnitude of 940 kv. The lower oscillogram (*b*) shows the same surge after 2.65 miles of line, when it has a front of 3.5 microseconds and a magnitude of 350 kv. Fig. 15 shows similar records except that the original surge had a front of 2.5 microseconds and a magnitude of 875 kv., and the attenuated surge has a front of five microseconds and a

FIG. 15—OSCILLOGRAMS OF MOBILE SURGE GENERATOR WAVES SHOWING ATTENUATION

(a) Original surge 2.5 microsecond front, 875 kv.
(b) Attenuated surge after 2.5 miles of line, 5-microsecond front, 425 kv.

magnitude of 425 kv. This indicates that the short steep front surge attenuated at a greater rate than the larger, slower front surge. These values of attenuation check quite closely with previous klydonograph data. Complete attenuation curves for various voltages and for various conditions are being obtained. Fig. 16 shows records on coupling. Of particular interest is the break in the curves of Figs. 14b and 15 bat about 200 kv. This marks the point where corona begins and shows its effect on attenuation. In Fig. 16 the upper oscillogram (*a*) shows the wave as generated and impressed upon Conductor *C*, the middle oscillogram (*b*) shows the induced wave on the middle or nearest conductor, phase *B*, and the bottom oscillogram (*c*) shows the induced wave on the other outside conductor, phase *A*, 56 ft. distant. It is noted that the induced wave in the conductor 28 ft. distant from the conductor on which the surge is impressed is 22 per cent and on that 56 ft. distant is 11 per cent of the original surge. These values are only slightly above the calculated values, which indicates that the actual image of the conductor is very little below the true image. The self-surge impedance of the line conductors has been determined quite accurately and checks very closely with calculated values when various factors of influence such as distance of the ground return, and increase in size of conductor due to corona, are taken into account. The influence of these factors has been evaluated. In addition, the other problems mentioned, such as the amount and nature of ground wire protection, the influence of ground resistance, the effect of buried conductors, the performance of lightning arresters on lines, and so forth, are being accurately determined and when completed the uncertainty regarding all these factors will have been removed.

## STATUS OF THE PROBLEM

Much progress has been made toward the solution of the lightning problem by the work of all the groups engaged in lightning investigations. Yet it is apparent that caution must be exerted in the interpretation of the results thus far achieved to prevent the hasty drawing of conclusions. Although accurate measurements have been made of many wave shapes and voltages, much more work is necessary to determine the variations in these values and to make our knowledge more definite. It must be realized that it is impossible to draw definite conclusions from what must

FIG. 16—OSCILLOGRAMS OF MOBILE SURGE GENERATOR WAVES SHOWING MUTUAL COUPLING

(a) Original surge, 515 kv.
(b) Induced surge in conductor 28 ft. distant, 115 kv., 22 per cent
(c) Induced surge on conductor, 56 ft. distant, 70 kv., 11 per cent

still be regarded as a relatively small number of records. Considering the infrequent occurrence of lightning surges it is quite probable that a measurement has not been made of a lightning stroke at the immediate point of generation and such a stroke might have a considerably steeper wave front and higher magnitudes than those measured thus far. At best all that has been measured thus far has been the maximum voltage as

limited by line insulation and although the crest can be estimated from the shape of the front and tail it is desirable to obtain records of disturbance occurring on lines having much greater insulation than is now available. The work by all groups is being continued on an expanded scale and additional groups are becoming active which means that the remaining questions will all be determined in time.

The authors wish to stress again the importance of this work to the industry as a whole. Not only does the volume of data available require great expansion, but different transmission systems have different problems. The satisfactory answer to the lightning question will be hastened by the active participation of many in a coordinated program to increase the number of observation stations and to avoid inefficient repetition of tests.

ACKNOWLEDGMENT

The authors of this paper have assumed the writing of it only because the number of men working on the problem was too large to permit the co-authorship of all who made major contributions. Particular acknowledgment is due the utilities whose hearty cooperation made the work possible and to the following men whose enthusiastic efforts produced the results discussed in this paper: O. Ackermann, A. M. Opsahl, J. J. Torok, C. G. Archibald, R. H. Southgate, A. S. Brooks, E. R. Whitehead, W. G. Roman, P. E. Stephens, J. E. Garrett, Robert Sparks, W. J. Kroeger, M. E. Gainder, and L. R. Smith.

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## Discussion

For discussion of this paper see page 928.

# Surge Characteristics of Insulators and Gaps

BY J. J. TOROK*
Associate, A. I. E. E.

*Synopsis.—This paper presents the surge characteristic, in the form of time lag curves, of transmission line and substation insulation. The forms of insulation discussed are:*

*I. Line insulation: suspension type with and without arcing rings, pin type, and wood alone and in combination with porcelain.*

*II. Post type insulators with and without arcing rings.*

*III. Safety gaps with either needle or spherical electrodes.*

*IV. Oil gaps.*

* * * * *

## Introduction

It has long been recognized that the duration as well as the magnitude of an impulse voltage will determine the nature of the flashover of an insulator or gap. Accordingly sporadic efforts to determine these characteristics have been made with varying successes. The methods employed can be classified into two groups, the "comparative" and the "absolute." The comparative method is based upon a particular wave and an assumed standard of insulation, such as the suspension insulator. Other forms of insulation are then tested in parallel with this standard, and the results are computed in terms of the insulating strength of the standard. With the "absolute" method the characteristics of the apparatus are determined directly from cathode ray oscillograms, and the results are plotted in the form of volt-time curves. The advantage of the latter method is quite apparent. If the volt-time curves of different forms of insulation are known, the relative strength of each under all types of waves can be seen by merely comparing the curves.

An intelligent application of such volt-time curves in the design of transmission lines and sub-station equipment will add greatly to the reliability and safety of the system. Furthermore, they make possible a more economical construction in terms of both initial cost and maintenance. With an exact knowledge of the performance of each piece of apparatus, the designer can proportion the insulation of the line and substation to obtain proper grading of line insulation, prevention of flashover at one or more points on the line, or in the substation, and correct placement of arresters. In addition, safety gaps for the protection of adjacent equipment can be properly designed and applied.

## Method of Obtaining Volt-Time Curves

A thorough description of the equipment and system used in these surge studies has been given elsewhere,[1] but briefly it is as follows: The high-voltage impulses are generated by a bank of condensers charged in parallel and discharged in series. For voltage and time determinations, the apparatus under test is parallel by a wire-wound, non-inductive potentiometer terminating in a cable which leads to the cathode ray oscillograph. The synchronization of the oscillograph and surge generator is obtained by means of three-electrode gaps. The constants of the generator are adjusted to give a wave having an abrupt front and a slowly attenuating tail, which, in general, simulates a rectangular wave.

The rectangular wave is the most desirable in the "absolute" method.[2,3] The procedure is as follows: The voltage of the surge generator is raised to a value just sufficient to cause flashover. A record of the breakdown is then made with the cathode ray oscillo-

Fig. 1—Cathode Ray Oscillogram of the Surge Flashover of an Insulator

graph. Such an oscillogram is shown in Fig. 1. The voltage rises abruptly to a given value at which it remains until breakdown occurs. The time lag of the insulator for this voltage is the time from the point at which the voltage first exceeds the 60-cycle crest breakdown value, to the time when the voltage is suddenly reduced by breakdown. The voltage of the generator is then raised to a slightly higher value and another record is taken. This procedure is followed until the time lag of breakdown becomes very short. With the data so obtained a breakdown volt-time curve can be easily constructed.

The conventional types of surge generator cannot produce a strictly rectangular wave. It is physically impossible to produce a perpendicular front as the charging current would become infinite. As a result, the fronts are sloped, but they may be made so steep that, for practical purposes, the time of rise can be neglected

*Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

1. For references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

except for very short time lags. Also the potentials of generators attenuate after reaching the crest. This reduction in voltage is very often accentuated by the formation of space charges and streamer currents.[4] Thus it cannot be strictly said that the voltage remains at a fixed value until flashover occurs. But here

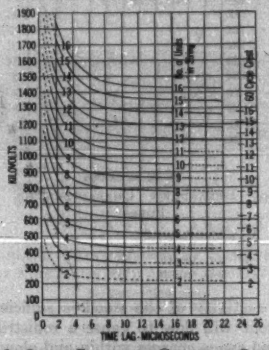


FIG. 2—SURGE FLASHOVER CURVES OF SUSPENSION INSULATORS, 10-IN. DISKS, 5¾-IN. SPACING

again, the deviation can be neglected except for extremely long time lags and for those of short duration, where the streamer currents become very large. At such points some minor approximations must be made to avoid discrepancies caused by changing wave shapes.

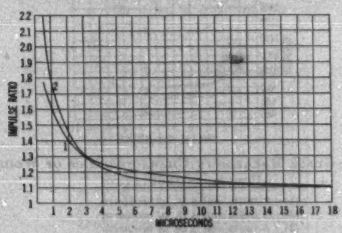


FIG. 3—IMPULSE RATIO BOUNDARIES FOR SUSPENSION INSULATOR STRINGS

(1) 11-unit string
(2) 2-unit string

All tests discussed below were made with the high-voltage end of the surge generator positive in polarity.

## INSULATOR TESTS

A group of tests was made on suspension insulator strings comprising 3 to 16 units of 10-in. disks having 5¾-in. spacing. A complete time lag curve was obtained for 3, 5, 7, 9, 10, 11, 12, 13, 14, and 16-unit strings. The other string lengths shown in Fig. 2 were extrapolated from these curves.[3] The relationship between the duration of the applied wave and the potential is well exemplified in the above curves.

The striking similarity of the long and short string characteristics suggests that they might all be represented by a single characteristic or by two boundary curves. Such a curve can be drawn by using the 60-cycle crest breakdown voltage as a basis, plotting against time the impulse voltage in terms of the 60-cycle value. The two curves shown in Fig. 3 are obtained in this manner. The upper curve corresponds to a two-unit string, while the lower curve is for eleven units. The curves for all other string lengths lie between those of the two- and eleven-unit strings. The term "Impulse Ratio Curves" is commonly applied to this form of characterization.

Quite often a lightning storm precedes or occurs at the beginning of the heavy precipitation, when the insulators have not yet become wet. For this condition the

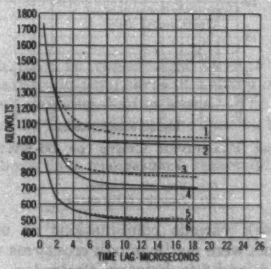


FIG. 4—COMPARISON OF WET AND DRY SURGE FLASHOVER OF SUSPENSION INSULATORS

(1) 11 units dry
(2) 11 units wet
(3) 8 units dry
(4) 8 units wet
(5) 5 units dry
(6) 5 units wet

surge flashover characteristic can be assumed to be that of a dry insulator. Since such an assumption is not always correct, it is necessary to determine the performance of insulators when dripping wet. The result of tests made on suspension insulators under heavy rain fall (0.2 in. per min.) are given in Fig. 4 with dry insulators for comparison.

The pin type insulators most commonly used on low-voltage lines, must also be considered in this analysis. There are many types of pin insulators in use, but fortunately their impulse characteristics are very much alike, and therefore can well be represented by a single example. Time lag and impulse ratio curves of a typical 66-kv. pin type insulator are given in Fig. 5.

## WOOD INSULATION

A crude survey of pin insulator installations indicated that only in exceptional cases were the pins grounded; all others were used in conjunction with wood construc-

tion. It happens also that ungrounded suspension insulators are very often used on wood pole lines. It is, therefore, essential to include in this study the effects of wood on line insulation.

It was believed that a more comprehensive idea of the performance of mixed insulation could be had if the characteristics of each were first determined, and then

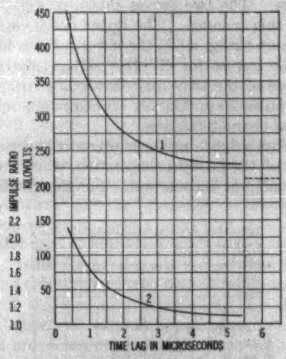


FIG. 5—SURGE FLASHOVER CURVE OF 66-KV. PIN TYPE INSULATOR

(1) Volt-time curve
(2) Impulse ratio curve

compared with various combinations as units. Accordingly tests were made on oak crossarms with spacings of 1, 2, 4, and 8 ft. between electrodes. A similar test was made on a spruce pole with 1, 2, 4, 8, and 13.5-ft. spacings. The results of these tests are given in

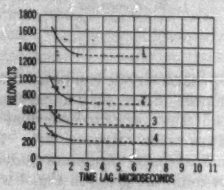


FIG. 6—VOLT-TIME CURVES OF THE SURGE BREAKDOWN OF OAK CROSSARM, 5 IN. BY 5 IN.

(1) 8-ft. length
(2) 4-ft. length
(3) 2-ft. length
(4) 1-ft. length

Figs. 6 and 7. The inconsistencies of flashover at any given condition and the complete lack of breakdown at long time lags is very marked. The scattering of the points can be attributed to the electrical instability of the material. But the strong tendency to breakdown during the first few microseconds of voltage application, or not at all, was unexpected.

This phenomenon may perhaps be explained in this way: When the voltage is first applied, the potential gradients along the wood will be determined by electrostatic relationships and space charge formations.

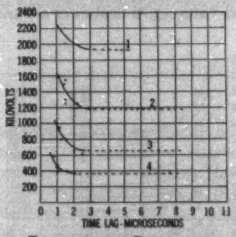


FIG. 7—SURGE BREAKDOWN CHARACTERISTICS OF WOOD POLES

(1) 13½-ft. length
(2) 8-ft. length
(3) 4-ft. length
(4) 2-ft. length

When the resistivity of the wood is sufficiently low enough current will flow to cause a redistribution of potentials and space charges within and along the surface so that the breakdown gradient is maintained at no point long enough for flashover to occur. The curves have been extended by a dotted horizontal line, below which breakdown did not take place.

Many combinations of wood and porcelain insulators may be obtained by merely varying the length of cross

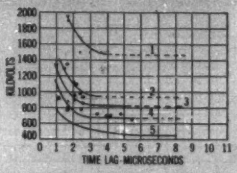


FIG. 8—SURGE BREAKDOWN CHARACTERISTICS OF WOOD AND PORCELAIN INSULATION

(1) 5 units and 8 ft. of crossarm
(2) 5 units and 4 ft. of crossarm
(3) 5 units and 2 ft. of crossarm
(4) 5 units and 1 ft. of crossarm
(5) 5 units only

section of the wood and the type or number of insulators. But for the sake of simplicity and clarity, a single group of combinations was chosen, wherein the porcelain insulation was fixed and consisted of a string of 5 suspension units, only the length of the wooden crossarm being varied. The data obtained from this group of combinations are shown graphically in Fig. 8.

## ARCING RINGS

Line insulators, especially the suspension types, are often equipped with arcing rings or horns. These devices change the electrostatic field about the insulator

as well as the path of the arc. It is, therefore, essential to obtain time lag curves on strings of insulators on which are mounted arcing rings or horns. However, the large variety of rings now in use would require hundreds of tests if each type were considered separately. Fortunately, the characteristics are nearly alike, and therefore they can be well represented here by a few typical samples.

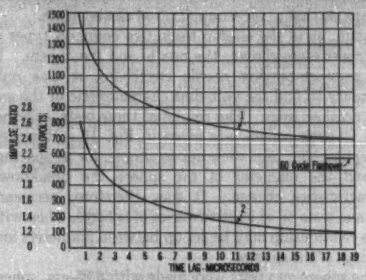


FIG. 9—SURGE CHARACTERISTIC OF SUSPENSION INSULATOR STRING OF NINE UNITS WITH ARCING RINGS (24 IN. BY 30 IN.)

1—Volt—time curve
2—Impulse ratio curve

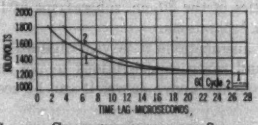


FIG. 10—SURGE CHARACTERISTICS OF STRAP AND TUBE ARCING RINGS FOR A 16-UNIT STRING

(1)—4-inch tube ring
(2)—¼-in. by 2-in. strap ring

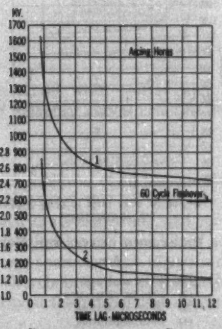


FIG. 11—SURGE CHARACTERISTICS OF SUSPENSION INSULATOR STRING OF NINE UNITS WITH ARCING HORNS

1. Volt-time curve
2. Impulse ratio curve

The time lag curve of a typical ring, used quite extensively, is shown in Fig. 9. The ring is of the flat strap type, oval in shape, its axial dimensions being 24 by 30 in., while the spacing between rings is 43.5 in. when mounted on a string of 8 units. The effect of increasing the projected area of the material of which the ring is made can be seen from Fig. 10.

The status of the arcing horn is much like that of the arcing rings, *i. e.*, many different types and shapes are in use, but their surge performances are all so similar that they too may be represented by a single example. Fig. 11 is the volt-time curve of a string of 9 suspension units equipped with arcing horns. The length of the string was 51¾ in., whereas the spacing between horns was 46½ in.

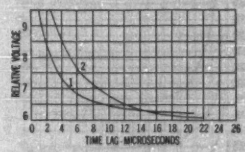


FIG. 12—RELATIVE IMPULSE FLASHOVER CURVES OF AN INSULATOR POST OF SIX PILLAR UNITS

1—Without arcing rings
2—With arcing rings

The above data will yield a reasonably good working knowledge of the behavior of transmission lines when subjected to surges. The nature of the impulses coming up to the substation can be established by examination of the curve or curves of insulation which most nearly agree with the specifications of the line.

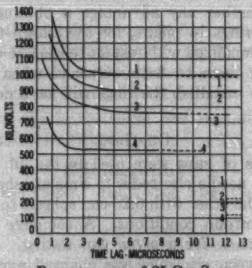


FIG. 13—SURGE BREAKDOWN OF 6.25-CM. SPHERE-GAPS UNDER OIL

(1) 3-in. separation
(2) 2-in. separation
(3) 1-in. separation
(4) ½-in. separation

## PILLAR TYPE INSULATORS

Similar flashover time lag tests were made and curves obtained with pillar insulators comprised of six units with and without arcing rings and the relative values are shown in Fig. 12. It will be noted that these curves

correspond very closely to those obtained for suspension insulators so that by choosing the proper number of suspension insulators the impulse strength may be made to correspond at practically all points with that of the pillars. It will be further noted that the addition of the arcing rings has caused an appreciable change in characteristics just as on suspension insulators, increasing

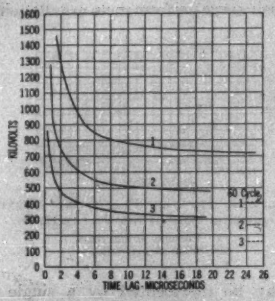


Fig. 14—Surge Breakdown of Needle-Gaps Under Oil

(1) 10-in. separation
(2) 5-in. separation
(3) 2½-in. separation

the time lag at the higher voltages and reducing the flashover of the lower surge voltages. It is questionable, however, whether any advantage is obtained by the addition of rings to pillars, for the reason that when properly rationalized with respect to the line there is no occasion for them to flash over and when lightning arresters are installed, the rings will have no function whatever.

## Oil-Gaps

Two types of gaps were used in the oil tests, one formed with needle electrodes to simulate sharp corner conditions, the other with 6.25-cm. spheres to represent rounded electrode conditions. A complete volt-time curve was made for a given gap setting. Then the spacing between electrode was changed and the test repeated. By this means some concept of the surge dielectric strength of oil is obtained for various shapes of gaps set at different gap lengths. The results of this group of tests are given in Figs. 13 and 14. It must be remembered, however, that these curves are for the breakdown of oil alone and not for creepage over insulating surfaces. The 60-cycle breakdown curve for these gaps is given in Figs. 13 and 14. Unfortunately the surge breakdown curves cannot be converted into impulse ratio time curves as a slight change in the quality of the oil will affect the surge characteristics but little, while the change in the 60-cycle breakdown value will be quite marked. Hence any impulse ratio curve of oil is meaningless unless all the electrical properties of the oil are specified.

## Air-Gaps

Occasionally air-gaps are connected to the lines, the object being to limit the surge voltage entering the substation and thereby afford some measure of protection for the transformers. If such gaps are to be used it is essential to know the surge characteristics of a group of gaps, so that a correct application can be made.

Again, as in the oil-gap tests, two common types of electrodes were chosen, the needle and the sphere. In the tests employing needle electrodes, it was only necessary to find the volt-time characteristic of the gap at several settings. The results of these tests, together with 60-cycle values, are given in Fig. 15. However, the sphere-gap tests were not so simple, for at spacings beyond the diameter of the sphere the breakdown characteristics change. It was, therefore, necessary to make tests on at least two sizes of spheres, wherewith some relationship may be set up between diameters and spacings of the spheres.

The sphere-gap tests were made with 6.25-cm. sphere electrodes in one case and 20-cm. electrodes in another. The 6.25-cm. spheres were tested at 10, 20¼, 40, and 58½-in. separations. The volt time curves at these separations are given in Fig. 16. Fig. 17 represents the characteristics of the 20-cm. sphere-gaps at 10, 20, 40, and 59¾-in. separations.

In many installations it is very desirable for both economic and space considerations to use small electrodes. From the above curves it can be seen that if

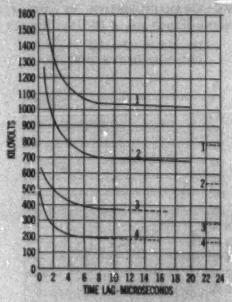


Fig. 15—Surge Breakdown Curves for Needle-Gaps in Air

(1) 60-in. separation
(2) 40½-in. separation
(3) 20-in. separation
(4) 10-in. separation

the spheres are separated by a distance no greater than their diameter, the impulse ratio is nearly unity under all types of waves. Increasing the separation at first causes an increase in impulse ratio only for waves of short duration, and then with further separation, the impulse ratio rises for even the longer waves. Although a constant voltage characteristic is the most desirable,

a gap setting allowing moderate overvoltages may be used as long as the time lag curve of the gap at that setting lies well below that of the apparatus protected and yet is high enough to maintain the insulation of the system at a reasonable value.

The curves in Fig. 16 cannot be placed upon the same basis as those of Fig. 17 by merely conversion of voltage into impulse ratio, because, as pointed out above, the diameter and spacing must also be considered. It was believed that these curves could be used in establishing a family of curves if one of the axes represented impulse ratio, and the other, spacing in terms of the diameters. However, either the basis of comparison was faulty or the nature of breakdown alters at large separations,

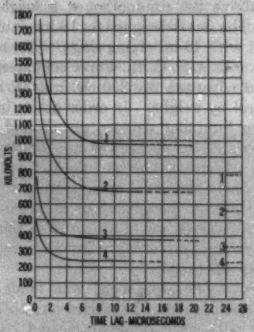


FIG. 16—SURGE BREAKDOWN CURVE FOR 6.25-CM. SPHERE-GAPS IN AIR

1-58 ½ inch separation
2—40 inch separation
3—20¼ inch separation
4—10 inch separation

because these curves when plotted were so different that no set of universal curves could be deduced from them.

## CONCLUSIONS

I. The surge flashover of an insulator is a phenomenon dependent upon the duration of the applied potential as well as its magnitude, and curves showing the volt-time relationship can be obtained.

II. The surge characteristics of an insulator can be plotted if its 60-cycle breakdown value and the impulse ratio curve for typical equipment are known.

III. By using volt-time surge breakdown curves the relative performance of widely different forms of insulation can be directly compared.

IV. In the event of an insulator flashover on a transmission line, the entire surge does not go to ground. The section of the wave preceding breakdown continues its course on the line, thereby making it possible to

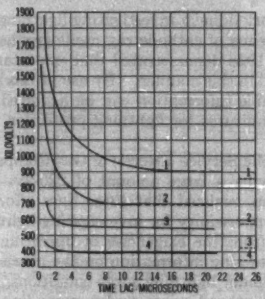


FIG. 17—SURGE BREAKDOWN CURVE FOR 20-CM. SPHERE-GAPS IN AIR

(1) 59¾-in. separation
(2) 40½-in. separation
(3) 20-in. separation
(4) 10-in. separation

flash over other insulators on the line, should they be weaker than the one which chopped the wave.

V. The added insulation offered by wood is roughly proportional to the length of wood used.

VI. Rain affects the surge flashover of insulators only at long time lag values.

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## Discussion

For discussion of this paper see page 928.

# Lightning Laboratory at Stillwater, New Jersey

BY R. N. CONWELL[1] and C. L. FORTESCUE[1]

Associate, A. I. E. E. Fellow, A. I. E. E.

*Synopsis.—This paper outlines the purpose of the cooperative installation of a lightning laboratory, the organization employed, and the various tests which have been made during the summer of 1929. In general, the paper presents the preliminary analysis of some of the most outstanding of a rather long series of tests and forms the background for a more complete paper giving a more detailed analysis which will be presented in the near future.*

* * * * *

THE work done in investigating lightning in the field by means of cathode ray oscillographs during the year 1928 demonstrated that important data can be obtained in this manner. By use of the instruments now available information can be acquired which will place expenditures for lightning protection on a sound basis.

The Public Service Electric & Gas Company of New Jersey, having a large amount of 220-kv. lines under construction, realized that these lines afforded an exceptional opportunity for investigating lightning conditions free from the exigencies of operating conditions and for obtaining information on the characteristics of such lines under lightning surge conditions, the characteristics of ground wires under grounding conditions that obtain on certain parts of the right-of-way, etc.

Such considerations led the Public Service Electric & Gas Company to cooperate with the Westinghouse Electric & Manufacturing Company in a joint investigation. The program consisted of an investigation of the characteristics of actual lightning strokes and of those physical characteristics of a transmission line which might have an effect on the performance of such lines under lightning conditions. Some of the features considered were the effects of attenuation, coupling between ground wire and phase wires, coupling between phase wires, the effect of the ground wire in reducing voltages on phase wires, and the surge impedances of towers and of lines.

*The Site.* The site selected for the conduct of these investigations was admirably suited for the purpose. Located in the hills of New Jersey approximately six miles from Newton in Sussex County, at an elevation of 500 feet, the power company had available a section of new 220-kv. transmission line extending 7.75 miles west to the Delaware River and approximately 1.3 miles east. This locality according to previous records was subject to from 30 to 40 lightning storms per year. In addition, the typography was rough and a great variety of ground conditions was available for test.

The line is a part of the Pennsylvania-New Jersey interconnection of the Public Service Electric & Gas Company with the Pennsylvania Power & Light Company and the Philadelphia Electric Company. The type A suspension towers have an over-all height of 77 ft., 9½ in. with the conductors arranged for flat horizontal configuration. The crossarm has an over-all length of 57 ft., the spacing between conductors being 28 ft., 6 in. Two ground wires are located midway and above the conductors at a height of 13 ft., $10^{9}/_{16}$ in. The line is designed for 18 insulator units and is equipped with 40-in. arcing rings. The conductor is 795,000 cir. mils A. S. C. R., 40 per cent steel by weight. The ground wires are 203,200 cir. mils A. S. C. R., 72 per cent steel by weight. In order not to influence the results from lightning strokes, the ground wires were not installed on the section of line under test. The availability of such a line as this, not yet in service, was particularly fortunate since during those periods when there was no possibility of measuring lightning strokes, the test crew could utilize their time, with the aid of a lightning generator, to investigating the surge characteristics of the line.

*Equipment.* The equipment was made mobile so that investigations might be carried on at other sections of the line with very different ground conditions or where the ground wire had already been installed, but the volume of work, together with the delay in getting the laboratory into operation this summer, has resulted in its being located on the one site.

The test equipment consisted of two trailers and two Fordson tractors. On each of the tractors there was installed a 5-kw. generator with an exciter to be utilized in supplying power for the Norinder oscillograph and the 1,000,000-volt lightning generator. In one of the trailers the Norinder oscillograph was located together with its auxiliary equipment, consisting of an oscillator, linear timing device, high voltage rectifier, vacuum pumps, switchboard, and work bench. At the other end of this trailer there were installed facilities for the development and printing of films and an electric refrigerator so that an ample supply of cold water will be available for the photographic processes. The second trailer contained the 1,000,000-volt lightning generator patterned after that at the Westinghouse High-Voltage Laboratory, at Trafford, Pa. This generator consisted of a 100,000-volt transformer arranged to charge 14 banks of 5 – 0.5 $\sigma f$. condensers in parallel through a full-wave kenetron rectifier. Through an arrangement of gaps and resistors, these banks were then discharged in series. The auxiliary equipment, in addition

1. Of the Public Service Electric and Gas Company and the Westinghouse Electric and Manufacturing Company, respectively.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

to the Fordson tractors with their 5-kw. generators, consisted of numerous surge impedances, a 50-cm. sphere-gap, klydonographs, and a number of capacity and resistance potentiometers. A portable signal system was utilized between the lightning generator and the oscillograph laboratory.

*Organization.* The laboratory was constantly attended by a competent staff consisting of not less than six engineers and at times during the summer there have been as many as nine engineers at work on this project. Although the personnel was derived from two organizations, it operated completely as a single unit during the entire period of tests.

We desire to pay tribute to those men who have actively participated in the work and whose technical skill and knowledge, together with their enthusiasm and tenacity of purpose, have produced such excellent results in the limited time available.

*Lightning.* Lightning generator and Norinder oscillograph arrived at Stillwater on June 17 and were put

Fig. 1—Two of the Lightning Surges Recorded at Stillwater, New Jersey

a. 1000-kv. lightning surge
b. 350-kv. lightning surge

into operation on July 1, 1929. The spring and summer preceding the placing of the laboratory into operation had been remarkable for the severity and frequency of lightning storms in this vicinity and although many storms were observed on either side of the line, it was not until August 14 that a storm traveled over the line. Between 11:51 a. m. and 12:07 p. m. four oscillograms were obtained which showed a range of fronts varying from 250 or 300 kv. per microsecond to 90 kv. per microsecond and a range of crests from approximately − 1600 kv. to + 350 kv. (Fig. 1).

It is to be regretted that more data on natural lightning were not obtainable, for a large volume is necessary under conditions where the line characteristics are known before the results can be derived and a practical application to transmission line design made.

## Tests with Lightning Generator

*Attenuation.* In order to determine the duration, as measured by the length of line, of surge voltages which might prove dangerous to the operation of a transmission line, surges were impressed with different wave shapes, the voltages varying from 200 to 1000 kv. over a length of line ranging from zero to 18 miles. Both positive and negative polarities were employed during these tests. Figs. 2, 3, and 4 show attenuation data in the form of plotted curves for the several types of waves used.

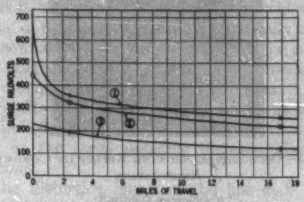



Fig. 2—Attenuation of Surges of Various Original Magnitudes (Steep Waves)

1. Attenuation of negative 700-kv. surge (½ μ sec. wave-front)
2. Attenuation of negative 436-kv. surge (½ μ sec. wave-front)
3. Attenuation of negative 218-kv. surge (½ μ sec. wave-front)

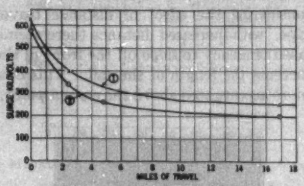



Fig. 3—Attenuation of Surges of Different Polarity

1. Attenuation of negative 621-kv. surge (wave-front of 3 μ seconds)
2. Attenuation of positive 574-kv. surge (wave-front of 3 μ seconds)

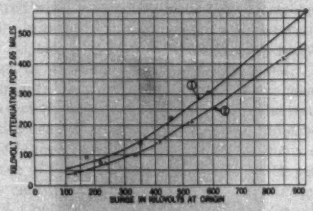



Fig. 4—Attenuation of Short Steep Waves and Slower Sloping Waves

1. Attenuation of positive surge (wave-front of ½ μ sec.)
2. Attenuation of positive surge (wave-front of 2 μ sec.)

The trend of the data obtained indicates the following relationships:

1. Considering crest voltage of the original surge and its attenuation, the attenuation is increased with the crest voltage over the length of line used. The rate of increase in attenuation is much more rapid

when the surge voltage exceeds the corona point of the line. The influence is shown by breaks in the line in Fig. 5. (Oscillogram C-6070-B.)

2. Considering the relation between the length of wave and its attenuation, the short wave attenuates more rapidly than a long wave of equal crest voltage.

FIG. 5—OSCILLOGRAM SHOWING EFFECT OF CORONA ON ATTENUATION

(Oscillogram C-6070-B)

3. Considering the relation between the polarity of the surge and attenuation above the corona point, positive surges attenuate more rapidly than negative surges of equivalent crest voltage and shape.

4. Considering the effect of distance traveled on wave shape, with increased distance there seems to be an increased tendency to slope off the front of the wave and to increase the length of the tail. This change in form is more accentuated above the corona point, and is

FIG. 6—OSCILLOGRAMS SHOWING ATTENUATION

A. Original wave, (oscillogram C-6068-A)
B. Wave after 2.65 miles, (oscillogram C-6068-E)

shown both in Figs. 6 and 7. (See oscillogram No. 6068-A and 6068-E.)

Fig. 7A shows the surges of Fig. 6 replotted to show the change in wave shape more clearly and is for a wave above the corona voltage. Fig. 7B shows similar waves replotted but below the corona point. Since oscillograms of natural lightning surges generally show a long tail, they will attenuate less rapidly because they are of the type indicated above as being the least susceptible to attenuation.

*Coupling.* In order to determine the effect on a phase wire of a surge on another phase wire or a ground wire, the coupling between the phase wires was measured varying both the crest voltage and polarity. The coupling factor may be defined as the ratio between the voltage of an impressed surge and the resulting induced surge on an adjacent wire. These data are important in the more advanced theory of lightning protection by means of ground wires. It is important to find out how close to actual values are the results obtained by the

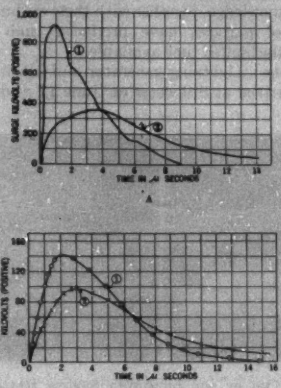



FIG. 7—OSCILLOGRAMS OF FIG. 6, REPLOTTED TO SHOW CHANGE OF SHAPE OF SURGE*

B. Below corona point
A. Above corona point

1. Original surge (at origin)
2. Attenuated wave (2.65 miles from origin)
1. Original wave (at origin)
2. Attenuated wave (2.65 miles from origin)

*Effect of distortion is being analyzed in paper by J. J. Torok

usual methods of computation using the method of images. In the tests, since no ground wires were available on the structures, the middle phase wire was utilized as a ground wire.

Fig. 8 shows curves of the coupling between adjacent conductors and outside conductors. The values as calculated by the usual formula and assuming the path in the earth to follow the image of the conductors are 11 per cent and 20 per cent between adjacent conductors and outside conductors, respectively. The curves show that these values increase with increase in voltage, which is possibly due to the effective increase in the size of conductors due to corona. The increase in the coupling factor is less for negative surges than for positive surges

and this seems in agreement with the fact that the attenuation is also less for negative surges than for positive surges.

In general, the results are summed up as follows:

1. Considering the effect of the surge crest voltage on coupling, the higher the crest voltage, above the corona point, the greater the coupling factor. (Oscillogram C-6070-A.) The oscillograms of Fig. 9 show the nature of this coupling.

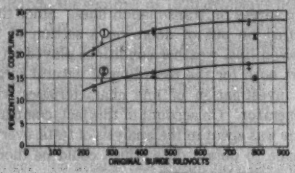



Fig. 8—Curves Showing Coupling Between Parallel Wires

1. Horizontal configuration 28 ft. spacing. Approximate 50 ft. above ground
2. Horizontal configuration 56 ft. spacing. Approximate 50 ft. above ground

2. Considering the effect of polarity on coupling at the higher voltages, the coupling factor is greater for a positive surge than for a negative surge of equal crest value.

3. Considering the effect of grounding the middle phase wire, the voltage induced between the two outside phase wires is decreased.

The tests are valuable for the determination of the correction to be made in line characteristics under transient conditions as calculated and are of use in

Fig. 9—Oscillograms Showing Coupling between Conductors, (Oscillogram C-6070-A)

a. Original surge
b. Induced surge in conductor 28 ft. distant
c. Induced surge in conductor 56 ft. distant

conjunction with other tests in estimating the behavior of natural lightning strokes to ground wires and lines and their probable effect in producing outages.

*Surge Impedance.* In order to determine surge impedances to be used in connection with computed values of natural lightning strokes, 1, 2, and 3 phases of the line were surged. Additional tests were made with one phase wire surged and the adjacent phase wire grounded to determine the effect of this condition simulating a line protected by ground wires. Tests were made with both polarities, various crest voltages, and wave fronts. Fig. 9 shows the points obtained in these tests together with a median curve indicated. Although the points are rather scattered they indicate that at low voltages the surge impedance is higher than the calculated value, which was 450 ohms, and that as the voltage is raised this value becomes less. This is probably due to the fact that the calculated value of 450 ohms is based on a return current coinciding with the image of the conductor, whereas it actually is probably somewhat lower and the drooping of the curve at higher voltages is undoubtedly due to the increase in the size of the conductor brought about by corona.

The results may be summed up briefly as follows:

1. The effective surge impedance of the line is reduced as the surge potential increases above the corona point.

2. The distortion factor of the line with corona is appreciable, and will be discussed fully in a subsequent paper.

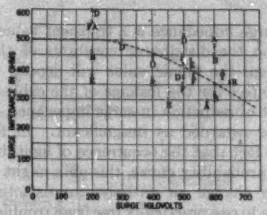


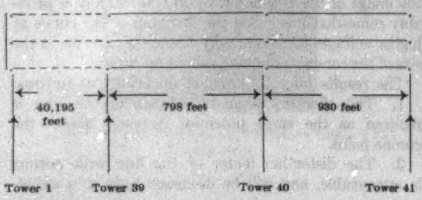

Fig. 10—Measured Surge Impedance of One Conductor

*Tower and Tower Ground Impedances.* Since the impedance to a surge between ground wire and ground is the dominant factor in determining the effectiveness of a ground wire in protecting against direct strokes, it is extremely important that this impedance be evaluated and its relationship to the tower footing resistance, measured in the usual manner, determined. Surge measurements were made on towers having meggered resistance of the order of 15 to 50 ohms. The results of these tests are shown in Table I. These indicate that the impedance to surges which of course includes the impedance of the tower itself may be from 10 per cent to 80 per cent greater than the meggered resistance.

*Buried Cable Tie Between Tower Footings.* Theoretical analysis has indicated that a buried cable tie between tower footings will effectively lessen the surge impedance of high resistance tower footings. The tower footings of several adjacent towers were tied together by 5/8-in. stranded cable buried from 6 in. to 8 in. below the surface of the ground. The values are included in Table I and it will be noted that while the cable results in a reduction of resistance of the order of 20 to one, the corresponding reduction in surge impedance is only of the order of two to one. This of course is to be expected

TABLE 1
SURGE IMPEDANCE OF TOWER GROUNDS

| Location ground | Cable connection | Megger resistance | Ground surge* impedance |
|---|---|---|---|
| T −39 | Off | 44 ohms | 76 |
| T −40 | Off | 60 ohms | 100 |
| T −39 +40 | Off | 25.3 ohms | 40 ohms |
| T −41 | Off | 16 ohms | 18.3 ohms |
| T −39 | On T −39 − 40 −41 | 2.2 ohms | 48.5 |
| T −40 | On T −39 − 40 −41 | 3.7 ohms | 34.2 |
| T −41 | T −41 | 3.5 ohms | 15.6 ohms |




*Based on a surge impedance of 450 ohms for the line.

since the surge impedance is a transient value and will depend upon the distributed constants of the buried cable, whereas the ohmic value will depend upon the integrated effect for the leakage of the cable to earth. The amount of reduction in surge impedance, however, is not to be regarded as insignificant. In fact, considering the fact that the occurrence of lightning surges follows the probability curve, this gain might easily be sufficient to change an entirely unsatisfactory line's performance to one practically free from trouble.

*Ground Wire Protection.* By using one of the phase conductors as a ground wire some measurements were made to evaluate the protection afforded by ground wires against induced strokes. The measurements made checked fairly well the values of this protection as calculated by the advanced methods including reflections at grounded points. However, since our own work on lightning in recent years as well as the independent work headed up by Professor Matthias in Germany, an account of which is given in *E. T. Z.*, of October 10, 1929, indicate that induced strokes are not an important factor on high-voltage lines, no great amount of time was spent in these tests and they are not considered of sufficient importance to justify the space of including them here. As previously brought out, ground wires with low surge impedance grounds are extremely effective in protecting against direct strokes. The results of these tests, discussed under surge impedance, coupling, and tower ground impedance, is directly applicable in evaluating the amount of this protection. The remaining unknown factors for a complete analysis are the voltage of the natural lightning where it strikes the ground wire and the characteristics of the lightning path. These can only be determined by a further, more detailed study of natural lightning.

## Conclusion

While the time available during the past summer has been limited to practically four months, a considerable amount of valuable information has been obtained which, although in many respects incomplete, has provided a better understanding of the effects of natural lightning surges on transmission lines. Since the work was carried on out of doors on a section of 220-kv. transmission line, weather conditions played an important part both for the recording of natural surges and for the investigation of line characteristics with the surge generator. On account of this fact, comparatively little time was spent in the analysis of tests, every effort being made to obtain data which could be thoroughly analyzed during the winter.

The present paper gives only a cursory analysis of some of the data particularly pertinent to the immediate requirements for line and ground wire construction. The total data obtained during the summer comprised something over one thousand films and in the short time available it was not possible to even examine all these data, but the contents will be found, it is believed, of considerable scientific as well as practical importance. A paper giving complete analysis of the results of these tests will be submitted to the Institute at a later date by Mr. Torok.

A large volume of additional data is needed in order to adequately classify and determine the effects of natural lightning strokes, and it is expected that the work started at Stillwater in the summer of 1929 will be continued next summer, although the location may be changed. The work with the surge generator, which is necessary for the determination of the individual factors involved in the design of transmission lines and their effect upon lightning strokes, will also be continued.

It is to be hoped that the continuation of this work will result in the final determination of the mathematical relationships existing between those factors affecting lightning surges on transmission lines, thus making possible the design of steel tower transmission lines which will render better service when constructed in situations exposed to severe lightning storms.

We wish to acknowledge gratefully the assistance of our colleagues in carrying out computations in connection with the data submitted and the general assistance in connection with the writing of the paper.

## Discussion

For discussion of this paper see page 928.

# Lightning Voltages on Transmission Lines

BY R. H. GEORGE* and J. R. EATON†

*Synopsis.—During the summer of 1929 studies were made to determine the characteristics of voltage transients set up on transmission lines by lightning. A cathode ray oscillograph and a number of surge voltage recorders were connected to a 140-kv. transmission line in such a manner that lightning disturbances were recorded by the instruments. This paper describes the equipment used, and presents the results obtained from the season's investigations.*

* * * * *

## Introduction

DURING the summer of 1929 extensive field studies were made to determine the characteristics of transient voltages set up on transmission lines due to lightning. Tests of this kind have been found necessary because in the present stage of the art, transmission line design and operation have advanced to such a point that lightning probably presents the only serious remaining problem pertaining to continuity of service. To attack this problem it has been found necessary to determine first the nature of the disturbances set up by lightning, and therefore fundamental studies have been in progress to study the electrical effects of lightning discharges on actual high-voltage transmission lines.

For some years studies of this general nature have been in progress in this and other countries, and many papers have been published describing the results. In 1926 the General Electric Company and the Consumers Power Company began a cooperative investigation, which has been continued in succeeding years, using the former's surge voltage recorders on the power company's transmission lines.[1] In 1928 the Consumers Power Company, in conjunction with Purdue University, installed on its transmission system a new type cathode ray oscillograph which had been developed in the University's laboratories. In the spring of 1929 the surge voltage recorder and cathode ray oscillograph investigations were combined into one extensive study. The cathode ray oscillograph was used to record the wave shape of transient voltages appearing on a transmission line during lightning storms, while the surge voltage recorders registered the magnitude and time of occurrence of these transient voltages at various points along the line.

## Description of Equipment

*Transmission Line.* This investigation was conducted about 40 mi. north of Grand Rapids, Michigan on a 140-kv. transmission line (known as T-20) which extends north and south a distance of 101 mi. from Junction Dam to Grand Rapids, Fig. 1. This is a single circuit line erected on one side of double circuit towers, as shown in Fig. 5. The conductors on the line are 110,000-circular mil copper, insulated with 10 Ohio Brass No. 25,622 disk insulators which are equipped with arcing horns on the lower end of the strings. The north half of the line and a section of about 10 mi. on the south end of the line are equipped with a No. 4 copperweld ground wire suspended from the peak of the towers.

The line traverses a relatively flat country, the soil of

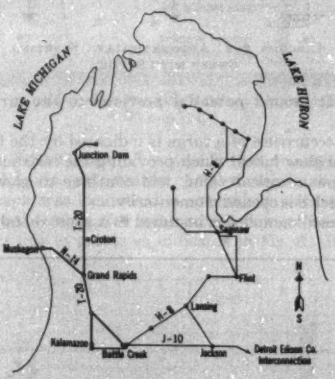



FIG. 1—CONSUMERS POWER COMPANY 140-KV. SYSTEM

Heavy lines indicate 30-cycle. Light lines indicate 60-cycle

which varies from light sand on the northern half of the line, to heavy clay on the southern end. Tower footing resistances vary over extreme limits of 1000 to 1500 ohms in the sandy section down to 3 to 5 ohms in the clay and swampy sections. Operation over a period of 10 to 12 years has shown that this line is subjected annually to many lightning storms which are swept eastward from Lake Michigan.

*Cathode Ray Oscillograph.* The cathode ray oscillograph used in this investigation is of the hot cathode type and with the exception of some improvements, has been described in a previous A. I. E. E. paper.[2] The principal improvements have been the change to a single sweep time axis and the addition of a signal for indicating the occurrence of a surge.

The sweep circuit which is set in operation by the

*Research Associate in High Voltage, Engg. Experiment Station, Purdue University, West Lafayette, Ind.

†Transmission Line Engineer, Consumers Power Company, Jackson, Mich.

1. For references see Bibliography.

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lightning surge, sweeps the beam once across the photographic film at a known rate of speed, producing a logarithmic time axis. On the arrival of a surge the grid-glow tubes, Fig. 2, close the circuit between points *A* and *B*, permitting current from the source 3 to flow through the resistance 4 and condenser 5, charging condenser 6, across which the deflecting plates are connected. The resistance 7 maintains the deflecting

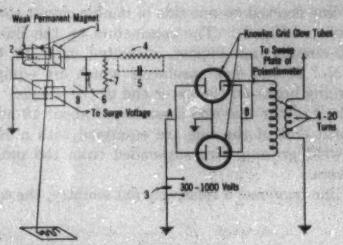


FIG. 2—CIRCUIT FOR AUTOMATICALLY STARTING TIMING SWEEP WITH SURGE

plates at ground potential previous to the arrival of a surge.

The occurrence of a surge is indicated by the flash of the grid glow tubes, which providing the resistance 7 is set below a critical value, will continue to glow until the switch 8 is opened momentarily.

The oscillograph was installed in a sheet metal building, Fig. 3, all parts of which were well grounded to shield the instrument from extraneous electrostatic fields. Connections from the transmission line to the oscillograph were made through an air insulated capacitor potentiometer shown in Fig. 4. The large plate *A* supplied voltage to initiate the sweep circuit which also denoted the arrival of a surge. The antenna wire *B* supplied voltage to the vacuum tubes which initiate the cathode beam. Voltage to the deflecting plates of the oscillograph was picked up by the small plate *C*, connections to which were carefully shielded from electrostatic fields which might be present due to other equipment in the vicinity. The plate *C* consisted of two parts, one below and one above the grounded wire screen. With the lower section only connected to the deflecting plates the beam sensitivity was one inch of deflection per million volts on the line, whereas with both upper and lower sections connected, the sensitivity was one inch deflection per 400 kv. on the line. These sensitivities were carefully checked using a million-volt lightning generator which was set up for studies of artificial lightning on another transmission line.[3] Transient voltages of various values were applied to the upper grid of the potentiometer and oscillograms were recorded in exact fashion as when the station was being used for recording lightning voltages. The applied voltage from the lightning generator was measured at the potentiometer by means of sphere-gaps, and these

FIG. 3—CATHODE RAY OSCILLOGRAPH STATION, SHOWING POTENTIOMETER AND CONNECTION TO LINE

Surge recorders on tower at left

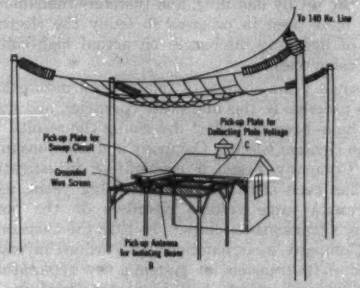


FIG. 4—CATHODE RAY OSCILLOGRAPH POTENTIOMETER ARRANGEMENT

measured values of voltage were compared with the deflections produced in the oscillograph.

The oscillograph was first put into operation for recording lightning voltage on May 11, and was operated during all lightning storms until the end of the season. The instrument was maintained in operating condition at all times but was not evacuated to operating pressures when no storms were present on the system. Upon warning from the system operator of storms in the vicinity, the oscillograph bell was pumped down to operating pressure and the set was put in readiness for registering voltage surges. As a rule about twenty minutes time was required for the set to be put in operation after a storm warning was received. The potentiometer was set for a ratio of one inch deflection per 400 kv. when storms were distant, and one inch deflection per 1000 kv. when storms were in progress in the immediate vicinity of the station.

*Surge Voltage Recorder.* The surge voltage recorder used was the General Electric two-electrode instrument which has been described in previous papers.[4] The

potentiometer used to connect it with the 140-kv. line, Fig. 5, was the conventional type consisting of an insulator string with grading shields and a ground connection to by-pass leakage currents around the shield supplying voltage to the instrument.[3] This type of potentiometer has been used during the past

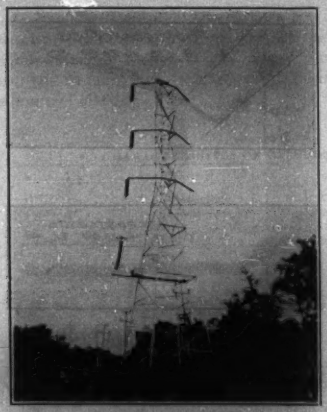

Fig. 5—Surge Voltage Recorder Installation, Showing Standard Tower

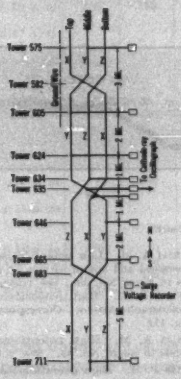


Fig. 6—Location of Surge Voltage Recorders and Cathode Ray Oscillograph on T-20 Transmission Line

two years because it eliminates the formation of slightly damped Lichtenberg figures which are known to give an erratic indication of line behavior. Voltage ratios of this type of potentiometer have been carefully checked in the General Electric laboratories and found to be 68:1, 75:1, and 77:1 for the various arrangements used in these studies. In all, 18 surge voltage recorders were kept in operation, the first one being installed and started May 8; all recorders were in operation by May 27, and were kept running continually until October 4.

*Location of Equipment along Line.* It was thought desirable to conduct these studies at a point considerably distant from the nearest substation in order that wave forms of lightning voltages would not be influenced by lightning arresters and other terminal equipment. Croton was chosen as the center of the investigation as it afforded a low-voltage power supply

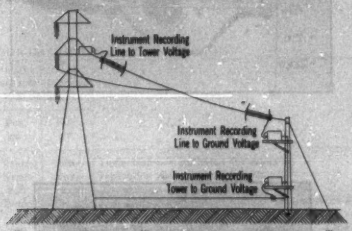


Fig. 7—Surge Voltage Recorder Installation at Towers 575 and 711

near the T-20 140-kv. transmission line, 40 miles from Grand Rapids, the nearest 140-kv. terminal. The oscillograph was located at a convenient point on the T-20 line at Croton, and surge recorders were connected along the line at points as indicated in Fig. 6. It may

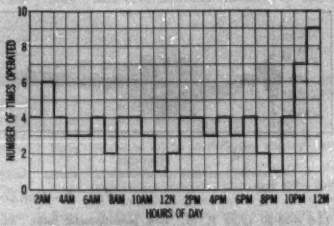


Fig. 8—Hours of Operation of Oscillograph

be noted that at the oscillograph station, recorders were connected to $X$, $Y$, and $Z$ phases. At points one and three miles both north and south from the oscillograph station, recorders were connected to the $Y$ phase, in order that some record might be obtained pertaining to the point of origin of lightning disturbances and to the voltage magnitude at various points along the line both directions from the oscillograph. With these instruments it was thought that data could be obtained which would correlate with that of the cathode ray oscillograph and which would also give information pertaining to attenuation of surge voltages as they travel along the line.

At tower 575 about 6 mi. north, and at tower 711 about 7½ mi. south of the oscillograph station, set-ups were made of three surge voltage recorders as shown in the diagram Fig. 7. These instruments, as may be seen from the diagram, were so arranged that one recorded voltage between line and tower, another voltage between line and ground, and a third between tower and ground. This set-up was made in an effort to study the distribution of voltage between the above mentioned parts when the line was subjected to lightning voltages. Theoretically, it appears that the voltage between line and ground should equal the sum of the voltages from line to tower, and from tower to ground. On lines equipped with ground wires there is a tendency for the towers to be raised to high voltage due to the charges induced on the ground wire. On towers whose footings rest in sandy or rocky soil of high resistance, the tower-to-ground voltage may be very high and may possibly be the same order of magnitude as the line-to-tower voltage to which the insulators are subjected. As tower 575 is in a section equipped with ground wire and as it is in sandy soil with a footing resistance of 1150 ohms, it offered an excellent opportunity for checking the above mentioned theory. Tower 711 presented the other extreme conditions in that it is in a section not equipped with a ground wire and stands in marshy

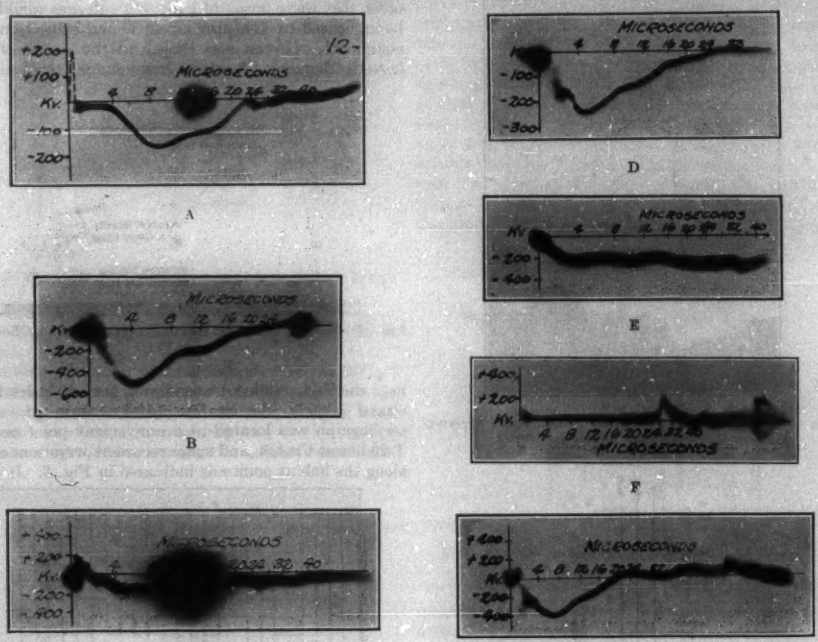


FIG. 9—OSCILLOGRAMS OF LIGHTNING VOLTAGES

A. 12-6 6-26-29 12:22 P. M. Low potentiometer ratio. Surge on T-20 line. No lightning visible at Croton but reported at station 60 mi. north. Corresponds to Surge No. 14. See voltage profile, Fig. 11a

B. 15-8 6-30-29 2:08 A. M. High potentiometer ratio. Surge on T-20 line. Lightning seen to strike near line south of Croton. Flashover found on X and Y phases at tower 682 (4.7 mi. from cathode ray oscillograph) thought to have resulted from this flash. Corresponds to Surge No. 21. See voltage profile, Fig. 11b

C. 19-7 7-13-29 5:43 A. M. High potentiometer ratio. T-20 line arced over and burned down at Tower 608 (2.7 mi. from cathode ray oscillograph). Corresponds to Surge No. 31. See voltage profile Fig. 11c

D. 19-19 7-13-29 9:41 A. M. Low potentiometer ratio. T.20 transmission line was deenergized and out of service at the time of this registration. Corresponds to Surge No. 33. See voltage profile Fig. 11a

E. 20-8 7-24-29 11:10 P. M. High potentiometer ratio. Lightning near cathode ray oscillograph station. Corresponds to Surge No. 40. See voltage profile Fig. 11b

F. 21-4 8-13-29 8:48 A. M. High potentiometer ratio. Storming at Croton. Corresponds to Surge No. 45. See voltage profile, Fig. 11b

G. 21-9 8-13-29 1:33 P. M. High potentiometer ratio. Storming at Croton. Corresponds to Surge No. 48. See voltage profile Fig. 11c

soil with a footing resistance of three ohms. In order that data obtained on both towers 575 and 711 might be correlated with that obtained on the cathode ray oscillograph, the connection to the line was made to *Y* phase.

## Results

*Cathode Ray Oscillograph.* The cathode ray oscillograph was operated during 28 storms through the course of the 1929 lightning season. Fig. 8 shows the number of times the oscillograph was operated during the various hours of the day.

*Surge Voltage Recorders.* Throughout the lightning season the surge voltage recorders registered a total of 53 surges. Of these, 48 were due to lightning, 1 was due to switching, and 4 resulted from unknown causes. The number and magnitude of surge voltages recorded are shown by the curve in Fig. 10. The characteristics of the lightning surge voltages are shown in Table II.

TABLE I

CHARACTERISTICS OF CATHODE RAY OSCILLOGRAMS OF LIGHTNING VOLTAGES

| Cathode ray oscillogram No. | Date | Time | Deflection | | Wave | | | Surge voltage recorder registration on 635 Y | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Pos. kv. | Neg. kv. | Front msc. | Time to half voltage msc. | Duration msc. | Pos. kv. | Neg. kv. | |
| 11– 3 | 6–19–29 | 12:11 a. m. | .. | .. | .. | .. | .. | Trace | Trace | Deflection not sufficient for analysis |
| 11– 7 | 6–19–29 | 4:00 a. m. | .. | .. | .. | .. | .. | None | None | Deflection not sufficient for analysis |
| 11– 8 | 6–19–29 | 4:05 a. m. | 0 | 150 | 3 | 20 | 40 | 250 | Trace | Arc-over on line. Location not known |
| 12– 6 | 6–26–29 | 12:22 p. m. | 200(?) | 170 | 8 | 18 | 36 | Trace | Trace | May have been positive voltage of very short duration preceding main surge |
| 15– 2 | 6–29–29 | 11:27 p. m. | .. | .. | .. | .. | .. | 200 | 200 | Deflection not sufficient for analysis. Line apparently grounded. Point unknown. Surge recorded by M. D. figures |
| 15– 3 | 6–30–29 | 12:05 a. m. | .. | .. | .. | .. | .. | None | None | Deflection not sufficient for analysis. |
| 15– 4 | 6–30–29 | 12:19 a. m. | .. | .. | .. | .. | .. | None | None | Deflection not sufficient for analysis |
| 15– 6 | 6–30–29 | 1:01 a. m. | 150 | 100 | 3 | 6 | 40 | None | None | Deflection not sufficient for analysis |
| 15– 8 | 6–30–29 | 2:08 a. m. | 0 | 530 | 4 | 8 | 30 | Trace | 540 | Line may have arced over on *X* and *Y* phases at tower 682 |
| 18– 7 | 7– 8–29 | 10:49 p. m. | 140 | 80 | 1 – | 3 | 50 | None | None | Front not registered. High frequency following crest for first 6 msc. |
| 18– 8 | 7– 8–29 | 11:00 p. m. | .. | .. | .. | .. | .. | None | None | Deflection not sufficient for analysis |
| 19– 7 | 7–13–29 | 5:43 a. m. | 250 | 150 | 0.5 | 2.0 | 50 | Trace | 300 | Oscillations during first 8 msc. Arc-over on line 2.7 mi. north of Croton. Beam poorly focused |
| 19– 8 | 7–13–29 | 5:47 a. m. | .. | .. | .. | .. | .. | None | None | May have been high frequency for first 2 msc. Probably result of switching surge |
| 19 -9 | 7–13–29 | 5:51 a. m. | .. | .. | .. | .. | .. | None | None | Deflection not sufficient for analysis |
| 19–10 | 7–13–29 | 5:54 a. m. | .. | .. | .. | .. | .. | None | None | Deflection not sufficient for analysis |
| 19–19 | 7–13–29 | 9:41 a. m. | 0 | 225 | 4 | 11 | 30 | None | 275 | High amplitude oscillations for first 3 msc. Line de-energized at time of surge |
| 19–20 | 7–13–29 | 9:44 a. m. | 80 | 120 | .. | .. | .. | None | None | Main wave very low amplitude. Damped oscillations beginning at 25 msc. Line de-energized at time of surge |
| 20– 3 | 7–24–29 | 5:14 a. m. | .. | .. | .. | .. | .. | Trace | Trace | Deflection not sufficient for analysis |
| 20– 7 | 7–24–29 | 11:07 p. m. | .. | .. | .. | .. | .. | None | None | Deflection not sufficient for analysis |
| 20– 8 | 7–24–29 | 11:10 p. m. | 0 | 220 | 3 | Flat top | 40* | None | None | Wave flat top for 40 msc. after which no record was obtained |
| 20– 9 | 7–24–29 | 11:11 p. m. | .. | .. | .. | .. | .. | None | None | Deflections not sufficient for analysis |
| 20–11 | 7–24–29 | 11:39 p. m. | .. | .. | .. | .. | .. | Trace | Trace | Oscillogram indefinite with very little deflection. Arc-over in Grand Rapids sub. Arcing ground |
| 21– 4 | 8–13–29 | 8:48 a. m. | 200 | 0 | .. | .. | .. | None | None | No deflection of beam except sharp peak at 30 msc. |
| 21– 8 | 8–13–29 | 1:29 p. m. | 100 | 0 | .. | .. | .. | None | None | No deflections of beam except sharp peak at 12 msc. |
| 21– 9 | 8–13–29 | 1:33 p. m. | 100 | 420 | 7 | 12 | 50 | Trace | 480 | High amplitude oscillation throughout first 3 msc. |
| 21–10 | 8–13–29 | 2:30 p. m. | 100 | .. | .. | .. | .. | None | None | Sweep circuit failed to operate. Only vertical line recorded |

Transient voltages on the line caused the beam of the oscillograph to be initiated on 26 occasions, resulting in time-voltage lines on the photographic film. The characteristics of these oscillograms are listed in Table I. Fig. 9 shows reproductions of the seven registrations which represented voltages above 200 kv. Some of the registrations showed almost no deflection and were practically straight lines on the zero axis. The oscillograph was so adjusted that it was actuated by a relatively low value voltage transient, in order that it might be fully turned on by any surge of appreciable magnitude. As the potentiometer ratio was necessarily adjusted to give the desired deflection for the highest value of voltage expected, many low magnitude transients turned on the beam but did not produce enough voltage on the oscillograph plates to give an appreciable deflection.

Lightning transients were simultaneously recorded on a number of the surge voltage recorders in operation, and therefore are indicative of the attenuation of voltage surges as they travel along the line. Voltages of high values (1000 to 1500 kv.) attenuated very rapidly as is illustrated by the profile of surge No. 21, Fig. 11B. This particular transient reduced in value from 1650 kv. to 540 kv. in a distance of three miles, or an average rate of almost 400 kv. per mile. Voltages of low values, of which Surge No. 37, Fig. 11H is an

example, apparently travel along the line with almost no decrease in voltage value.

The information gained at towers 575 and 711, Fig. 7, was not so conclusive as might have been expected.

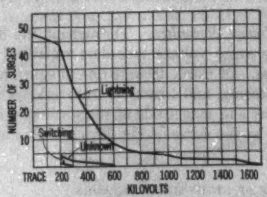


FIG. 10—NUMBER OF SURGES EXCEEDING VARIOUS VALUES OF VOLTAGE

Surge voltage recorder data

Evidently the difference between the line-to-tower and line-to-ground voltage is not ordinarily of sufficient magnitude to be definitely indicated by the surge voltage recorder, which due to its inherent characteristics, records only approximate values of voltage. The line-to-tower voltage sometimes registered higher than

TABLE II

CHARACTERISTICS OF LIGHTNING VOLTAGES

Surge Voltage Recorder Data

| Type of surge | Number of surges | Highest recorded voltage Kv. |
|---|---|---|
| Oscillatory | 39 | 1650 |
| Unidirectional | 9 | 280 |
| Oscillatory having positive value exceeding the negative value | 10 | 690 |
| Oscillatory having negative value exceeding the positive value | 21 | 1650 |
| Oscillatory having positive and negative values equal | 8 | 570 |
| Unidirectional of positive polarity | 1 | 280 |
| Unidirectional of negative polarity | 8 | 280 |
| Recorded by highly damped Lichtenberg figures | 35 | 1650 |
| Recorded by highly damped and medium damped figures mixed | 12 | |
| Recorded by medium damped Lichtenberg figures | 1 | 400 |

the line-to-ground voltage, and vice versa. However, a number of registrations of tower-to-ground voltages was obtained which indicated that transmission line towers may be frequently raised to a rather high voltage with respect to ground. Registrations of tower-to-ground voltages are listed in Table III.

The one switching surge recorded reached a maximum value of 260 kv. and was recorded by Lichtenberg figures of highly damped characteristics. Surge voltages resulting from unknown causes were four in number with a maximum value of only 500 kv.

*Correlation of Cathode Ray Oscillograph and Surge Voltage Recorder Data.* Profiles of voltages measured on the surge recorders simultaneously with registrations on the cathode ray oscillograph are illustrated by the curves of Fig. 11. Some of these profiles are of individual interest.

TABLE III

VOLTAGES RECORDED BETWEEN TOWER AND GROUND

Surge Voltage Recorder Data

Tower 575. Supports ground wire. Footing resistance 1150 ohms.

| Surge No. | Voltage in kv. | | | | | |
|---|---|---|---|---|---|---|
| | Line-to-tower | | Line-to-ground | | Tower-to-ground | |
| | + | − | + | − | + | − |
| 9 | 275 | 530 | 280 | 1100 | 10 | 34 |
| 22 | 270 | 270 | None | None | None | Trace |
| 31 | 400 | 290 | 285 | 625 | 28 | Trace |
| 32 | 450 | 450 | 285 | 280 | 54 | 12 |
| 48 | 675 | 600 | 350 | 1070 | None | 140+ |

Tower 711. No ground wire. Footing resistance 3 ohms.

| Surge No. | Voltage in kv. | | | | | |
|---|---|---|---|---|---|---|
| | Line-to-tower | | Line-to-ground | | Tower-to-ground | |
| | + | − | + | − | + | − |
| 18 | None | None | None | None | None | Trace |
| 31 | 285 | 390 | No record | | 6.8 | 5.5 |
| 33 | 265 | 300 | No record | | 6.8 | 3.5 |
| 42 | 265 | 275 | No record | | 3 | 3 |
| 47 | 330 | 290 | 265 | 330 | 3 | 3 |
| 49 | 650 | 1500 | 520 | 650 | 6.8 | 3 |

Surge No. 21, Fig. 11B, and its corresponding oscillogram 15-8, Fig. 9B, gives the most complete record of any obtained throughout the season. The stroke of lightning which produced it was observed by the oscillograph operators, and later inspection of the line showed flashovers on phases $X$ and $Y$ at tower 682, approximately 4.7 miles from the oscillograph station. Scrub oak in contact with the base of the tower were killed by the electrical discharge although very little burning was noted. The wave recorded, Fig. 9B, is smooth and shows no indication of having been chopped, although flashover took place on the phase to which the oscillograph was connected. The record seems quite consistent in view of the fact that the footing resistance of tower 682, on which flashover occurred, is 600 ohms. With this value of resistance in series with the discharge path, it might be expected that the wave would have a point of discontinuity representing the time of flashover; but thereafter the shape of the wave would not be materially affected by the breakdown, although the magnitude would be reduced. The values of voltage recorded by the surge voltage recorders are very high as compared with the commonly accepted value of insulator flashover for the type of wave recorded. Cloud fields terminating on the rings of the potentiometers, or other factors, may possibly have caused the recorders to give erratic readings.

Surge No. 31, Fig. 11C and its corresponding oscillogram 19-7, Fig. 9C, represent the records obtained at the time of a line failure at tower 608, 2.7 mi. north of the oscillograph station. A lightning discharge apparently established an arc between the top and middle conductors ($Y$ and $Z$ phases) and flashed over the bottom insulator string ($X$ phase). The middle conductor was burned off at a point about four feet from the in-

sulator string. Tower 608 is only 1600 ft. from tower 605 on which a surge voltage recorder was connected to $Y$ phase. The recorded value of voltage, 675 kv. from line to tower, seems somewhat low. This section of line is equipped with a ground wire and is characterized by tower footing resistances ranging from 100 to 250 ohms. It is possible that the charge on the ground wire raised the potential of the structure of tower 605, thereby reducing the line-to-tower voltage. The oscillogram recorded is somewhat lacking in detail as the beam was poorly focused.

Oscillogram 19-19, Fig. 9D, and its voltage profile, Surge 33, Fig. 11D, are of interest in that they were recorded at a time when the line was out of service, and therefore are in no way influenced by the power frequency voltage. The wave shape is, however, quite similar to others recorded at times when the line was in operation.

From Fig. 6 it may be seen that both the oscillograph and a surge voltage recorder were connected to the $Y$ phase at tower 635. Comparison of the data obtained from these two instruments, Table IV, shows their relative performance.

From the above table it may be seen that the oscillograph recorded many voltages which produced no registrations on the surge voltage recorder. Of the four surges which registered on the recorder but not on the oscillograph, only one was sufficient to produce a measurable Lichtenberg figure on the film. This figure represented a positive voltage of very low value and a negative voltage of 300 kv. A momentary interruption to the oscillograph power supply experienced at about the time of this registration may account for the failure of the oscillograph to operate.

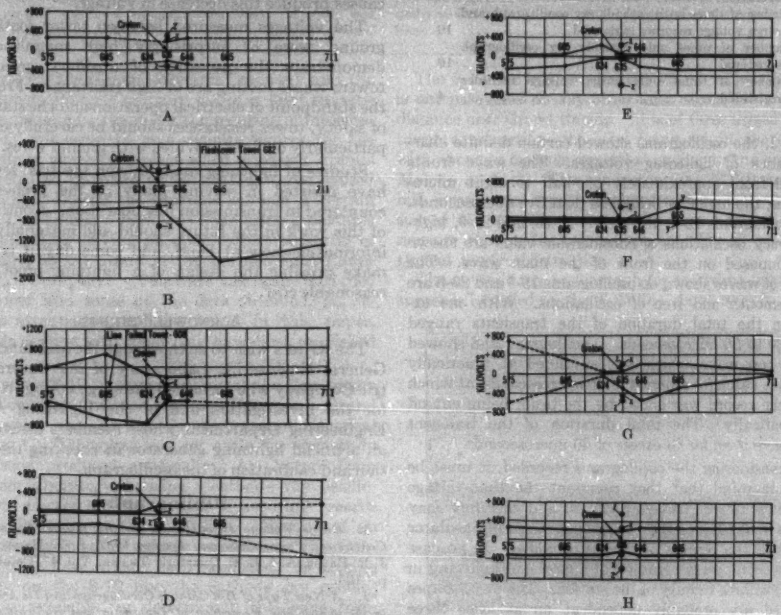


FIG. 11—PROFILES OF VOLTAGES ALONG LINE

Surge voltage recorder data

Horizontal divisions represent miles

| | | | | | | |
|---|---|---|---|---|---|---|
| A. | Surge No. 14. | See oscillogram | 12-6. | Fig. 9A |
| B. | " " 21. | " " | 15-8. | " 9B |
| C. | " " 31. | " " | 19-7. | " 9C |
| D. | " " 33. | " " | 19-19. | " 9D |
| E. | " " 40. | " " | 20-8. | " 9E |
| F. | " " 45. | " " | 21-4. | " 9F |
| G. | " " 48. | " " | 21-9 | " 9G |
| H. | " " 37. | | | |

## DISCUSSION OF RESULTS

*Wave Shapes.* As may be seen from Fig. 9 and

TABLE IV

RELATION BETWEEN OPERATION OF CATHODE RAY OSCILLOGRAPH AND SURGE VOLTAGE RECORDER ON Y PHASE AT TOWER 635

| | |
|---|---|
| Total number of cathode ray oscillograms | 26 |
| Total number of surge voltage recorder registrations | 16 |
| Number of times surge voltage recorder registered when cathode ray oscillograph was not in operation | 2 |
| Nimber of times both cathode ray oscillograph and surge voltage recorder registered | 10 |
| Number of times only cathode ray oscillograph registered | 16 |
| Number of times only surge voltage recorder registered | 4 |

Table I, the oscillograms showed certain definite characteristics of lightning voltages. The wave fronts ranged from approximately one-half to eight microseconds, the majority being less than five microseconds. On oscillograms 12-6, 18-7, 19-7, 19-19, and 21-9, high-frequency oscillations of considerable value are shown superimposed on the front of the main wave. The fronts of waves shown on oscillograms 15-8 and 20-8 are very smooth and free of oscillations. With one exception the total duration of the transients ranged from 30 to 50 microseconds. Oscillogram 20-8 showed a flat top wave which was sustained at practically constant value for a period of 40 microseconds, at which time the record was ended by the beam being cut off automatically. The total duration of the transient may have been far in excess of 40 microseconds.

In considering the oscillograms recorded, it must be borne in mind that they represent the time-voltage characteristics of traveling waves, and therefore may not be indicative of the voltage impressed on insulator strings at the centers of the disturbances. In no case was an oscillogram recorded of a stroke of lightning in the immediate vicinity of the station. The wave shapes recorded are probably dependent on at least three factors: the time characteristics of the lightning discharge, the geometry of the cloud field, and alterations from various influences as the waves traveled along the line to the oscillograph station. The records, however, are probably representative of the waves to which station equipment is subjected due to storms over connecting transmission lines.

The records of both the cathode ray oscillograph and the surge voltage recorder throughout the past summer showed a predominance of negative surges. Since both instruments recorded a number of positive surges, the above tendency cannot be due to inherent characteristics of the equipment.

The rates of attenuation of voltage surges recorded in these studies have checked in general those obtained in other tests with surge voltage recorders and with artificial lightning. No data are available from these tests which would indicate the factors affecting reduction of voltage with travel along the line. Studies with artificial lightning will probably be necessary to determine if loss of energy, change of wave shape, or other causes produce this decrease in voltage.

The voltages measured between tower footing and ground were of surprisingly high magnitude and demonstrate the necessity of auxiliary grounds on towers whose footing are of high resistance. From both the standpoint of electrical operation and the standpoint of safety, tower resistances should be carefully checked, particularly on lines provided with ground wires.

Studies of lightning made during the past few years have assisted in solving many of the problems encountered in transmission line operation. Continuation of this work in the future should add materially to the information now at hand, and some day it is hoped, make possible the design of a lightning-proof line of reasonable cost.

ACKNOWLEDGMENTS

The writers wish to acknowledge the assistance of the General Engineering Laboratory of the General Electric Company who furnished the surge voltage recorders for the investigation and of the Lightning Arrester Engineering Department whose members assisted with an artificial lightning generator in checking the operation and calibration of the oscillograph.

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## Discussion

For discussion of this paper see page 928.

# Traveling Waves on Transmission Lines
## with Artificial Lightning Surges

BY K. B. McEACHRON,* J. G. HEMSTREET,† and W. J. RUDGE*
Member, A. I. E. E. Associate, A. I. E. E. Associate: A. I. E. E.

*Synopsis.—The paper describes tests on a transmission line of the Consumers Power Company using a portable million-volt impulse generator.*

*Data were secured on attenuation with one, two, and three conductors in parallel, with and without ground wires. A study was made of the influence of ground wires in reducing voltages induced by overhead discharging clouds and also the effect on surges of entering or leaving a section of line having ground wires. A brief study was made comparing steel and copper for ground wires. The effect of ground resistance in tower footings was considered and a method given for measuring surge impedance of transmission lines.*

IN May 1929 the General Electric Company and the Consumers Power Company began a joint investigation, having for its object the securing of information which will serve to give definite figures for the various effects which take place when overhead circuits are subjected to traveling waves such as those caused by lightning. During the previous summer a certain amount of preliminary work was done using a portable impulse generator having an open circuit potential of 400 kv. on a 66-kv. circuit of the Turners Falls Power and Electric Company.[1] This work has been continued this summer and some of the data obtained, particularly on attenuation, will be found in this paper. Other data dealing with choke coils have been published ecently.[2]

The historic S-19 transmission line of the Consumers Power Company between Croton Dam and Grand Rapids, which was the first line to transmit electrical energy at 110,000 volts, was set aside for the study of transients produced artificially. At Croton Dam an outdoor laboratory, housing a cathode ray oscillograph, was erected for the purpose of securing records of natural lightning on the T-20 line.[3] Results of an investigation with surge voltage recorders on the Consumers system have already been published.[4] In making the study on the S-19 line the cathode ray oscillograph was available for determining the wave form of impulses at the laboratory end of the line.

The impulse generator used in these tests was a portable million-volt equipment[5] consisting of 40 banks of capacitors, each bank having a capacity of 0.50 $\mu$ f. The banks are charged in parallel to 25 kv. and discharged in series as is done in the Marx circuit.[6] The connections are so arranged that the polarity of the generator may be changed at will, which is very necessary for the type of tests to be described in the paper. The power requirements for the impulse generator are such that it may be operated from a 110-volt lighting circuit. Fig. 1 shows the million-volt generator set for test at Croton Dam.

The S-19 line is approximately 45 mi. in length and is not paralleled by any other lines except for a short distance near Grand Rapids. It is of three legged steel tower construction, the steel being set in the earth with concrete footings somewhat similar to the present Malone anchors. The conductors are 72,670 circular mil, seven strand copper, insulated with seven insulators spaced 4¾ in. The line does not have a ground wire nor are the conductors transposed. Fig. 2 shows a typical tower construction.

The cathode ray oscillograph for recording lightning surges is installed on the T-20 line about 1000 ft. from

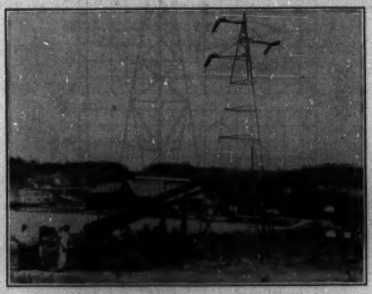

FIG. 1—ONE MILLION-VOLT IMPULSE GENERATOR SET UP FOR TESTS

the Croton Dam generating station and the S-19 line was extended to this point, four additional towers being required. The impulse generator was set up one span away from the oscillograph and the line provided with jumpers at this point, so that the impulse could be sent either to the oscillograph for checking the open circuit wave, or out on the line. It is also possible to connect with the T-20 line and this was done for the purpose of checking the calibration of the cathode ray oscillograph on this line.[3]

Most of the measurements given in this paper were made with sphere-gaps which were moved along the line by truck, communication being maintained with the impulse generator and oscillograph stations by tapping local telephone lines.

*General Electric Company, Pittsfield, Mass.
†Consumers Power Company, Jackson, Mich.

1. For references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Jan. 27-31, 1930.*

### Attenuation

The problem of attenuation of surges on transmission lines is important from the operating standpoint as well as being of great importance from a purely scientific point of view. Knowledge of attenuation makes it possible to determine the distance that surges can travel and still be dangerous to connected apparatus. In this paper attenuation will be understood to refer to the decrease in crest surge voltage without regard to change of wave shape.

Corona loss[7] is now generally regarded as one of the most important factors affecting attenuation. Some attempts have been made to deduce the rate of attenuation of surges from the constants in the known empirical formulas for corona loss on lines at power frequency voltages. It is extremely improbable, however, that the final state of breakdown of the air occurring at these frequencies is reached in the duration of the lightning surge especially if its time above the corona voltage is short as in the case of an insulator flashover on or near the front of the wave. Without entering into any extended theory of attenuation, a brief discussion of the more important factors will be given.

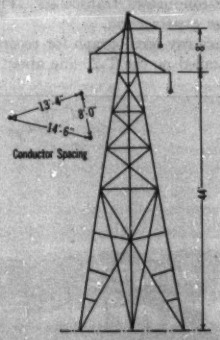


Fig. 2—Typical Three-Post Tower Showing the Arrangement of Conductors

### Effects of Parallel Conductors

The formation of corona around a conductor occurs when the potential gradient in this space exceeds a value known as the critical corona voltage. This gradient is very nearly proportional to the charge on the conductor. At a given potential the charge is proportional to the electrostatic capacity of the conductor to the earth. The electrostatic capacity of the conductor to earth is affected by the presence of other charged conductors nearby, being increased when the other conductors are charged to the opposite sign and decreased when they are changed to the same sign.

When a surge is traveling on a number of conductors inparallel, as is always the case on an actual transmission line, the capacity to earth is of one conductor reduced by the presence of surges of the same sign on the other conductors. Thus the charge on each conductor at a given surge voltage is less and so the potential gradient and consequently the corona is less on each conductor than would be the case with a single conductor. Following out this line of reasoning one would expect to find the attenuation less when several conductors in parallel were carrying the same surge. The tests made show conclusively that increasing the number of conductors in parallel decreases the attenuation.

### Effect of Polarity

It is a well-known fact that there is a considerable difference in the appearance of positive and negative corona.[8] With dissimilar electrodes, as in a pin-type insulator, flashover will take place at a lower potential when the cap is positive than when negative, although as the rate of potential application is increased the positive and negative spark potentials approach a common value.[9] Thus one would expect that a difference would exist in the corona loss for positive and negative impulses and that in general the loss for the positive impulse would be greater. On this basis, the attenuation with negative impulse should be less than for the positive impulse, which was in general found to be true. Since, however, the insulator tests referred to showed that as the time to breakdown became less the difference between positive and negative impulses disappeared, it is reasonable to expect that with extremely short waves positive and negative attenuation would be equal. The only tests made with short wave were made with a chopped wave having a seven-microsecond front which was probably much too long to give equal values of attenuation for positive and negative surges.

### Effect of Length of Waves

The state of breakdown of the air in the corona area around a conductor is changing very rapidly during the passage of a surge, and consequently the attenuation varies on different parts of the surge. This would affect the attenuation of surges, the amount depending upon the wave shape. Thus if the corona loss[10] was greatest during the initial stages of breakdown, a short wave would suffer more attenuation than a long wave. The tests made have shown that attenuation is dependent on wave shape.

### Effect of Ground Wire

With a traveling wave the ground wire takes up a charge of opposite sign to that of the wave in the line conductor and as pointed out previously this results in an increased charge on the line conductors which results in an increased corona loss at a given potential. This effect tends to increase the attenuation. On the other hand the increase in charge results in an increase of energy of the surge which tends to decrease the attenuation. It has been assumed[11] that the resultant

effect of the ground wire is to increase the attenuation, but the attenuation was found to be less with the ground wire, especially in the case of the negative impulse on the line conductor. Apparently the increases in surge energy and corona loss are more or less balanced in the case of the positive impulse but with the negative surge the increase in surge energy seems to be greater than the increase in corona loss resulting in a decreased attenuation.

## Test Results

The attenuation tests were made using three different

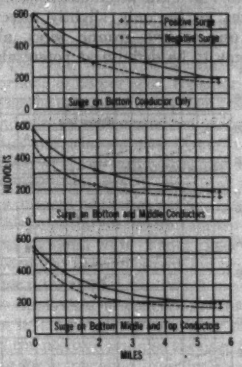


Fig. 3—Attenuation with Steep Waves on One, Two, and Three Conductors

wave forms, a fast wave reaching its crest in less than one microsecond, a slow wave reaching its crest in seven microseconds, and a chopped wave produced by cutting off the slow wave at its crest by the use of a parallel sphere-gap. These waves of both positive and negative polarity were applied to a single conductor and also to two and three conductors in parallel. As the S-19 line was not provided with a ground wire the influence of the ground wire on attenuation was studied by grounding the conductors at approximately one-half mile intervals.

In Fig. 3 are given curves showing the variation in measured crest voltage with distance along the line for both positive and negative steep waves applied to a single conductor and to two and three conductors connected in parallel at the impulse generator. The applied voltage decreases with the number of conductors in parallel because of the increased load on the surge generator due to the decreased surge impedance when several conductors are connected in parallel. The positive wave in each case shows more attenuation for potentials in excess of 200 kv. than does the negative.

The attenuation tests with the slow wave extended over a distance of 30 mi. from the impulse generator. The results are given in Fig. 4. These data cover both positive and negative impulses on one, two, and three conductors. The results with a single conductor show that the negative impulse has decreased from 475 kv. to 90 kv. and the positive from 415 kv. to 60 kv. as a result of traveling 30 miles. It is interesting to compare these results with those given by Lewis[7] which were obtained from studies with the surge records from lightning storms. Lewis gives a formula derived by Foust and Menger in which the voltage $e$ at a point $s$ miles from the point of inception is as follows:

$$e = \frac{e_o}{k\,s\,e_o + 1}$$

where $e_o$ is the voltage at the point of origin, and $k$ a factor found empirically.

This equation fits the data given in Fig. 4 fairly well for the first ten miles beyond which the loss due to corona becomes small. Mr. E. W. Boehne has suggested that $s$ in the equation be replaced by $s^n$ which with the proper values for $n$ checks the curves closely. In Fig. 5 are given the values for $n$ and $k$ for the various conditions of the test. The values of both $n$ and $k$ are dependent on many factors which the present investiga-

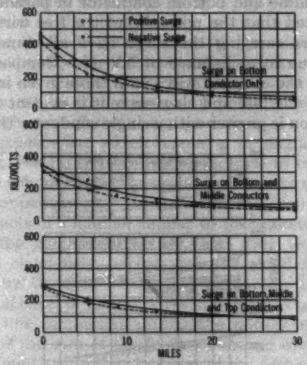


Fig. 4—Attenuation with Slow Waves on One, Two, and Three Conductors

tion did not diclose. The values given apply only to the slow wave used and the particular line tested.

It is of interest to note that on the Turners Falls Line[4] a brief study of attenuation on a single conductor gave for $n$ a value of 0.75 and $k$ 0.00069 with an $e_o$ of 230 kv. These values are quite different from those obtained on the S-19 line and indicate that the values of $n$ and $k$ must be determined for each individual condition considered.

The results of the tests made with the chopped slow wave are given in Fig. 6, which shows not only the decrease of the positive and negative surge with distance but also show the potential on the free conductor where

such existed. It is interesting to note that the change of potential of the free wire with distance is very small and approaches the potential of the conductors carrying the original surge. When the surge was applied to the bottom conductor the top conductor assumed an initial potential of about 30 per cent of the applied. This increased to 50 per cent when the impulse was applied

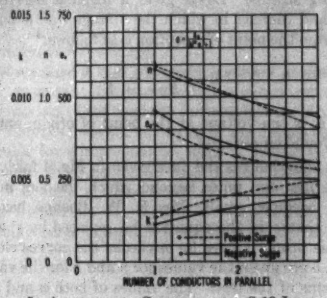


FIG. 5—ATTENUATION CONSTANTS FOR S-19 LINE

to the middle and bottom conductor in parallel. It is to be noted that the potential of the free wire and of conductors carrying the surge have all come to the same value in a distance of 5.7 mi. Comparing the results of the chopped wave with those given in Figs. 3 and 4 for the fast and slow wave it is evident that the attenuation is greater with a single conductor than with

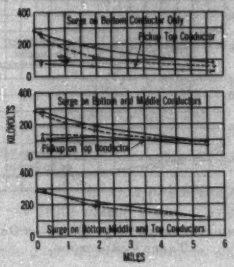


FIG. 6—ATTENUATION WITH CHOPPED SLOW WAVES ON ONE, TWO, AND THREE CONDUCTORS

simultaneous surges on multiple conductors, and that this effect is much more pronounced with the chopped wave than with the others. This may be due to the transference of a larger percentage of the wave energy to the free conductors in the case of the chopped wave. Some indication of this energy transfer is found in the voltages measured on the free conductor as seen in Fig. 6.

Considerable work was done in the study of attenuation with ground wires, the results shown in Fig. 7 being representative of the results obtained. Two sets of curves are given, one with the top conductor grounded and one set with the top and middle conductors acting as ground wires. Plotted with these curves are the results for the same conditions with no grounded wires. The impulse was always applied to the bottom conductor at tower *C*. Tests were made with both positive and negative impulses. In comparing these tests it should be remembered that the top and middle conductors are 8 ft. and 14 ft. respectively, from the bottom conductor, which means that the top conductor acting as a ground wire will influence the bottom conductor more than the middle wire will when it is grounded.

Referring to Fig. 7 the attenuation with the positive impulse seems to be only slightly affected by the presence of one or two ground wires, although the tendency seems to be definite at potentials above 200

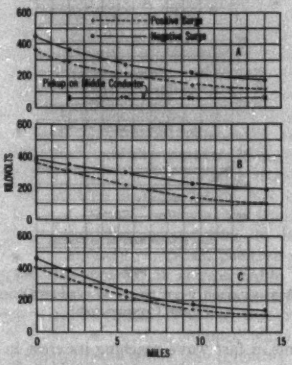


FIG. 7—ATTENUATION ON LINE UNDER INFLUENCE OF GROUND WIRES

*A* surge on bottom conductor—top conductor grounded
*B* surge on bottom conductor—top and middle conductor grounded
*C* surge on bottom conductor—no ground wires

kv. for a decreased attenuation with ground wires. Expressed in distance of travel to suffer the same reduction in potential, the positive impulse without ground wires traveled 5.8 mi. to reduce from 360 kv. to 190 kv. while with one ground wire the corresponding distance was 6.8 mi. and with two ground wires the distance was 7 mi.

With negative impulses of a potential of the order used in these tests the attenuation was considerably decreased by the presence of ground wires. To illustrate, from the curves without the ground wires it may be seen that the potential decreased from 380 kv. to 180 kv. in a distance of 7.4 mi. while with one ground wire the distance required for the same decrease was 14 mi. and with two ground wires, extrapolating the results slightly, this distance is of the order of 15 mi.

These results indicate that for positive impulses the ground wires have but little effect on the attenuation. In the case of negative impulses it appears that the

presence of one ground wire so decreases the attenuation that the impulse may travel twice as far with the ground wire as without. Two ground wires increase this effect slightly. The idea that ground wires should damp out traveling waves quickly does not seem to hold; in fact the tests show that the reverse is true. This does not mean that ground wires are not useful in reducing the potential which would otherwise have been present when the line is under a discharging cloud, nor does it mean that the ground wire would not be helpful in case of a direct stroke of lightning to the ground wire or line wires. As shown in the section dealing with the "Study of Ground Wires" the reduction of potential during the release of the bound charge on the S-19 line is of the order of 20 per cent, while the calculated value was in the neighborhood of 23 per cent, considering the middle wire acting as the ground wire. When the top wire acts as the ground wire the calculated reduction is of the order of 30 per cent and it is assumed that by test this reduction might also be of the order of 30 per cent. Assume by way of illustration that a potential of 460 kv. be taken as the induced potential without ground wire and 300 kv. as the potential on the bottom wire with the top wire acting as a ground wire. From Fig. 7 the respective attenuations for the bottom conductor bring the curves together after a travel of 7 mi., which means that as far as terminal apparatus is concerned the effect of the ground wire is lost after traveling over the distance of 7 mi. With the positive impulse the case for the ground wire is better for in traveling 7 mi. impulses which began as a traveling wave of 400 kv. without the ground wire and 260 kv. with it would be 170 kv. and 135 kv. respectively, which shows that the original 30 per cent difference had been reduced to 20 per cent by traveling 7 mi. on the S-19 line. In 11.5 mi. this difference has been reduced to about 10 per cent.

These tests indicate that the ground wire acts most efficiently when the storm is close to the point considered as will always be the case with line insulators, or when storms are close to station apparatus. It is fortunate that this condition exists for the most damaging impulses undoubtedly will be found nearest the point of inception.

## Study of Ground Wires

A brief review of the theory of the ground wire will first be given in order that the significance of the tests to be described may be more fully appreciated.

When a cloud over a transmission line becomes charged all of the conductors of the transmission line including the ground wires take up charges having a polarity opposite to that of the cloud. This action is easily understood when it is remembered that charges of unlike sign attract with the result that charges of a polarity opposite to that of the cloud are drawn up from the ground onto the ground wires while similar charges on the line conductors are not only drawn from the ground by leakage over insulators, but from other sections of line not under the cloud.

When the lightning discharge takes place the charges on the ground wires are free to pass directly to the earth while the charges on the line conductors travel into other portions of the system as traveling waves. It is the function of the ground wires to reduce the potential appearing on the line conductors just after the lightning discharge takes place but before the charges begin to travel along the line wires. The mechanism of this reduction is frequently divided into two parts which will be referred to as the first and second actions of the ground wire.

It has already been pointed out previously in this paper that when parallel conductors have charges of the same sign, the capacity to ground and the charges at a given potential are both less than they would have been without the charges on parallel conductors. This is exactly the case with the ground wire which initially has a charge of the same sign as that on the line conductors so that the line conductors have a smaller charge and a smaller capacity to ground because of the presence of a similar charge on the ground wire. It is assumed that the charge on the ground wire runs off to earth in zero time, so that the line conductors find themselves with an increased capacity, because of the elimination of the charge on the ground wire, but with the same charge that they had with the original capacity. As the product of the potential and the capacity is equal to the charge which is constant, an increase in capacity results in a decrease in potential which constitutes the *first effect* of the ground wire.

The *second effect*, which is smaller in magnitude than the first, results from a further increase in capacity of the line conductors as the ground wires take up charges of the opposite sign. In this case the grounded conductor acts in a manner similar to the manner in which all of the conductors acted when they were in the original cloud field, except that the cloud field is replaced by the field of the line conductors to ground. The total effect of ground wires in reducing the potential on the line conductors during the release of a bound charge is the sum of the first and second effects. It is interesting to note that the sum of the first and second charges on one or more ground wires is just equal to the charges they would have had if no other conductors were present. For purposes of calculation, the first and second effects of the ground wire are conveniently considered together, and in the tests to be described the effects were studied together, but the second effect was also studied separately.

## Study of the Total Effect

It is not possible to reproduce exactly the conditions existing in a cloud field with the apparatus at present available. However, a fair measure of the effect on the potential of the line conductors, of changing the charge on the ground wire may be obtained by the use of traveling waves, although the ground wire theory is predicated on static conditions. As pointed out previously, the potential of any one conductor is affected by charges

on the parallel conductors, and this is true whether the charges are moving or stationary.

In making the tests to show the total effect, the three conductors were connected together at Croton Dam and an impulse applied to all three in parallel, as shown in Fig. 8. The middle conductor was grounded successively at towers 50, 52, and 55 which had resistances of 76.4 ohms, 28.4 ohms, and 7.5 ohms respectively. Voltages were all measured at tower 56.

Although in practise the different conductors will

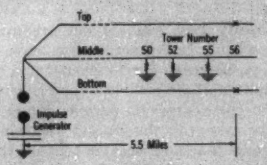


Fig. 8—Set-Up for Study of Total Ground Wire Effect

assume different potentials because of their different heights, this difference was neglected as being small, the same surge being applied to all three conductors. The surge applied had a front of about 10 microseconds and traveled a distance of 5.5 miles to reach tower 56, where the measurements were made. The results obtained are given in Table I and show the protective value of the ground wire which is the same for both positive and negative impulses.

TABLE I
TOTAL GROUND WIRE EFFECT

| Tower at which middle conductor was grounded* | Voltages measured kv. at tower 56 | | | Protective factor | |
|---|---|---|---|---|---|
| | Top | Middle | Bottom | Top | Bottom |
| No grounds | 178 | 168 | 177 | 100% | 100% |
| 50 | .. | 40 | 146 | .. | 83.5 |
| 50, 52 | .. | 34 | 145 | .. | 83.0 |
| 50, 52, 55 | 143 | 4.3 | 142 | 80.6 | 80.0 |

*The ground resistances were—Tower 50, 76.4 ohms; Tower 52, 28.4 ohms; Tower 55, 7.5 ohms.

The calculated protective factors for the total effect assuming the middle conductor at earth potential are 79 per cent and 77 per cent for the top and bottom conductor respectively.

The data obtained for the bottom conductor are plotted in Fig. 9 and show a protective factor of slightly less than 80 per cent where the curve crosses the zero ground wire voltage axis.

It is interesting to note that the greatest reduction of potential occurred at the first tower although the tower resistance was 76.4 ohms, the ground wire potential being reduced to 24 per cent and the line conductor to 83.5 per cent of the original values. This indicates that a large part of the benefit of the ground wire for reduction of induced discharges will be retained with tower footing resistance of the order of 75 ohms. Of course still better results will come from still lower resistances, particularly from the standpoint of direct strokes of lightning near the towers.

Numerous other tests have been made at different locations on the S-19 line, some with steel and some with copper ground wire, which also check the calculated values closely.

## Study of the Second Effect

The second ground wire effect involves a consideration of the change in potential of a conductor when the ground wire assumes a charge of opposite sign as a result of being placed in the field of the charged conductor.

In order to get experimental data on this effect a transition point was created on the S-19 line at a distance of 5.5 mi. from the impulse generator which was far enough for measurements to be unaffected by reflections from the impulse generator. At this point the top and middle conductors were cut. In one case grounds were put on the top and middle conductor from tower 58 to 160, a distance of 11.5 mi. while the same conductors were left floating from tower 57 to the impulse generator. Both positive and negative waves having fronts of 7 microseconds were applied to the bottom conductor and voltage measurements made with spheres at suitable points along the line both in the grounded and ungrounded sections of the line.

This test was repeated with the reverse conditions, the top and middle conductors being grounded from tower 57 to the impulse generator location. The impulses were applied as before to the lower conductor

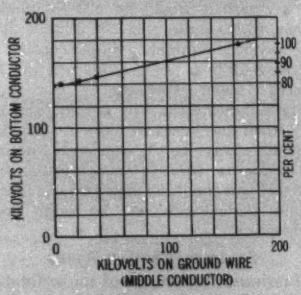


Fig. 9—Protective Factor using Ground Wire

and emerging from under the grounded conductors at tower 57. These data are shown plotted in Fig. 10 and bring out some important conclusions. Considering case I, in which the impulse enters the grounded section at tower 57, a point of inflection occurs in the attenuation curves which shows a reduction in potential due to the presence of the ground wires. The change in the curves occurs at a point about one mile back from the beginning of the ground wire section. The effect of the ground wires may be seen by extrapolating the curves

without the ground wires which indicates a reduction of about 8 per cent due to the ground wires. It should be possible to apply the attenuation curve *C* of Fig. 7 for the first three or four miles of this curve, but for some unknown reason curve *C* shows considerably increased attenuation for the same initial value of potential.

In Fig. 10, case II, the attenuation curves are shown for an impulse passing from the ground wire section into a section without ground wires. In order to show the

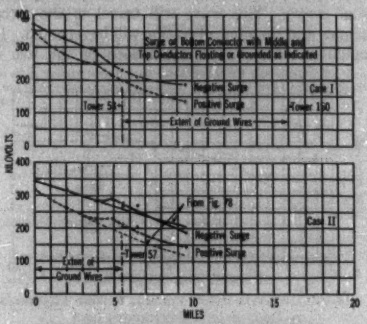


Fig. 10—Effect on a Surge of Entering or Leaving a Section Equipped with Ground Wires

change in potential clearly, the attenuation curve *B* from Fig. 7 has been superimposed and indicates an increase of potential of 8 per cent for the negative impulse and slightly more for the positive impulse. As with case I, the effect of the ground wire is felt a distance of about one mile back from the transition point. Measuring only crest potentials with a sphere-gap the effect of the partial reflection would extend back from the point of change in impedance and a distance slightly greater than half the length of the wave front. If the wave had been perpendicular, full crest potential would have measured up to the reflection point, assuming, of course, no time lag for the measuring sphere-gaps.

It should be noted in connection with these curves that the attenuation is much the same for positive waves, whether under the ground wire or not, while with the negative waves there seems to be a definite tendency for less attenuation under the ground wires. This situation is clearer in connection with case II than it is for case I. These results agree with those discussed in connection with Fig. 7 under the general subject of attenuation.

Considering all of the values obtained a value of 8 per cent may be taken as the second ground wire effect, which is to be compared with the 6 per cent calculated reduction when passing from a conductor having a surge impedance of 530 ohms to a surge impedance of 470 ohms which was calculated for the S-19 line with the top and middle conductors grounded.

Thus the sum of the first and second ground wire effects gives a total reduction of 20 per cent for one ground wire. With two ground wires the first effect will be increased. The tests indicate that the second effect is not materially changed when two ground wires are used instead of one. These tests with traveling waves show that ground wires on a transmission line under a discharging cloud afford about that degree of protection indicated by the usual theoretical formula.

### Copper vs. Steel Ground Wire

A limited number of tests was made in an effort to determine the relative merits of copper and steel conductors acting as ground wires. The tests made, which relate only to traveling wave effects at comparatively low voltages, do not show any marked difference between copper and steel ground wires. One set of test results is given in Fig. 11, showing the voltage measured back along the grounded conductor from a grounded point. These waves show the copper to have slightly lower reflected potentials than the steel wire but the difference is too small to be more than an indication. This curve is also interesting in that it shows that potentials as high as 200 kv. may exist a distance of 2000 ft. away from the grounded point, although much steeper gradients than this can no doubt be obtained with steeper waves. In the case under consideration the grounded point was at tower 55, the steep wave impulse being applied at a point over 5 mi. away.

For protection from direct strokes of lightning the

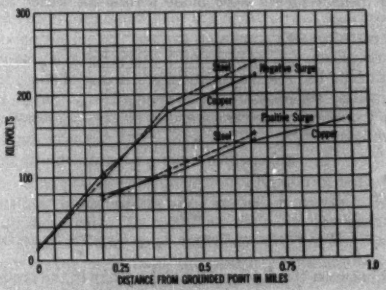


Fig. 11—Surge Voltage on a Steel or Copper Conductor Measured from a Grounded Point Back Toward the Impulse Generator

copper ground wire may have some advantage from the standpoint of current carrying ability. Not enough is yet known about the direct stroke condition to make any definite statements regarding the relative merits of copper and steel.

### Effect of Ground Resistance

In studying ground wires it is worth while to give some thought to the value of ground resistance under impulse conditions compared to grounds measured in the steady state. The effect of two ground resistances

in parallel but varying distances apart will also be briefly considered.

Measurements of tower footing resistance were made with a megger constructed especially for this purpose. The resistances were found to vary from 12 to more than 1500 ohms. The resistances of tower footings over the section of line used in most of the tests described in this paper are given in Fig. 12.

To measure a ground resistance under impulse con-

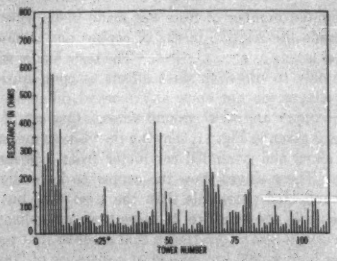


Fig. 12—Tower Footing Resistance on 10-Mi. Section of S-19 Line

ditions, a pipe was driven into the ground approximately 200 ft. from the impulse generator. An impulse current was sent from the generator through a water tube resistance into the pipe ground. Sphere-gap measurements were made across the water tube

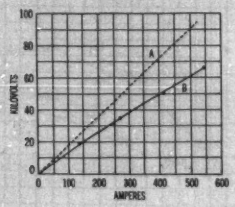


Fig. 13—Volt-Ampere Curves of a Ground Resistance

and between the pipe ground and a stake in the ground far enough away not to be influenced by the current flowing in the vicinity of the pipe ground. In every case the transient resistance was less than that measured under steady state conditions, which is in agreement with cathode ray oscillograph tests made at Pittsfield.[12] The results of one such test is given in Fig. 13, which shows that the ground resistance with a transient current of 550 amperes is about 67 per cent of the steady state resistance.

When a surge passes a point which is grounded through a resistance the voltage is reduced according to the relation $E/E_o = 2\,R/(2\,R + Z)$, where $E_o$ is the initial voltage and $E$ the transmitted voltage. The per cent reduction due to varying values of resistance is shown by Fig. 14. When a wave passes two grounded points sufficiently far apart the reduction is correctly represented by applying this formula twice, once to the original wave and once to the transmitted wave which passes the first resistance. When this transmitted wave reaches the second resistance there will be a new transmitted wave beyond the second resistance and also a negative reflection traveling back toward the first resistance. Another reflection of reversed polarity will take place which will have the same polarity as the original wave. This wave will travel to the second resistance and the same operation will be repeated. If a rectangular wave is considered each of the two re-

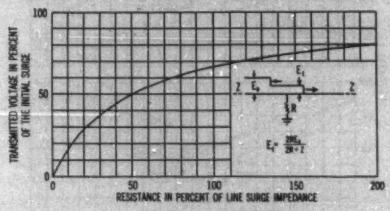


Fig. 14—Transmitted Surge Voltage beyond a Resistance to Ground on a Continuous Line

sistances will operate independently if the distance between them is equal to more than half the wave length. If the distance is less, the transmitted potential will be correspondingly higher until the condition is reached of a single resistance of half value when the distance between them is reduced to zero. This relation is shown in Fig. 15, which shows that if two resistances

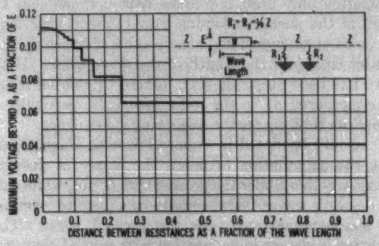


Fig. 15—Fraction of Rectangular Wave Transmitted beyond Two Ground Resistances

equal to one-eighth of the surge impedance are connected between line and ground farther apart than half the wavelength only 4 per cent of the wave is transmitted, while if the same two resistances are connected at the same point the transmitted wave will be 11 per cent. This does not mean, however, that it is better to ground a ground wire at a few points far apart rather than many points close together, but it does indicate

that two grounds of, for example, 50 ohms each are better if separated some distance apart than one ground of half the resistance in one location. This seems to indicate the desirability of keeping the ground resistance of towers uniformly as low as possible rather than having wide variations in tower footing resistance, even though some are low, but with a high average.

The following tabulation shows how distance between resistances affects the transmitted wave when using surges having a front of approximately 10 microseconds.

TABLE II

EFFECT OF DISTANCE BETWEEN RESISTANCE TO GROUND ON THE PROPAGATION OF A SURGE

The surge voltage with no resistance connected was 405 kv. $R_1$, $R_2$, $R_3$ were tower footings having resistances ranging between 58 and 66 ohms (megger).

| Voltage meas. at | Spacing between resistances | | | |
|---|---|---|---|---|
| | Zero* | 500 ft. | 5000 ft. | Distant* |
| $R_1$ | 56 kv. | 56 kv. | 51 kv. | 56 kv. |
| $R_2$ | 30 | 21 | 10 | 7.7 |
| $R_3$ | 10.3 | 8 | 3 | 1.1 |

*Calculated assuming $R/Z$ = 8 per cent

The test values which were measured at spacings of 500 and 5000 ft. lie in the range that would be expected from the theory.

## Measurement of Surge Impedance

Some difficulty has been experienced in measuring the surge impedance of the transmission line conductors.

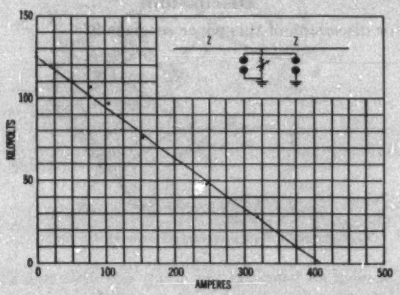


Fig. 16—Determination of Surge Impedance by Measurement of Voltage and Current to Ground with a Variable Resistance and Sphere-Gaps

The method finally adopted was to connect a variable resistance between line and ground at a point sufficiently remote from the generator to be sure that traveling wave conditions were established and plot a curve between amperes through the resistance and the potential to ground as in Fig. 16. The current values are determined from the potential measured across the grounding resistor, while the voltage measurements are taken between the line and a separate ground at a point such that the $I\,R$ drop in the resistance of the ground is included. If the measurement is not made at the end of a line the voltage at zero current is to be divided by one-half of the current at zero volts, which will give the surge impedance. If the measurement is made at the end of a line remote from the generator the voltage at zero current divided by the current at zero voltage will give the surge impedance. The advantage with this method lies in the possibility of determining the curve quite accurately by taking measurements with several resistances without being forced to measure the current at zero potential.

## Conclusions

A million-volt impulse generator of sufficient capacity for field use with limited power facilities available has been shown to be satisfactory in use, and still higher potentials can be obtained when necessary.

The tests have shown the following:

1. Surges attenuate less rapidly when other near-by parallel conductors are carrying similar surges.

2. In general positive surges attenuate more rapidly than do negative surges, although in some tests but little difference was found.

3. Short waves, such as a wave chopped on the front by an insulator flashover, attenuate more rapidly than do longer waves of the same crest value.

4. An additional constant has been introduced into the formula for attenuation which seems to give better agreement with the test results.

5. The presence of the ground wire reduces the attenuation considerably for the negative wave and to a lesser degree for the positive impulse. This decrease in attenuation is important if found to be universally true, for it tends to cancel the reduction of induced potential as a result of a discharging cloud after the resulting traveling wave travels a distance of several miles. This of course does not affect the reduction in potential due to the ground wire at the point of inception.

6. The ground wire theory of reduction of induced potentials was checked using traveling waves. The results agree with the protective ratio for the ground wire given by the usual calculation. For the conductor arrangement used, the calculated reduction was 21 and 23 per cent, while the test showed 20 per cent reduction for the total ground wire effect.

7. The second ground wire effect was also checked with traveling waves and it was found that when entering or leaving a section with one or two ground wires the surge voltage was decreased or increased 8 per cent respectively. These approximate the calculated value based on the change in surge impedance. These results indicate that very little is to be gained by putting up additional ground wires near a station to reduce an incoming impulse. From the standpoint of additional protection from lightning discharges which originate close to the station their use may be justified.

8. The test indicates that there is little difference

between steel and copper conductors from the standpoint of their ability to transmit impulses.

9. The theory of voltage reduction due to two resistances varying distances apart connected between conductor and ground when subjected to traveling waves was checked by test. This work shows that if but two grounds of equal value are to be used the greatest reduction in wave transmitted beyond the resistances occurs when the resistances are at least half a wavelength apart. Thus two resistances of 40 ohms a half mile apart will more effectively ground the line than one resistance of 20 ohms. This seems to indicate that uniform low resistance is preferable to widely varying resistances.

10. Transient ground resistance is less than the resistance measured under steady state conditions.

11. The surge impedance of a transmission line may be satisfactorily determined from a series of voltage and current readings with varying values of resistance between line and ground.

The authors wish to express their appreciation to the officials of both the Consumers Power Company and the General Electric Company who have made this joint investigation possible. Much credit is due to Messrs. Brune, Eaton, Wade, and others who were responsible for conducting the tests in the field and to Messrs. Boehne, Brinton, and Brownlee who also assisted in the preparation of the paper.

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## Discussion

For discussion of this paper see page 928.

# Lightning Investigation on 220-Kv. System of the Pennsylvania Power & Light Company (1928 and 1929)

BY NICOLAS N. SMELOFF[1] and A. L. PRICE[2]

Associate, A. I. E. E. Non-Member

*Synopsis.—The purpose of this paper is to describe the results of a lightning investigation conducted during 1928 and 1929 on 114 circuit miles of a 220-kv. system located in a territory where severe lightning storms are frequent. During the 1929 investigation, which was a continuation and expansion of previous years' work, a number of devices was successfully used, such as surge voltage recorders, cathode ray oscillographs, electric field intensity recorders, and lightning stroke recorders. Some of these devices are new.*

*Many valuable data on magnitude and wave shape of actual lightning surges were obtained, proof of the existence of both single- and multiple-phase faults due to lightning; some data on the shielding effect of overhead ground wires and qualitative data on the nature and time of discharge of lightning strokes, together with the atmospheric gradients resulting therefrom, were also obtained.*

## General Review

INVESTIGATIONS of lightning with particular reference to its effect on the transmission line and associated station apparatus comprising the 220-kv. system of the Pennsylvania Power & Light Company have been in progress since 1926. Data obtained in 1926 and 1927 are available in a paper[3] presented before the A. I. E. E. in 1928.

The investigation conducted in 1926 and 1927 emphasized the need of greater knowledge of the basic phenomena of lightning with the result that during

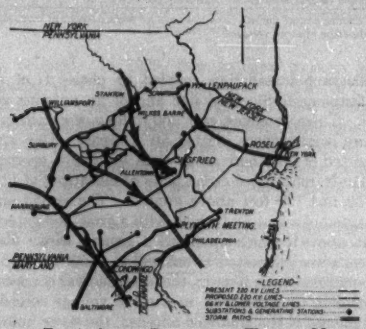


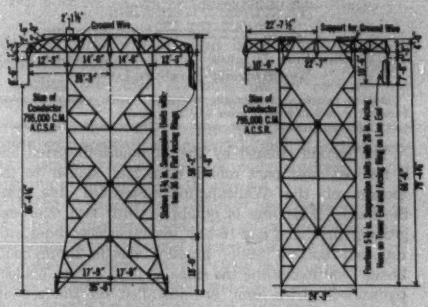

FIG. 1—SYSTEM DIAGRAM AND WEATHER MAP

1928 and 1929 the study was extended to include the wave shape of lightning surges on transmission lines and experimental antennas, more accurate storm observations, supplemented by measurements of electric field intensities and their rates of change, and data on the causes of the surges due to induction or conduction from charged clouds. The operating records were secured in more detail, including the location and position of flashed insulators and tripout records regarding single- and multiple-phase failures. The broadening of the scope of this investigation was due not only to improvement in technique of cathode ray oscillograph operation with regard to its application in the field, but also due to the application of entirely new devices developed for this investigation.

In nature and amount of data collected, the results of the investigation during the past two years are very gratifying. They permit a better understanding of what is needed for a systematic solution of transmission line lightning problems.

## Line Data

The 220-kv. system of the Pennsylvania Power & Light Company consists of the Wallenpaupack-Siegfried




Plymouth-Siegfried Line Wallenpaupack-Siegfried Line

FIG. 2—STANDARD TYPE "A" SUSPENSION TOWERS

and Plymouth-Siegfried lines. These lines, together with future interconnections, are shown in Fig. 1. The lightning study was confined to these two lines, particularly the Wallenpaupack-Siegfried line.

General characteristics of the Wallenpaupack-Siegfried line were published in a previous paper.[3] Early in 1929, a so-called "counterpoise" was installed for a distance of about 2½ miles along a section of the line where flashed insulators had been particularly numerous

1. System Planning Engineer, Pennsylvania Power & Light Co., Allentown, Pa.

2. General Engineering Laboratory, General Electric Company, Schenectady, N. Y.

3. For all references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

(see Figs. 3 and 18). This counterpoise was a buried No. 00 copper cable which connected the tower footings. In addition to the counterpoise, the insulator assemblies on the outside conductors were increased during the 1929 lightning season, from 14 to 16 units over the 40-mile section of the line adjacent to Wallenpaupack.

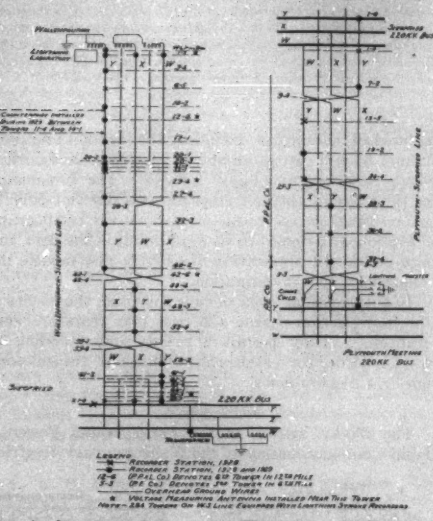


FIG. 3—ONE LINE DIAGRAM OF WALLENPAUPACK-SIEGFRIED AND SIEGFRIED-PLYMOUTH LINES

Showing locations of lightning laboratory, surge voltage recorders, antennas, overhead ground wires, and counterpoise

The terrain crossed by the Plymouth-Siegfried line is for the most part rolling farm land similar to the section of the Wallenpaupack-Siegfried line near Siegfried. This line is equipped with two overhead ground wires, and has 16-unit insulator assemblies with top and bottom 36-in. grading shields throughout. Locke 7500 insulators, the same as used on the Wallenpaupack-Siegfried line, are installed on the section owned by the Pennsylvania Power & Light Company. Fig. 2 shows typical towers for both lines.

## FACILITIES

This investigation was conducted, and facilities made available, cooperatively by the General Electric Company and the Pennsylvania Power & Light Company. The Public Service Electric and Gas Company of New Jersey and the Philadelphia Electric Company cooperated in supplying lightning weather data and in the general analysis of all data obtained. The Philadelphia Electric Company also supplied operating data on its section of the Plymouth-Siegfried line.

Apparatus employed and the scope of the investigation are indicated in Table I. Locations of measuring instruments with reference to the transmission lines are shown in Fig. 3.

In 1928, in addition to the previously used surge voltage recorders, a lightning laboratory was established at Wallenpaupack. It consisted of a cathode ray oscillograph installation coupled to phase *Y* of the Wallenpaupack-Siegfried line and of an antenna station. These antennas, each 300 ft. long, were arranged in two parallel spans located 50 ft. apart. One span consisted of four horizontal wires vertically arranged on 110-ft. rope guyed cedar poles at elevations of 12½, 25, 50, and 100 feet above ground. The second span consisted of a wire 50 ft. high with a grounded antenna 12 ft. above it which simulated a ground wire. Each antenna was connected at one end to earth through a two-megohm water resistor, the other end was connected through a potentiometer to a surge voltage recorder. In the case of the grounded antenna, the surge voltage recorder was coupled to the ungrounded end.

In 1929, additional facilities were provided. A second cathode ray oscillograph was installed and coupled to the 50-ft. antenna without overhead ground wire. These two cathode ray oscillographs at the Wallenpaupack lightning laboratory (Fig. 4) were manned by four trained operators.

Fig. 5 shows the circuit employed in obtaining records with the cathode ray oscillograph coupled to the transmission line. The surge voltage, upon its arrival, automatically operated the oscillograph by means of a three-electrode trip gap connected to the insulator string potentiometer shown at the left of the diagram. The deflection plates were connected to a potentiometer consisting of an insulator string with grading shields. In order to secure a record over an appreciable period of time, a logarithmic sweep was used to elongate the

TABLE I
MEASURING DEVICES AND FACILITIES

| *A—Instruments used on Lines* | No. of instruments 1928 | 1929 |
|---|---|---|
| Cathode ray oscillograph[4] | 1 | 1 |
| Surge voltage recorders[5] | 39* | 28 |
| Lightning stroke recorders[6] on towers | 0 | 284 |
| High-speed phase current recording ammeters | 0 | 6 |
| *B—Instruments Coupled to Antennas* | | |
| Cathode ray oscillograph | 0 | 1 |
| Surge voltage recorders | 7 | 12 |
| *C—Weather Data* | | |
| Weather observations from operating stations | 29 | 160 |
| Weather observations including location of lightning strokes, from Fire Towers and Wallenpaupack Lightning Laboratory | 1 | 4 |
| Radio set weather indicator at Wallenpaupack Lightning Laboratory | 0 | 1 |
| Electric field intensity recorder[4] | 0 | 1 |
| Rate of change of field recorder[4] | 0 | 1 |
| *D—Operating Data* | | |
| Overhead (tower climbing) patrols—Wlpk.-Sieg. Line | 5 | 20 |
| Siegfried-Plymouth Line | 2 | 3 |
| Operating records from 220-kv. operating stations | | |

*Excludes 6 surge voltage recorders used for measurement of wave shape and duration of surge voltages.

more important portion of the time axis. Constants shown in Fig. 5 are for a 40-microsecond record, but these were changed to secure longer records during a portion of the season.

During both years, surge voltage recorders were coupled to the transmission line by means of insulator string potentiometers with grading shields. The potentiometer shown to the right in Fig. 5 was the type generally used except that the middle grading shield

Fig. 4—Photograph of Wallenpaupack Lightning Laboratory

was omitted. In 1929, four antenna stations were installed at the locations indicated in Fig. 3. The installations near towers 23-4, 42-6, and 65-3 consisted of 300-ft. spans of a single wire 50 ft. above ground. Near tower 12-6 two antennas were installed, on the same poles, at heights of 25 and 50 ft. above ground. Surge voltage recorders were coupled to all of these antennas.

Three newly developed instruments, the electric

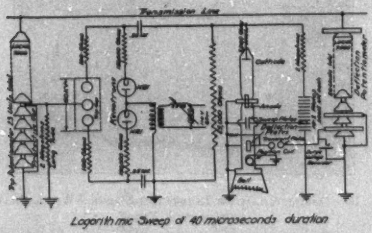



Fig. 5—Cathode Ray Oscillograph Circuits—Wallenpaupack Lightning Laboratory 1929

field intensity recorder, the rate of change of electric field intensity recorder, and lightning stroke recorders were made available and first used in 1929.

In order to determine whether faults on the 220-kv. circuits were single- or multiphase, high-speed phase-current recording ammeters were installed at Wallenpaupack and Siegfried.

## Lightning Weather Data

In order to gain a more general insight into the lightning storm conditions in the territory under investigation, and to supplement the data collected by the power company, information regarding lightning storms was obtained from neighboring power companies.

Lightning weather observations were secured from approximately 160 observation points in the operating territories of all the power companies in a district from Altoona east to New York and from Wallenpaupack south to Washington, in addition to reports from the lightning laboratory and several fire towers in New Jersey and Pennsylvania. Typical storm paths are shown in Fig. 1, which indicates the storm paths followed on June 19, 1929. Generally, the storms move from west to east or from northwest to east southeast.

## Results

*Cathode Ray Oscillograms.* The first oscillogram of a

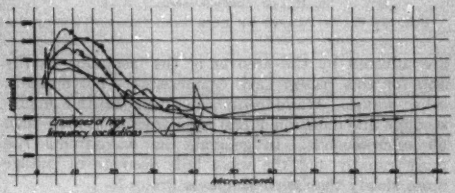



Fig. 6—Wave Shapes of Lightning Surges—Group 1

lightning surge was obtained in 1928 and has been previously described.[7]

During the 1929 lightning season cathode ray oscillograms of 95 voltage surges on phase *Y* of the Wallenpaupack-Siegfried line were obtained at the lightning laboratory at tower 1-3, and 11 cathode-ray oscillograms were obtained of voltage surges on the antenna at the lightning laboratory.

Of the 95 oscillograms obtained of voltage surges on the line, 50 measured under 100 kv. at the cathode-ray oscillograph, 30 measured between 100 and 300 kv., and 15 measured above 300 kv. The cathode ray oscillograph connections allowed measurements of voltages superimposed on the normal 60-cycle wave, while the surge voltage recorders measured total voltage to ground.

The wave shapes of the 15 surges above 300 kv. and that of the surge obtained in 1928 have been classified into three groups. These are shown in Figs. 6, 7, and 8 respectively.

*Group 1—Fig. 6.* The general characteristics of the wave shapes shown in this group are those common throughout all the oscillograms obtained. These waves rise to 75 per cent of crest voltage value in from 2 to 5 microseconds, reach crest value in 3 to 11 microseconds, decrease to 50 per cent crest value in 14 to 20 microseconds and pass through zero in 18 to 30 microseconds.

After passing through zero, these surges rise to a low value of voltage of opposite polarity to that of the first loop and maintain this low voltage until the end of the record, 45 to 90 microseconds. The first loop of the voltage surges in this group is of positive polarity.

*Group 2—Fig. 7.* Wave shapes 1 and 2 in this group

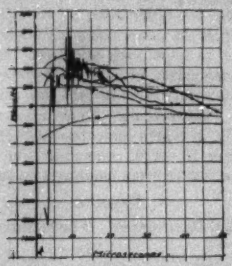


FIG. 7—WAVE SHAPES OF LIGHTNING SURGES—GROUP 2

are affected by the arcover of the insulation nearby and for this reason have characteristics not noted in other waves. Wave-fronts range from 1.6 to 8 microseconds and duration of first loops from 29 to more than 50 microseconds. In general, the wave-fronts rise more rapidly and the wave tails decrease in voltage more slowly than wave shapes in group 1.

*Group 3—Fig. 8.* Wave shapes in this group are of

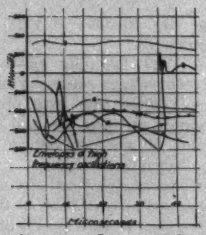


FIG. 8—WAVE SHAPES OF LIGHTNING SURGES—GROUP 3

composite nature in that they have more than one peak value without a polarity reversal. A rather long period (at least 30 or 40 microseconds) of high sustained voltage results from this double peaked characteristic. Negative polarity predominates in this group.

The actual oscillograms of one surge from each of these groups are shown in Figs. 9, 10, and 11 respectively. Pertinent data relative to these surges is as follows:

*Oscillogram, Fig. 9 (Group 1, wave shape 7 of Fig. 6).* This oscillogram was obtained at the Wallenpaupack lightning laboratory at 7:39 p. m. on June 19, 1929, apparently coincident with the tripping of the Wallenpaupack-Siegfried line. Fig. 12 shows the profile of voltage in times-normal (180 kv.) which occurred at points on phase $Y$ along the transmission line. This voltage profile is an envelope of two surges of opposite polarity too near together in time to be separated on the surge voltage recorder films. It indicates that the highest voltage of positive polarity which correlates with the oscillogram, Fig. 9, was at the Wallenpaupack Station with the next highest voltage about 30 miles away.

A voltage at this time of 15 kv. was measured on

FIG. 9—OSCILLOGRAM OF LIGHTNING SURGE—WAVE SHAPE 7 OF GROUP 1, FIG. 6

the 60-ft. grounded antenna at the lightning laboratory.

The field intensity recorder indicated a voltage gradient of 12 kv. per foot.

A cloud-to-ground stroke of indefinite distance but over 10 miles south and 13 degrees east of the line was seen from the laboratory at the instant this oscillogram was obtained. Lightning was reported from several points between Wallenpaupack and Siegfried. Storm paths for the day are shown in Fig. 1.

*Oscillogram, Fig. 10 (Group 2, wave shape 2 of Fig. 7).* Oscillogram 2 was obtained at 1:39 p. m. on May 29, 1929, coincident with a tripout of the Wallenpaupack-Siegfried line.

Flashed insulators were found on all three phases at

FIG. 10—OSCILLOGRAM OF LIGHTNING SURGE—WAVE SHAPE 2 OF GROUP 2, FIG. 7

tower 9-3, two days after this tripout, the insulation on that structure being 16 units on phases $Y$ and $W$ and 14 units on phase $X$. Fig. 13, which shows the profile of voltage along the line on Phase $Y$, checks this location as being the point of highest voltage.

A voltage of 39 kv. (negative) was recorded on the 60-ft. grounded antenna at Wallenpaupack.

The field intensity recorder indicated a voltage gradient of 5 kv. per foot. At the instant the oscillo-

gram was obtained, the observer saw a stroke approximately 4.2 miles southeast of the laboratory. Two storms were in progress, the one had its center between the sixth and tenth mile from Wallenpaupack, the other 3 to 5 miles northeast of the laboratory. Storm clouds were not nearer to the laboratory than 1½ miles at the time the oscillogram was obtained.

Observers saw all three phases flash over the dead-end protective gaps at the Wallenpaupack station, which is 840 feet north of the lightning laboratory. This flashover accounts for the sudden reversal of polarity shown in this oscillogram (Fig. 10) and is interesting as a comparison with the oscillogram obtained in 1928, shown as wave shape No. 1 in this same group (Fig. 7). In the case of wave shape No. 1 a flashover occurred over the protection gap on phase *X* at tower 1-2 which is 460 ft. from the lightning laboratory. When the phase to which the oscillograph was coupled, flashed over, there was a sudden reversal of polarity, the voltage rising from 1260 kv. negative to 310 kv. positive in one microsecond; however, when the flashover was on an adjacent phase only, there were oscillations of about 2000 kilocycles superimposed on the main wave without reversal of polarity.

Fig. 11—Oscillogram of Lightning Surge—Wave Shape 8 of Group 3, Fig. 8

*Oscillogram Fig. 11 (Group 3, wave shape 8 of Fig. 8).* At 7:42½ p. m., 3½ minutes after oscillogram Fig. 9 was obtained, oscillogram Fig. 11 was recorded at the same place. Records indicate that the line was not

TABLE II

CATHODE RAY OSCILLOGRAMS OF TRANSMISSION LINE SURGES, CREST VOLTAGES OVER 100 KV. (YEAR 1929)

| Kv. max. | Polarity of first loop | Nature of wave | Time in microseconds to reach: At least 75% of max. voltage recorded | Max. voltage recorded | 50% max. on tail of wave | Zero of first loop | Original disturbance on line: Distance in miles from osc. | Kv. measured near origin |
|---|---|---|---|---|---|---|---|---|
| 1260 | Neg. | Osc. | 3.3 | 3.3 | 3.7 | 4 | 10 | 2400 |
| 810 | Neg. | Osc. | 36 | 36 | 7 | 37 | 21 | 1360 |
| 740 | Pos. | Osc. | 7 | 7 | 16 | 22 | 0–3 | 690 |
| 740 | Neg. | Uni. | 6.5 | 6.5 | 43+ | 43+ | 0–3 | 640 |
| 630 | Pos. | Osc. | 11 | 11 | 20 | 29 | 0–3 | 860 |
| 600 | Neg. | Uni. | 0–1.6 | 4 | 14.5 | 45+ | 0–3 | 550 |
| 600 | Neg. | Uni. | 0–7.5 | 0–7.5 | 69+ | 69+ | 40 | 2400 |
| 530 | Pos. | Osc. | 3 | 7–8 | 18 | 24 | 0–3 | 580 |
| 500 | Pos. | Osc. | 0–8 | 0–8 | 32 | 45 | 0–3 | 470 |
| 390 | Pos. | Osc. | 6 | 6 | 14 | 18 | 0–27 | 480 |
| 390 | Pos. | Osc. | 6 | 6 | 35 | 55 | ? | ? |
| 360 | Pos. | Uni. | 0–1.6 | 4 | 45+ | 45+ | 0–3 | 400 |
| 330 | Pos. | Osc. | 1.6 | 1.6 | 16 | 29 | 0–3 | 300 |
| 330 | Neg. | Uni. | ? | ? | 12 | 75 | 58 | 2400 |
| 330 | Pos. | Osc. | ? | ? | 18 | 25 | ? | ? |
| 300 | Pos. | Osc. | 8 | 8 | 24 | 45 | ? | ? |
| 280 | Pos. | Osc. | 4 | 4 | 11 | 20 | 32 | 610 |
| 260 | Pos. | Uni. | 0–1 | 5 | 26 | 45+ | 0–3 | 300 |
| 260 | Pos. | Osc. | 5 | 5 | 27 | 36 | ? | ? |
| 260 | Pos. | Osc. | 2 | 5 | 25 | 35 | 44 | 2400 |
| 260 | Pos. | Osc. | 0–2 | 19 | 40 | 42 | 61 | 2400 |
| 250 | Pos. | Osc. | 0–1.3 | 3 | 5.5 | 9.5 | ? | ? |
| 245 | Pos. | Uni. | 0–1.2 | 0–1.2 | 22 | 33+ | ? | ? |
| 210 | Pos. | Uni. | 0–5 | 0–5 | 85+ | 85+ | 17 | 720 |
| 210 | Pos. | Uni. | 9 | 9 | 10+ | 10+ | ? | ? |
| 205 | Pos. | Uni. | 0–3.5 | 0–3.5 | 13 | 89+ | 0–3 | 300 |
| 180 | Pos. | Osc. | 5 | 5 | 23 | 32 | ? | ? |
| 180 | Pos. | Uni. | 0–1.5 | 5 | 20 | 45+ | ? | ? |
| 180 | Pos. | Osc. | 0–1 | 6 | 27 | 35 | ? | ? |
| 180 | Pos. | Osc. | 2.5 | 4.5 | 18 | 26 | ? | ? |
| 180 | Pos. | Osc. | 0–17 | 0–17 | 28 | 40 | 48 | 1100 |
| 170 | Pos. | Uni. | 0–1 | 20 | 43+ | 43+ | 44 | 2400 |
| 160 | Pos. | Osc. | 0–1 | 5 | 13 | 24 | ? | ? |
| 155 | Neg. | Osc. | 17 | 17 | 24 | 31 | 40 | 2400 |
| 150 | Neg. | Uni. | 0–1.5 | 4 | 45+ | 45+ | ? | ? |
| 140 | Neg. | Uni. | 0–1.5 | 20–28 | 45+ | 45+ | ? | ? |
| 140 | Neg. | Uni. | 4 | 32 | 38 | 43+ | 44 | 2400 |
| 135 | Neg. | Osc. | 0–2 | 0–2 | 6 | 10 | ? | ? |
| 130 | Pos. | Osc. | 3 | 3 | 11 | 33 | ? | ? |
| 130 | Pos. | Uni. | 0–1 | 20 | 81+ | 81+ | ? | ? |
| 120 | Neg. | Uni. | 0–2 | 80 | 156+ | 156+ | ? | ? |
| 120 | Pos. | Osc. | 6 | 6 | 12 | 15 | ? | ? |
| 110 | Pos. | Uni. | 0–4.5 | 0–4.5 | 9.5 | 14 | 3 | 2400 |
| 105 | Neg. | Uni. | 0–1.5 | 40 | 96+ | 96+ | ? | ? |
| 105 | Pos. | Uni. | 0–2 | 82 | 82+ | 82+ | ? | ? |

Osc.—Oscillatory highly damped.
Uni.—Unidirectional.
? —Point of origin of surge not definite from surge voltage recorder records.

closed until 3 or 4 minutes after the previous tripout at 7:40 p. m. so it is very probable that oscillogram 8 was obtained while the line was deenergized.

On June 21, two days after this oscillogram was obtained, flashed insulators were found on phase $Y$ at tower 23-2, phase $X$ at tower 23-4, and phase $W$ at towers 23-2, 23-3, and 23-4. The negative polarity of the voltage profile, Fig. 12, which correlates to this oscillogram, indicates that the highest voltage for this surge was at this location.

*Summary of Cathode Ray Oscillograms of Transmission Line Surges.* Wave shape data relative to the transmission line surges measuring above 100 kv. as determined from the cathode ray oscillograms are shown in Table II. These are arranged in decreasing order of crest voltage. The oscillograms have various wave shape characteristics and for this reason in Table II under the heading "Time in microseconds to reach" four columns are given: First, the lapse of time in the initial voltage rise (in several cases this is given between zero and a definite time value, the portion of the wave previous to this time not being recorded); second, the time required to reach the maximum voltage recorded; third, the time between the beginning of the surge and half maximum voltage on the tail of the wave; and fourth, the time duration of the first loop of the wave.

The last two columns in Table II show the approximate distance from the oscillograph to the source of the surge on the transmission line as judged by the maximum kilovolt measured by the surge voltage recorders.

Voltages reach 75 per cent of their crest in an interval of time ranging from less than 1.0 to 36 microseconds, then 100 per cent of crest value in 1.2 or less to 82 microseconds, decrease to 50 per cent of crest value in 3.7 to 156 microseconds, and reach zero of the first loop in 4 to 156 microseconds. 50 per cent of surges reach at least 75 per cent of their value in less than 3 microseconds.

A majority of the surges have a wave front of 3 to 8 microseconds and a duration of the first loop of 15 to 40 microseconds. Approximately 70 per cent are positive in polarity and 30 per cent negative for the first loop. Within the time range of the oscillograms approximately 60 per cent are slightly oscillatory and 40 per cent unidirectional.

All of the extremely high voltages which were measured on phase $Y$ of the transmission line by surge voltage recorders were 3 or more miles distant from the lightning laboratory, and, therefore, have attenuated considerably. It should also be remembered that the oscillograph was coupled to the transmission line at a point 840 ft. from its terminal where reflections may be pronounced.

## Surge Voltage Recorder Data

Fig. 14 shows that about 50 per cent of the lightning surges on the Wallenpaupack-Siegfried line and 15 per cent of those on the Plymouth-Siegfried line, were above 5 times normal. (900 kv.)

Of the 45 surge voltages measured on the Wallenpaupack-Siegfried line during 1929, apparently 44 originated on this line, while one was propagated from the Plymouth-Siegfried line. Fifteen of the 21 surges registered on the Plymouth-Siegfried line apparently originated on the Wallenpaupack-Siegfried line. A similar ratio of surge voltage origin held for the 1928 lightning season.

While voltages of about 2400 kv. were registered on both lines, not all of the high voltages were coincident with tripouts. This is shown in Fig. 15.

*Nature of Surge Voltages.* The voltages, as indicated by Lichtenberg figures, are highly damped, ($H\ D$), and at the point of highest registration are frequently unidirectional; but, if the voltage along the entire line be considered, the surge is usually classified as oscillatory. Table III indicates the polarity characteristics

TABLE III
POLARITY CHARACTERISTICS OF LIGHTNING SURGES—YEARS 1928 AND 1929

| | Wallenpaupack-Siegfried | | Siegfried-Plymouth | |
|---|---|---|---|---|
| | Number | Maximum voltage | Number | Maximum voltage |
| Polarity | | | | |
| Undirectional | | | | |
| Positive | 9 | 13.3-15.5 | 3 | 12.5-14.5 |
| Negative | 4 | 4.2 | 2 | 4.5 |
| Oscillatory | | | | |
| H. C. V. *positive | 16 | 13.3-15.5 | 4 | 10.1 |
| H. C. V. *negative | 37 | 13.3-15.5 | 17 | 12.5-14.5 |
| H. C. V. *positive and negative equal | 1 | 1.6 | 6 | 1.6 |

*H. C. V.—Highest crest voltage.

of surges obtained on these two 220-kv. lines, the surge being classified as oscillatory if voltages on the line of both polarities were registered coincidentally.

Table III indicates a preponderance of oscillatory surges, either polarity high, but with a tendency toward a greater number with high negative voltage.

*Attenuation.* Figs. 12, 13, and 16 are typical voltage profiles of surges measured along the transmission line. Many profiles such as shown in Fig. 16 were recorded; they represent profiles with very rapid attenuation. Such voltage profiles are sometimes obtained with difficulty because of the rapid succession of surges on the line. In several instances, surge voltage recorder registrations show superimposed Lichtenberg figures which indicate that at least two surges occurred within a few minutes time.

Table No. 4 gives values of the constant $K$ in the attenuation equation[8] $e = \dfrac{E_0}{K\,s\,E_0 + 1}$

where

$E_0$ = maximum voltage recorded—kv.
$e$ = voltage at any point—kv.
$s$ = distance in miles between points where $E_0$ and $e$ are recorded
$K$ = A constant
Attenuation $= -K e^2$

The constant $K$ in the above equation is calculated from surge voltage recorder measurements at the point of maximum registration and the measurement at the nearest adjacent recorder station. Only those measurements which were not obscured by several Lichtenberg figures are tabulated.

Of the 10 more slowly attenuated surges, those having an attenuation constant of 0.0003 or less, 9 were of negative polarity. In the range of $K$ greater than

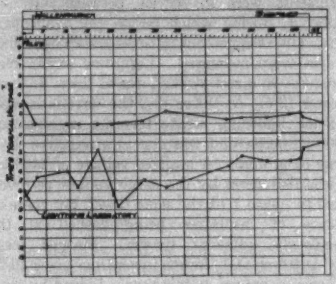


Fig. 12—Voltage Profile of Lightning Surge No. 28

0.0005 the majority of the surges were of positive polarity. These data indicate that surge voltages on this line of negative polarity, attenuate more slowly than do those of positive polarity.

*Effects of Lack of Continuity of Overhead Ground Wires.*

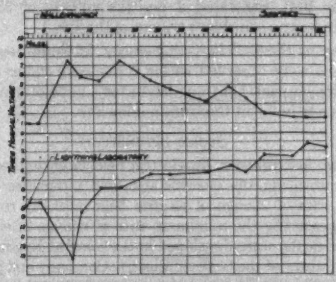


Fig. 13—Voltage Profile of Lightning Surge No. 15

As shown in Fig. 3, the section of the Wallenpaupack-Siegfried line between towers 20-2 and 61-2 was the only portion of this system not protected by overhead ground wires during the period under study. Surge voltage recorders were coupled to phase $Y$ one tower either side of the end of the overhead ground wires for studying the effects on the surges at these transition points. During 1928 the average of 10 surges which passed one or both these locations at voltage values in excess of 300 kv., averaged 430 kv. on the side of the open line and 360 kv. under the overhead ground wire. In 1929 an average of 15 surges was 580 kv. on the open line and 700 kv. under the overhead ground wire. The

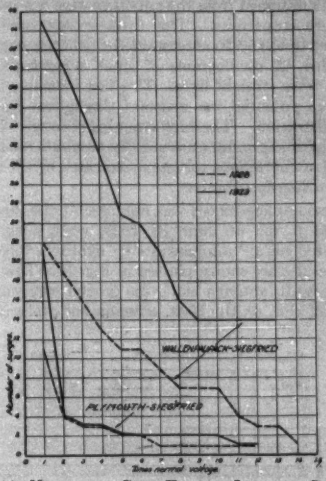



Fig. 14—Number and Crest Value of Lightning Surges

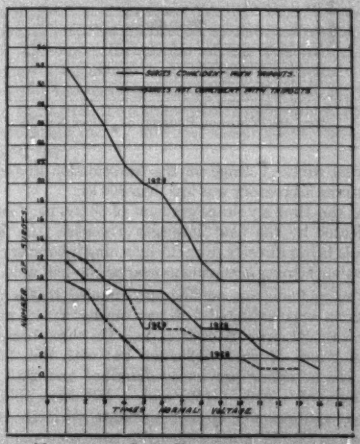



Fig. 15—Number and Crest Value of Lightning Surges on Wallenpaupack-Siegfried Line

Showing relation of surge voltages to circuit tripouts

number of these surges originating under the overhead ground wire and on the open line was about equal.

The above data indicate that no substantial change

in voltage occurs near the end of the overhead ground wires when a surge passes this point.

### Antennas

Data obtained from the antennas were not numerous but are important. The cathode ray oscillograph coupled to the 50-ft. antenna at the lightning laboratory recorded 11 oscillograms of small magnitude, all of which were straight lines. This fact indicates that the antenna potential was constant throughout the period of registration. The high damping resistance between antenna and ground undoubtedly accounts for the long period of continuous voltage as indicated by the cathode ray oscillograms obtained.

One complete record was obtained at the laboratory at 2:33 p. m., on June 19, 1929, when a surge was measured on all antennas at the lightning laboratory. The results are shown plotted in Fig. 17. The voltage on the 50-ft. antenna under the ground wire was about one-half that on the 50-ft. antenna not protected with

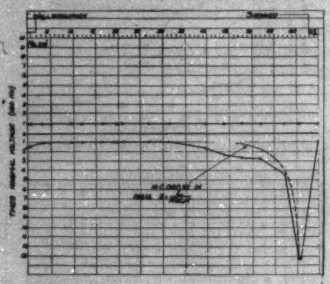


Fig. 16—Voltage Profile of Surge No. 76

ground wire. Voltage on the transmission line at the lightning laboratory was less than 300 kv.

At this time a voltage gradient of 53 kv. per foot was indicated by the field intensity recorder, the storm clouds being directly over the lightning laboratory with lightning strokes occurring as near as one-half mile.

The cathode ray oscillograph coupled to the 50-ft. antenna was actuated 7 times during a 3½ minute interval just prior to 2:33 p. m. On three occasions, oscillograms of small deflection but with the straight line characteristic previously described and with crest voltages of + 210, + 150, and − 150 were obtained. These oscillograms do not correlate with the surge shown in Fig. 17 which appears to have occurred before the oscillograph actuating circuit was reenergized after a previous operation.

Lichtenberg figure registrations at this time were of type $II$[9] indicating a time to reach crest in the range of 10 to 1,000,000 microseconds. Antennas located along the line produced only three small magnitude voltage records during the entire season, all being on the antennas near tower 12-6.

### Direct Strokes

Lightning stroke recorders[4] developed in the High-Voltage Engineering Laboratory of the General Electric Company were adjusted to register only currents above 50,000 amperes, and installed on 91 per cent of the towers of the Wallenpaupack-Siegfried line by the end of the 1929 lightning season. From 174 to 284 of these instruments were in service between July 17 and October 1, during which period the Wallenpaupack-Siegfried line tripped out 22 times and 28 lightning surge voltages were measured. Lightning stroke recorders indicated two direct strokes, one at tower 40-2 and one at tower 12-5. At tower 40-2 the current as estimated from the lightning stroke recorder registrations was 60,000 amperes, and was due to a negative cloud discharge to ground. A positive voltage of 2400 to 2800 kv. was registered by the surge voltage recorder connected to phase $Y$ at the same tower, but there was no evidence of insulators being flashed at this or immediately adjacent towers. Flashed insulators found at tower 41-1 (fourth tower from tower 40-2) may have been damaged at this time. Judged by the phase current recording ammeters, the coincident tripout was due to a fault on phase $X$.

At tower 12-5 on a portion of the line where the counterpoise was installed, a negative cloud discharge of about 100,000 amperes was indicated by a lightning stroke recorder. The nearest surge voltage recorder in operation at the time, the one connected to phase $Y$ at tower 10-2, registered a positive voltage of 350 kv. There was no coincident tripout of the line.

During the 1929 lightning season, 24 cloud-to-ground strokes were observed within a one mile radius of the Wallenpaupack lightning laboratory, none of which are known to have hit the transmission line.

### Storm Intensity

Two instruments, an electric field intensity recorder for measuring the electrostatic field intensities and a time rate of change of electric field intensity recorder for measuring the maximum rate of change of electrostatic fields, were developed in the General Engineering Laboratory of the General Electric Company and placed at the lightning laboratory during 1929 to obtain field experience in operation. Many records were obtained with these instruments and are included in another paper presented before the Institute.[6]

Voltage gradients measured, averaged from 55 kv. per foot for strokes occurring near the laboratory to about 8 kv. per foot for strokes 8 miles distant. The maximum registration was 85 kv. per foot.

Records of 33 storms indicated that lightning fields during any single storm were usually of one predominant polarity either positive or negative. About 20 per cent of these storms were of mixed polarity, the balance was

about equally divided between those predominantly positive and predominantly negative.

One record of particular interest which correlates with the data obtained by surge voltage recorders coupled to antennas at the lightning laboratory indicated a voltage gradient of 53 kv. per ft. This is shown in Fig. 17.

TABLE IV
ATTENUATION CONSTANTS OF LIGHTNING SURGES

| No of surges having attenuation constant $K$ within limits indicated in Column 2 | | | |
|---|---|---|---|
| Neg. polarity | Pos. polarity | Total | Limits of $K$ |
| 9 | 1 | 10 | Less than 0.0003 |
| 6 | 4 | 10 | Between 0.0003 and 0.0005 |
| 8 | 12 | 20 | Greater than 0.0005 |

| | Pos. | Neg. |
|---|---|---|
| Maximum $K$..... | 0.012 | 0.0086 |
| Minimum $K$..... | 0.000012 | 0.000065 |

## Flashed Insulators

Fig. 18 indicates that on the Wallenpaupack-Siegfried line a total of 92 insulator assemblies was flashed in 1929, and 171 assemblies during 1926 to 1928 inclusive. These figures indicate an average of 2½ assemblies flashed per tripout due to lightning in 1929 and 4½ assemblies flashed per tripout for the three previous years.

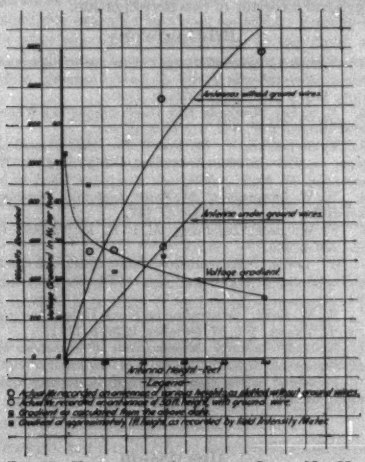



Fig. 17—Voltages on Antennas—Surge No. 23

Most of the insulators are flashed on the outside phases as is shown in Table V, and of those marked, only a portion have glaze burns by dynamic arc, the others apparently being flashed by impulse currents only.

In Fig. 18 the number of surge voltages exceeding 5 and 10 times normal at surge voltage recorder stations indicates comparable voltages for 1928 and 1929, but actually there were more than twice as many individual surges of high magnitude in 1929. It appears that a greater percentage of the surges in 1929 was of a type that registered high voltages at one or two recorder stations only.

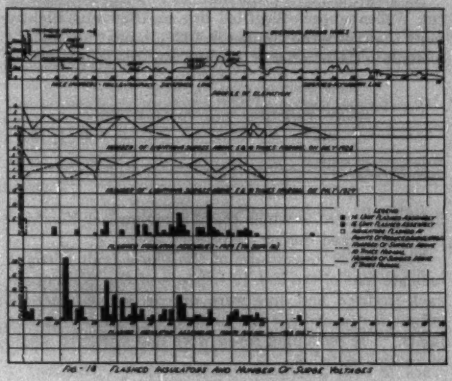


Fig. 18—Flashed Insulators and Number of Surge Voltages

In the section of the line (Fig. 18) where the counterpoise was installed no flashed insulators were found in 1929, although this section of the line had a large number of insulators flashed in previous years. It is, of course, too early to conclude whether the improvement came from the counterpoise installation or whether it represents merely different storm paths during the present year.

On the Wallenpaupack-Siegfried line during 1929, exclusive of flashed assemblies at points of reduced insulation near terminal apparatus, only about 10 per cent of the insulators were flashed under 25 miles of overhead ground wire as against 90 per cent flashed in 40 miles of line unprotected by overhead ground wire. Owing to the lesser number of overhead patrols in previous years, comparison similar to the above cannot be made.

TABLE V
FLASHED INSULATORS ON WALLENPAUPACK-SIEGFRIED LINE

| Phase | 1926 to 1928 incl. | | | 1929 | | |
|---|---|---|---|---|---|---|
| | Glaze burns | Flash tracks | Total | Glaze burns | Flash tracks | Total |
| East..... | .. | .. | 59 | 26 | 12 | 38 |
| Middle..... | .. | .. | 30 | 11 | 10 | 21 |
| West..... | .. | .. | 82 | 28 | 5 | 33 |
| Total..... | | | 171 | 65 | 27 | 92 |

Flashed insulators on the Plymouth-Siegfried line

have averaged about 1½ insulator assemblies flashed for each tripout attributed to lightning.

### Tripouts

From Table VI it will be seen that the tripouts attributed to lightning in 1929 were nearly three times the number of those occurring in 1928.

As shown in Fig. 14, the number of surge voltages on the Wallenpaupack-Siegfried line in 1929 was slightly more than twice the number in 1928, indicating that the increase in the number of tripouts was due to the greater lightning hazard to which the Wallenpaupack-Siegfried line was exposed, during the present year.

TABLE VI
220-KV. TRIPOUTS DUE TO LIGHTNING

| Line | 1928 | 1929 |
|---|---|---|
| Wallenpaupack-Siegfried | 14 | 38 |
| Siegfried-Plymouth | 2 | 1 |

The relative magnitudes of the phase fault currents indicate that of the last 19 tripouts of the Wallenpaupack-Siegfried line, five were due to single-phase-to-ground faults, and not less than seven were multiphase faults. The remaining seven were due either to single or multiphase faults.

### Switching Surges

Incidental to the lightning investigation, numerous switching surge voltages were measured. The upper voltage limit for these surges appears to be about 900 kv. (5 times normal). Most switching surges are under 3 times normal. During 1929 the upper limit for switching surge voltages on the Wallenpaupack-Siegfried line was 2.8 times normal.

The interruption of short-circuit currents did not give rise to greater voltages than other switching operations nor were energizing or deenergizing surge voltages appreciably different.

### Conclusions

1. Records obtained from storm reports show that in general storms cross this system from west to east or from northwest to east southeast.

2. Wave fronts of lightning surges recorded on the transmission line have a range from a fraction of a microsecond to 82 microseconds. A common characteristic was a front between 3 and 8 microseconds, a duration of the first loop of 15 to 40 microseconds, and a slightly oscillatory nature. Positive polarities predominate.

3. Not all high voltages are accompanied by tripouts of the circuit.

4. Lightning surges may be unidirectional (either polarity high) or slightly oscillatory.

5. Surge voltages of positive polarity attenuate more rapidly than those of negative polarity.

6. The quantitative value of protection afforded by overhead ground wires cannot be deduced from the limited data. One record on antennas indicates a protection of about 50 per cent against induced voltages.

7. Preliminary data indicate that high voltages due to direct strokes having currents of over 100,000 amperes, are infrequent.

8. An average of from 3 to 5 insulator assemblies were flashed per tripout of the circuit and about 70 per cent of these show glaze burns by dynamic arcs. Most of the flashed assemblies were on the outside phases.

9. A considerable percentage of tripouts are due to multiphase faults.

### Acknowledgments

Acknowledgment is made to Messrs. E. Bell, E. A. Evans, G. J. Gross, H. B. Newsom, N. Rohats, and others[10] for field work, analysis, and correlation of data, and to Messrs. C. M. Foust, C. A. Jordan, E. S. Lee, W. W. Lewis, H. S. Phelps, H. K. Sels, and A. E. Silver for general direction of this investigation.

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10. Personnel of the General Electric Company and Pennsylvania Power & Light Company.

## Discussion

For discussion of this paper see page 928.

# Lightning Investigation on the Ohio Power Company's 132-Kv. System

BY PHILIP SPORN* and W. L. LLOYD, Jr.†

Member, A. I. E. E. Member, A. I. E. E.

***Synopsis.***—*Description is given of the Lightning Field Investigation on the 132-kv, Philo-Canton, 73-mile, two-circuit line made during 1929 with surge recorders, cathode ray oscillograph, lightning stroke recorders, and a lightning generator. Data are presented on the magnitude of lightning voltage surges, the attenuation of these surges as they travel along the line, and the difference in attenuation between positive and negative lightning surges. The preponderance of positive lightning surges is indicated; but the fewer negative surges produce the highest voltage on the line.*

*The lightning stroke recorders gave data on the polarity of the direct strokes, and the magnitude of the current in the lightning stroke.*

*Lightning arrester performance on lightning and switching surges is analyzed, and typical surges obtained by the cathode ray oscillograph are given for both cases.*

*The magnitude and shape of lightning waves occurring on the line are shown and these waves analyzed as to duration of front, tail, and total length. These data are discussed as they relate to the proximity and rate of discharge of clouds producing lightning surges.*

*General conclusions are drawn based on the data obtained in the investigation.*

## I. Introduction

THE importance of continuity of service on high-voltage transmission lines under our present day method of central station generation and transmission of power is too well known to require extended comment. Estimates have been made, and many records show, that from 60 per cent to 90 per cent of the total number of outages on overhead transmission lines are caused by the influence of lightning on the line itself or on the connected apparatus. Line outages, other than those due to lightning, are more or less under control, such, for example, as those caused by improper or erratic relay operation, obstructions in the right of way, etc. Lightning, however, remains as one element over which, at the present time, we do not have complete control, and concerning which we have had, up until a few years ago, only very little authentic information. It is for these reasons that the investigation work covered by this paper was undertaken.

Intensive field research work has been in progress since 1927 in an attempt to solve some of the lightning problems connected with the transmission lines covered by this paper. A report on some of this work on this same system has been published previously.[1]

While a considerable quantity of information was gathered in 1927 and 1928, it had resulted primarily in laying bare the problem as a whole, and in indicating more clearly further lines along which data and information were needed. The purpose of the investigation herein described was to continue the work started in 1927 and 1928 and to explore some of the newly indicated paths of needed knowledge.

The program laid out in 1929 consisted in general of:

1. Continuing the use of surge voltage recorders used in past seasons.
2. Installing a cathode ray oscillograph coupled to the line.
3. Installing lightning stroke recorders to obtain data on direct lightning strokes.

The use of the cathode ray oscillograph on this system is entirely new, as is also the use of lightning stroke recorders.

This lightning investigation was carried through on a cooperative basis by the General Electric Company, the Ohio Power Company, and the American Gas and Electric Company, each company supplying part of the equipment and personnel.

## II. System Investigated

The 1929 lightning investigation was conducted on the Philo-Canton 132-kv. lines of the Ohio Power Company, these being part of the system on which the investigation work was performed in 1927 and 1928. A map of the 132-kv. network, of which the Philo-Canton line forms one link, is shown in Fig. 1. A detailed description of this network has been given previously,[2] as has also a description of the line characteristics.[1] In brief, the line is a two-circuit steel tower line, the circuits being in vertical configuration and with one ground wire installed at the peak of the tower. The dimensions of the standard tower are shown in Fig. 2. The insulator strings are equipped with grading shields on the line side and with arcing horns on the ground side of all insulator strings. The records for this line during the lightning seasons of 1925, 1926, and 1927 have already been published,[1,3,3,4] In choosing a transmission system for carrying on this year's work, it was felt that the lightning experience background of the Philo-Canton Line would be of distinct advantage in continuing the work which was started in 1927. Another

*American Gas and Electric Company, New York.

†General Electric Company, Pittsfield, Mass.

1. *Lightning and Other Experiences with 132-Kv. Steel Tower Transmission Lines*, M. L. Sindeband and P. Sporn, A. I. E. E. Trans., Vol. 45, 1926, p. 770.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

2. *1926 Lightning Experience on 132-Kv. Transmission Lines*, Philip Sporn, A. I. E. E. Trans., Vol. 47, p. 668.
3. *1927 Lightning Experience on 132-Kv. Transmission Lines of the American Gas and Electric Company*, Philip Sporn, A. I. E. E. Quarterly Trans., Vol. 48, April 1929, p. 480.
4. *Surge-Voltage Investigations 132-Kv. Transmission Lines of the American Gas and Electric Company*, Philip Sporn, A. I. E. E. Quarterly Trans., Vol. 47, October, 1928, p. 1132.

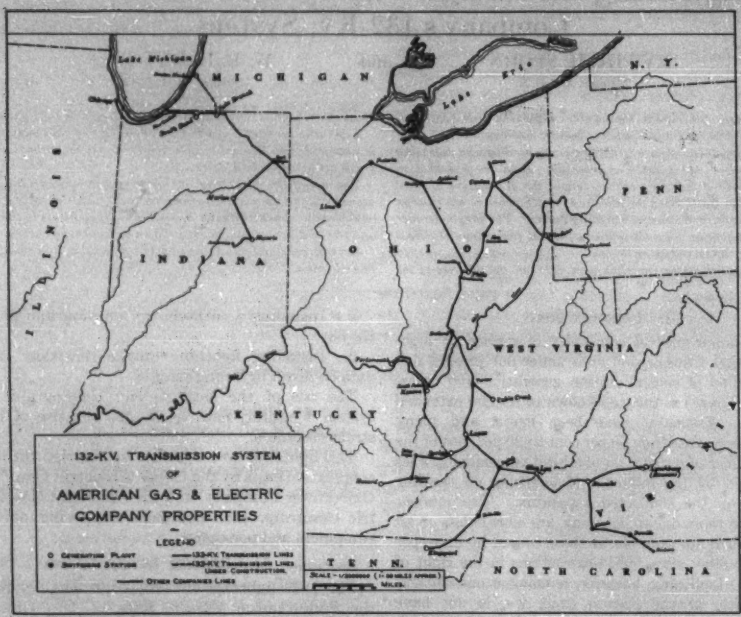



FIG. 1—132-KV. TRANSMISSION SYSTEM OF AMERICAN GAS AND ELECTRIC COMPANY PROPERTIES

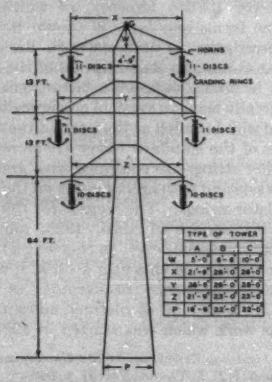



FIG. 2—STANDARD TOWER OF PHILO-CANTON 132-KV. LINE

feature presented by this line is that it had a substation tapped to both circuits at about the midpoint, thus offering the possibility of tests on the effect or influence of non-dead-end station apparatus on line surges.

## III. SCOPE OF INVESTIGATION

The locations of surge recorders, cathode ray oscillograph and lightning stroke recorders are shown in Fig. 3 and accompanying table. Surge recorders were located at the Canton Station to determine the effectiveness of lightning arrester operation. On a section of the line about 16 miles long surge recorders were located at approximately one mile intervals to determine the attenuation of surges originating on or near this section of line. This 16-mile section was chosen adjacent to the Newcomerstown substation which is at the approximate center of the line, and where both circuits are tapped to a common bus. The surge recorders, in addition to supplying attenuation data, served to supply confirming information for the cathode ray oscillograph which was located at the Newcomerstown substation. At Newcomerstown there were also placed surge recorders on the lightning arresters with the idea of studying lightning arrester performance and getting data which could be correlated with the cathode ray oscillograph records.

By the use of the cathode ray oscillograph it was expected to obtain information on crest value of lightning surges occurring on the line, and in addition, the shape, duration, and reflection characteristics of surges.

This location at Newcomerstown substation was selected for the oscillograph as it offered an opportunity of studying the performance of lightning waves on reaching a substation where there is considerable station equipment, such as post type insulators, bushings, transformers, and nearby steel work. Since in the past, and during the present year, cathode ray oscillographs at other points, with the exception of one, where lightning investigations have been or were being conducted, have been located on parts of the line quite remote from station equipment, it was felt this installation might furnish additional pertinent data due to its proximity to station equipment.

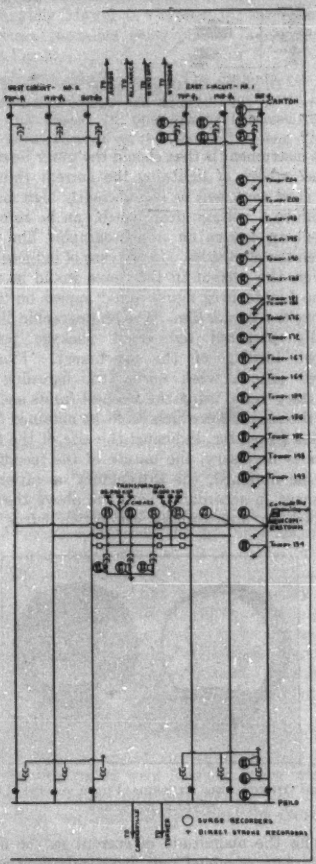



FIG. 3—LOCATION OF SURGE RECORDERS, LIGHTNING STROKE RECORDERS, AND CATHODE RAY OSCILLOGRAPH

On the Philo-Canton 132-kv. line of the Ohio Power Co., 1929

LIGHTNING INVESTIGATION—1929

Philo-Canton 132-Kv. Line

| Surge Recorder Station No. | Location | Miles from Canton | Miles from back station | Instrument connections | Date of installation |
|---|---|---|---|---|---|
| 2901 | Canton | .. | .. | Bot. $\varphi_1$—bus side choke coil | 5/ 6/29 |
| 2902 | Canton | .. | .. | Top $\varphi_2$—line side choke coil | " |
| 2903 | Canton | .. | .. | Mid. $\varphi_2$—line side choke coil | " |
| 2904 | Canton | .. | .. | Bot. $\varphi_2$—line side choke coil | " |
| 2905 | Canton | .. | .. | L. A. amps.—Top $\varphi_2$ 35.3 $\omega$ | " |
| 2906 | Canton | .. | .. | L. A. amps.—Mid. $\varphi_2$ 34.3 $\omega$ | " |
| 2907 | Canton | .. | .. | L. A. amps.—Bot. $\varphi_1$ 35.7 $\omega$ | " |
| 2908 | Tower 204 | 23.3 | 23.3 | Bot. $\varphi_1$ | 5/ 7/29 |
| 2909 | " 200 | 24.1 | 0.80 | Bot. $\varphi_1$ | " |
| 2910 | " 198 | 24.87 | 0.77 | Bot. $\varphi_1$ | " |
| 2911 | " 195 | 25.64 | 0.77 | Bot. $\varphi_1$ | " |
| 2912 | " 190 | 27.15 | 1.51 | Bot. $\varphi_1$ | " |
| 2913 | " 185 | 28.65 | 1.50 | Bot. $\varphi_1$ | " |
| 2914 | " 181 | 29.74 | 1.09 | Bot. $\varphi_1$ | " |
| 2915 | " 176 | 30.97 | 1.23 | Bot. $\varphi_1$ | " |
| 2916 | " 172 | 32.13 | 1.16 | Bot. $\varphi_1$ | 5/ 8/29 |
| 2917 | " 167 | 33.21 | 1.08 | Bot. $\varphi_1$ | " |
| 2918 | " 164 | 34.19 | 0.98 | Bot. $\varphi_1$ | " |
| 2919 | " 159 | 35.26 | 1.07 | Bot. $\varphi_1$ | " |
| 2920 | " 156 | 36.27 | 0.91 | Bot. $\varphi_1$ | " |
| 2921 | " 152 | 37.21 | 0.94 | Bot. $\varphi_1$ | " |
| 2922 | " 148 | 38.33 | 1.12 | Bot. $\varphi_1$ | " |
| 2923 | " 143 | 39.26 | 0.93 | Bot. $\varphi_1$ | " |
| 2924 | Newc't'wn | 40.09 | 0.83 | Top $\varphi_1$—Circuit No. 1 | 5/23/29 |
| 2925 | " | | 0.83 | Mid. $\varphi_1$—Circuit No. 1 | " |
| 2926 | " | | 0.83 | Bot. $\varphi_1$—Circuit No. 1 | " |
| 2927 | " | | 0.83 | Bus at L. A. $\varphi_1$ | 5/12/29 |
| 2928 | " | | 0.83 | Bus at L. A. $\varphi_2$ | " |
| 2929 | " | | 0.83 | Bus at L. A. $\varphi_3$ | " |
| 2930 | " | | 0.83 | L. A. amps. $\varphi_1$ 33.4 $\omega$ | 5/23/29 |
| 2931 | " | | 0.83 | L. A. amps. $\varphi_2$ 32.5 $\omega$ | " |
| 2932 | " | | 0.83 | L. A. amps. $\varphi_3$ 30.3 $\omega$ | 6/ 6/29 |
| 2933 | Tower 134 | 41.09 | 0.98 | Bot. $\varphi_1$ | 5/12/29 |
| 2934 | Philo | 73.3 | 32.22 | L. A. amps. $\varphi_1$ 37.0 $\omega$ | 6/13/29 |
| 2935 | " | 73.3 | 32.22 | Bot. $\varphi_1$—line side choke coil | 5/ 9/29 |
| 2936 | " | 73.3 | 32.22 | Bot. $\varphi_1$—bus side choke coil | " |
| K-2 | Newc't'wn | 40.09 | | Bot. $\varphi_1$—Circuit No. 1 | 5/22/29 |
| | Tower 180 | | | | 8/19/29 |

The lightning laboratory, housing the oscillograph, together with coupling potentiometers, are shown in Fig. 4. The oscillograph itself, ready for operation, is shown in Fig. 5.

Since the moment a lightning surge will appear at the measuring station cannot be predicted, it is necessary to have the incoming surge itself place the cathode ray oscillograph in operation. This consists in applying a high negative voltage to the cathode to obtain the stream of electrons making up the cathode ray and in applying a gradually increasing voltage to the sweep plates of the oscillograph to obtain a deflection of the cathode ray on the photographic film proportional to the time and at right angles to the deflection produced by the lightning surge. These operations must be carried on in an extremely brief interval of time if the front of the in-coming voltage surge is to be fully

5. *Lightning Investigation of Transmission Lines*, by W. W. Lewis and C. Foust, see p. 917.

determined. A circuit for accomplishing this was devised by engineers of the General Electric Company.[6] The diagrammatic connections of this circuit are shown in Fig. 6. A tap on the initiating potentiometer string, causes the three-electrode sphere-gap to discharge and carry out the above operations whether the incoming lightning surge is positive or negative.

The lightning stroke recorder is an entirely new

Fig. 4—Cathode Ray Oscillograph Lightning Measurement Station

At the Newcomerstown Substation of the Philo-Canton line

development. The purpose of this instrument, which was proposed by F. W. Peek, Jr., and developed by W. L. Lloyd, Jr., is to tell when and where a direct stroke of lightning to a transmission line takes place. There was reason to believe that the steel towers or ground wires of certain lines, at least, might be struck without always producing a 60-cycle dynamic short circuit or outage of the line. It was desired to know the

Fig. 5—Portable Cathode Ray Oscillograph

At the Lightning Measurement Station in Newcomerstown, Ohio

percentage of direct strokes causing tripouts as compared with the percentage not causing tripouts, also the percentage of tripouts produced by direct strokes as compared with the percentage produced by induced voltage surges. The polarity of the cloud and the magnitude of the current in the lightning discharge were of considerable theoretical interest. Since lightning might strike anywhere at any time the instrument had to be simple enough in construction and operation to permit its use on several towers along a line without attendants.

The instrument consists essentially of a small size surge recorder, without timing mechanism, which is placed across a section of the tower steel. The theory

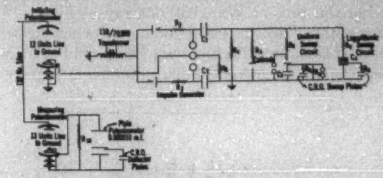


Fig. 6—Diagram of Connections for the Automatic Operation of the Cathode Ray Oscillograph by the Incoming Lightning Surge

of this instrument is that should the tower be struck by a direct stroke of lightning the current through the tower steel work will be of sufficiently high magnitude to produce a voltage drop which can be recorded by Lichtenberg figures on a photographic film inserted between the electrodes. In the case of induced strokes, however, the current in the tower would be so small that no Lichtenberg figure would appear on the lightning stroke recorder film. The photographic film is in a specially prepared light-proof package permitting daylight loading of the instrument. Films were changed once a week during the lightning season. Laboratory tests, using the steepest fronts and current up to the maximum which could be obtained from the lightning generator, indicated the size of the film and electrodes necessary, the nature of the records which would be obtained, the satisfactory operation of the instrument in accordance with the above theory, and furnished an approximate calibration curve for de-

Fig. 7—Interior and Exterior Views of the Lightning Stroke Recorder

termining the magnitude of current in the lightning stroke. An assembled and disassembled view of the instrument is shown in Fig. 7. A field installation is shown in Fig. 8.

These recorders were located on each tower where a surge recorder was located. One recorder was also

6. *Lightning—Progress in Lightning Research in the Field and in the Laboratory*, F. W. Peek, Jr., A. I. E. E. Quarterly Trans., Vol. 48, April 1929, p. 436.

located at Newcomerstown substation on the steel structure adjacent to the lightning laboratory. By placing the lightning stroke recorders at the same location as the surge recorders, it was possible to correlate the data obtained from both the lightning stroke recorders and surge recorders.

## IV. Operation of Oscillograph Station and of Instruments

*Surge Recorders.* The surge recorder investigation, covering the lightning season of 1929, extended from approximately May 1 to October 15, the exact dates when surge recorders were placed in service being given in Fig. 3.

*Cathode Ray Oscillograph.* The cathode ray oscillograph was installed May 22; from then until October 15 it was placed in operation whenever lightning storms were reported on the system between Philo and

Fig. 8—Field Installation of Lightning Stroke Recorder

Showing recorder on tower leg

Canton. This necessitated the constant attendance of an oscillograph operator at the lightning measurement station when storms were at all probable during this time. The oscillograph was placed in operation by the surge to be measured, but it was necessary for the operators to adjust the potentiometer according to the proximity of the storm, to keep the proper vacuum, to turn the photograph film after each exposure and replace the film after every twelve exposures. The operators also made observations of the storms and noted the time of each exposure.

*Lightning Stroke Recorders.* The lightning stroke recorders were placed in operation July 16. Thereafter, the film packs were changed every week until October 1. After development of the films, an examination was made to determine the indication of a direct stroke.

## V. Surge Recorder Data and Analysis

To better analyze the surge data obtained, all surges have been classified as to cause under six headings, as follows:

1. Those due to lightning only, where it was known a lightning storm was in progress over the system and no switching occurred.
2. Those due to lightning and switching, where the circuit tripped during a lightning storm, and a record was obtained.
3. Those due to switching operations on the line, where the character of switching surges were known, that is whether they were energizing or deenergizing surges.
4. Switching surges occurring so rapidly that the energizing and deenergizing characteristics could not be separated.
5. Surges of unknown origin, where no cause could be assigned.
6. Surges of doubtful origin, where the recorded surge was believed to be due to electrostatic interference on the potentiometers and not primarily associated with characteristic surges causing disturbance.

A total of 115 surges was recorded during the season; these surges are classified, as above described, in Table I.

TABLE I
TOTAL NUMBER OF SURGES

| Cause of surge | Total No. | Selected No. |
|---|---|---|
| Lightning | 41 | 24 |
| Lightning and switching | 7 | 7 |
| Switching—Energizing No. 1 | 3 | 3 |
| " " No. 2 | 0 | 0 |
| " Deenergizing No. 1 | 19 | 19 |
| " " No. 2 | 1 | 1 |
| Mixed energ. and deenerg. No. 1 & No. 2 | 10 | 10 |
| Unknown | 27 | 0 |
| Doubtful | 7 | 0 |
| | 115 | 64 |

The "Selected" number of surges in the second column represent the 115 surges after deducting those which recorded on the three bus recorders at Newcomerstown only. These three recorders appeared to be influenced by stray fields in the station, so that when these recorders only registered, the records were considered of doubtful significance.

A further study of these surges was made to determine their polarities and this analysis is given in Table II.

The maximum voltage recorded (in times normal—

TABLE II
PREDOMINATING NATURE OF SURGES WITH MAXIMUM RECORDED VOLTAGES
(Times Normal)

| Cause of surge | Positive | | Negative | | Oscillatory | |
|---|---|---|---|---|---|---|
| | Pos. | Neg. | Pos. | Neg. | Pos. | Neg. |
| Lightning | 3.4 | .. | .. | 2.1 | 4.2 | Tr. |
| Lightning and switching | 6.5 | .. | 7.1 | 14.3 | 3.2 | Tr. |
| Switching-Energizing No. 1. | 2.8 | .. | .. | 2.4 | 2.3 | 2.7 |
| " " No. 2. | .. | .. | .. | .. | .. | .. |
| " Deenergizing No. 1 | .. | .. | .. | .. | 4.9 | 2.8 |
| " " No. 2 | Tr. | .. | .. | .. | .. | .. |
| Mixed energ. and deenerg. No. 1 and No. 2 | 3.0 | .. | .. | .. | 2.7 | 4.5 |
| Unknown | 4.9 | .. | .. | 2.4 | 3.8 | Tr. |
| Doubtful | 4.2 | .. | .. | 3.6 | 3.4 | Tr. |

"Tr." is trace—slightly above 108 kv.

normal being 108 kv.) is given for the maximum surge under each classification. The maximum crest value of any pure lightning surge is 8.4 times normal positive. The maximum voltage recorded on combined lightning and switching surges was 14.3 times normal negative with a positive indication for this same surge of 7.1 times normal, occurring at the same place the 14.3 occurred. There was also recorded a positive surge of 6.5 times normal at the time of a lightning storm when the line was known to have tripped out.

To indicate the relative frequency and magnitude of lightning surges on the line Fig. 9 has been drawn. This shows that of 31 lightning surges, about 25 per cent were above 4½ times normal, 10 per cent above 6 times normal, 6.5 per cent above 8 times normal, and 3 per cent, or 1 surge, above 14 times normal. The general character of this curve checks and confirms quite well data obtained previously and last year on the same question on other systems. Under switching conditions,

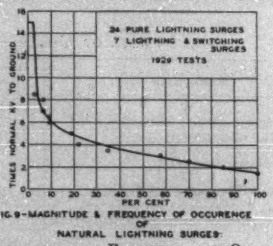



FIG. 9—MAGNITUDE AND FREQUENCY OF OCCURRENCE OF NATURAL LIGHTNING SURGES

the maximum value of surge recorded was 4.9 times normal on deenergizing the line, and 2.7 times normal on energizing the line. Both of these surges were highly damped oscillations. The maximum surge classified as unknown and doubtful reached a value of 4.9 positive times normal but both groups are considered unimportant for purposes of this analysis.

All surges have further been analyzed as to characteristics, that is, whether all positive or negative or predominantly of one polarity. Some surges were obtained this year, as in the past, where most instruments recorded one polarity, but the opposite polarity was also registered at other instruments at apparently the same time. Such surges have been classified as unidirectional (positive or negative) with an indication of the prevalent polarity. This analysis is given in Table III.

The important fact brought out by Table III is that 61.0 per cent of the lightning surges were pure positives, 12.2 per cent predominantly positive, 14.7 per cent pure negative, 4.9 per cent predominantly negative, and 7.2 per cent highly damped oscillations. Further, switching surges are mostly oscillatory, with a few unidirectional surges indicated; these however were of small magnitude.

If the number of positive surges only were taken as an indication, it could be concluded that the greater portion of surges is of induced origin; on the other hand, the highest surge recorded (in point of voltage) was negative. The only safe conclusion at the present, therefore, is that both positive and negative surges can be of an

TABLE III
PREDOMINATING NATURE OF SURGES
(Number Recorded)

| Cause of surge | Positive | | Negative | | | |
|---|---|---|---|---|---|---|
| | Pure | Predom. | Pure | Predom. | Oscillatory | Total |
| Lightning | 25 | 5 | 6 | 2 | 3 | 41 |
| Lightning and switching | 1 | 2 | .. | 2 | 2 | 7 |
| Switching–Energizing No. 1 | 1 | .. | 1 | .. | 1 | 3 |
| " " No. 2 | .. | .. | .. | .. | .. | .. |
| Switching Deenergizing No. 1 | .. | .. | .. | .. | 19 | 19 |
| " " No. 2 | 1 | .. | .. | .. | .. | 1 |
| Mixed energ. and deenerg. No. 1 and No. 2 | 4 | .. | .. | .. | 6 | 10 |
| Unknown | 11 | 5 | 5 | 1 | 5 | 27 |
| Doubtful | 1 | 2 | .. | 1 | 3 | 7 |

appreciable magnitude. More light may be thrown on this by additional direct stroke recorder data.

*Attenuation Data.* Attenuation data on natural lightning were obtained for two different surges. During the year tests were also run using artificial lightning and the attenuation checked with Lichtenberg figures secured on the surge recorders which were in normal operation throughout the season. A study was also made with the cathode ray oscillograph of the attenuation of artificial lightning surges along the line and reflections from the open and closed ends of the line.

*Lightning Arrester Tests.* The lightning arrester surge recorders yielded 53 surge records. In most cases a correlating voltage at the terminals of the lightning arrester was obtained, where current discharges through the arrester were recorded. The summary of these data

TABLE IV
LIGHTNING ARRESTER OPERATION

| | | Cause of surge | |
|---|---|---|---|
| | | Lightning | Switching |
| No. of surges recorded | | 12 | 41 |
| Max. | Current–amperes | 294 | 243 |
| | Correlating voltage–kv. | (1) | 300 |
| Max. | Recorded voltage–kv. | 380 | 450 |
| | Correlating current–amperes | 105 | 226 |

(1.) 225 kv. or less (no record on S. V. R.)

is shown in Table IV. The data in Table IV shows that the lightning arrester, in the case of switching surges, has discharged a current of 226 amperes per leg at 450 kv. Since it is known switching surges do not exceed some 550 kv. on these lines, there are no definite data to show that the arrester has held the voltage down appreciably on switching surges. The arrester has, however, discharged a maximum current of 226 amperes per leg at 450 kv. which is a point definitely in favor

of the lightning arrester. Of course this would not effect its economic justification, if the system apparatus is built to withstand an indefinite number of surges of switching origin and magnitude without failure.

The maximum lightning voltage surge on the arrester recorded 380 kv. with a correlating current of 105 amperes. This again shows the arrester is performing, but a quantitative measure of its performance is lacking. That is, there are no data available to show how much the discharge current of 105 amperes recorded helped to bring down the lightning voltage which might have existed without the arrester, or how much the arrester aided in holding down the voltage to 380 kv.

TABLE V

CHARACTERISTICS OF THE LIGHTNING SURGES MEASURED WITH THE CATHODE RAY OSCILLOGRAPH ON THE PHILO-CANTON LINE DURING 1929

| No. | Date | Max. kv. | Polarity | Time in microseconds: To 75% (On rising front) | To max. (On rising front) | To 50% (On falling tail) | To zero (On falling tail) |
|---|---|---|---|---|---|---|---|
| **Fast or steep-fronted surges:** | | | | | | | |
| 341 | 6/30 | 97 | + | 0.2* | 1* | 20 | 70* |
| 457A | 8/23 | 245 | + | 0.5* | 4 | 12 | 55 |
| 462 | " | 190 | + | 0.2* | 1* | 10 | 80 |
| | | | Average | 0.3* | 2* | 17 | 70* |
| **Slow or slanting-fronted surges:** | | | | | | | |
| 457B | 8/23 | 70 | + | 8 | 16 | 37 | 65 |
| 458 | " | 70 | + | 8 | 16 | 37 | 48 |
| 463 | " | 55 | + | 4 | 20 | 38 | 65 |
| 464 | " | 70 | + | 7 | 15 | 52 | 95* |
| | | | Average | 7 | 17 | 41 | 68* |
| **Very slow or slanting-fronted surges:** | | | | | | | |
| 459 | 8/23 | 85 | + | 10 | 30 | 45 | 65 |
| 461 | " | 85 | + | 10 | 30 | 42 | 60 |
| 460 | " | 108 | + | 13 | 28 | 43 | 55 |
| | | | Average | 11 | 29 | 43 | 60 |
| **Average of ten surges:** | | | | 6 | 16 | 34 | 66 |

*Estimated approximate values

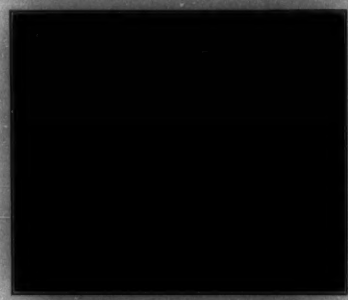
## Cathode Ray Oscillograph Data and Analysis

*Lightning Surges.* During the time the cathode ray oscillograph was in operation 29 storms occurred in the vicinity of Newcomerstown. Ten oscillograms of lightning were obtained. Although the oscillograph was set to record with equal sensitiveness both positive and negative surges, all ten surges recorded were positive. Table V gives the characteristics of these surges. Fig. 10 shows typical oscillograms from among these ten.

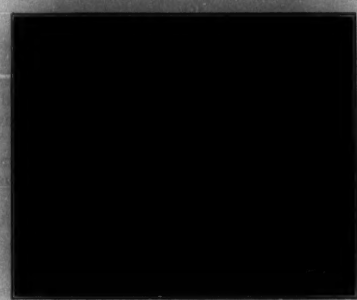
From Table V it will be seen that the time to reach 75 per cent of maximum voltage on the front of the lightning wave varied from ¼ of a microsecond for the fastest waves to 13 microseconds for the slowest waves, while the total front of the waves varied from one to 30 microseconds. The length of the waves, to half maximum value on the tail, varied from 12 microseconds to 52 microseconds while the total length of the waves, to zero, varied from 48 microseconds to approximately 95 microseconds. All waves recorded were of low voltage. Fig. 11 gives the average of the three steepest surges, the average of the three least steep and the average of all ten surges plotted in rectangular coordinates.

Since all ten surges were of low voltage and positive polarity it would appear that they were induced voltage surges rather than surges resulting from direct hits. Furthermore, the surge voltage recorders indicated no simultaneous high voltages, the lightning stroke recorders no simultaneous direct hits, and no accompanying tripout occurred.

Since the surges recorded by the cathode ray oscillo-



A



B

Fig. 10—Cathode Ray Oscillograms of Natural Lightning Surges

graph were so low in voltage, it is not surprising to find that all of the surges were not of the steepest front. Theoretical study and calculations indicate that for a 1000-ft. cloud and a cloud discharge rate of ten microseconds, less than 15 per cent of the theoretical maximum voltage should appear on a line by induction.[7] Thus, whereas a voltage of 4000 kv. could appear on a highly insulated line 40 ft. above earth, if an overhead

7. "Lightning," F. W. Peek, Jr., *General Electric Review*, Volume 32, No. 11, November 1929, p. 603, (see Figs. 30 and 31).

cloud were to discharge instantly, less than 15 per cent of this voltage or approximately 500 kv. is the maximum induced voltage which can appear with a 1000-ft. overhead cloud discharging in ten microseconds. The highest voltage measured was well below this value indicating the cloud at a distance rather than directly overhead. Since the fronts of the seven slowest surges

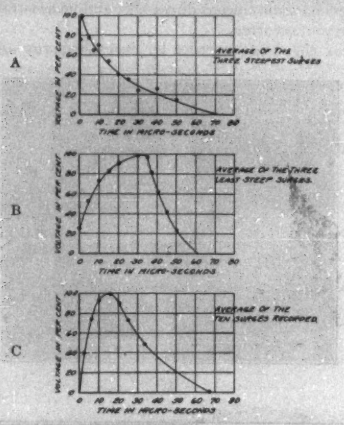



Fig. 11—Wave Shapes of Natural Lightning

Recorded during 1929 by the cathode ray oscillograph at Newcomerstown, Ohio

are not steep, high voltages are not to be expected or, conversely, since the voltages are low it is not surprising that all of the surges were not of the steepest front. The three steepest surges were apparently the result of rapid discharges of a distant cloud since these, also, were of low magnitude.

The relative order of magnitude of induced voltage surges may be given by the following tabulation.

| | Rapid cloud discharge | Slow cloud discharge |
|---|---|---|
| Near cloud..... | High induced voltage | Low induced voltage |
| Distant cloud..... | Low induced voltage | Very low or zero |

According to the above classification, the ten surges recorded by the cathode ray oscillograph during 1929 may be grouped as follows:

| | Rapid cloud discharge | Slow cloud discharge |
|---|---|---|
| Near cloud..... | None | Seven |
| Distant cloud..... | Three | None[8] |

*From the above discussion it would appear probable that a rapid cloud discharge producing a wave of the type represented by the average of the three steepest waves would be the most important on high-voltage lines. See Fig. 11A.*

*Switching Surges.* Several oscillograms of switching operations were obtained during the regular switching operations of the line (see Table VI). Four of these were obtained when the line was being deenergized and one when the line was being energized. The highest voltage recorded, 4.5 times normal line to neutral maximum voltage, was obtained when the line was being deenergized. The actual length of the line was 73.3 miles. The switching was done on the high-voltage side at either Philo or Canton, with the cathode ray oscillograph at Newcomerstown near the midpoint of the line. Fig. 12 gives an oscillogram of a typical switching surge in rectangular coordinates.

## VII. Lightning Stroke Recorder Data and Analysis

Two direct strokes to the line were indicated by the lightning stroke recorders. The first took place to tower 185 on July 25. Fig. 13 gives the record obtained from which it was determined that the cloud was negative and that a current of approximately 175,000 amperes had flowed down the tower during the stroke. This was the first record ever obtained of a stroke which was actually known to have struck a transmission line.

Fig. 14 gives the correlated data obtained in connection with the discharge. A positive voltage surge was released on the line. The surge voltage recorded, at the tower struck, measured a maximum voltage of 8.4 times normal positive, but it is of course possible that this value was higher by an amount at least equal to the limit of accuracy of the instrument. The surge attenuated rapidly on each side of the tower and after five miles was not further indicated by the surge voltage recorders. No tripout occurred.

The second measured direct stroke occurred at tower 159 during the storm of August 23. Fig. 15 gives the record obtained. A positive voltage of 6.5 times normal was recorded by the surge voltage recorder at the same tower while a positive voltage of 3.5 times normal was recorded at tower 156 one mile away. No other voltage measurements were obtained. The line tripped but no damage was done and voltage could be immediately restored to the line. The indication is that in spite of a direct stroke tripout, the arc jumped clear of the string from ring to horn, without damage to the porcelain insulators.

In this case, unfortunately, the film pack of the recorder had been improperly assembled so that only one record, rather than two, was obtained. A negative cloud was, however, again indicated. A lightning current in the tower of approximately 100,000 amperes was estimated.

The first of the three direct strokes which apparently occurred to the line during 1929 occurred on July 5 before the lightning stroke recorders were installed on

8. Possibly some of the above seven surges should be included here, depending upon what constitutes a "near" cloud.

TABLE VI

| No. | Date | Switching | Max. kv. | Nature | Approx. frequency (cycles) | Indicated length in miles | Time to maximum | Duration of film |
|---|---|---|---|---|---|---|---|---|
| 669 | 9/14 | Off | 327 | Oscillatory | .. | .. | 10,000 ms. | 12,000 ms. |
| 440 | 7/28 | On | 136 | " | 500 | 108 | 500 | 6,000 |
| 441 | " | Off | 490 | " | 500 | 108 | 500 | 6,000 |
| 338 | 6/29 | Off | 68 | " | 200 | 43 | 300 | 5,000 |
| 439 | 7/28 | Off | 136 | " | .. | .. | .. | 6,000 |

the line. The surge voltage recorders indicated a negative surge voltage of 14.3 times normal voltage. A line tripout occurred without damage to the insulator strings.

## VIII. Attenuation Data and Analysis

Two lightning surges of relatively high magnitude were recorded on the instruments located on the 16 mile attenuation set-up. One surge had a maximum value of 8.4 times normal positive, and the other a maximum of 14.3 times normal negative. The positive surge was a pure positive as indicated by all instruments; and the negative surge was recorded negative at all instruments except at the one instrument where the surge apparently

Fig. 12—Typical Switching Surge

Recorded by the cathode ray oscillograph upon deenergizing of the Pino-Canton line

originated, there being recorded here also a crest value of 7.1 times normal positive. The attenuation of the crest value of these surges is shown in Fig. 16.

The attenuation data on these two surges, together with three similar surges recorded on this line in 1928, have been grouped and plotted in Figs. 23 and 24. These will be discussed later. In Fig. 17 the two surges shown in Fig. 16 have been replotted on a single group of coordinates; that is, the data obtained on both sides of the point of apparent origin of the surge have been grouped together; and it will be seen that there is a very marked difference in the rate of attenuation of the positive and negative surges, the positive surge attenuating considerably faster than the negative surge; thus, whereas the positive surge at 8.3 times normal potential attenuates to 50 per cent of its value in 1.3 miles, it takes the negative surge 2.75 miles to reach a corresponding attenuation.

During the season surges from a 1,000,000-volt field lightning generator were placed on the three phases of the No. 1 circuit separately and in groups, and the magnitude of the crest voltage measured from Lichtenberg figures obtained from the surge recorders. Results of these tests are shown in Figs. 18, 19, and 20, where Fig. 18 represents the decay of the crest value when the surge was applied to one line wire only, Fig.

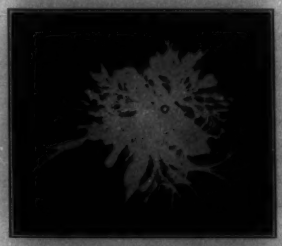


Fig. 13—The First Record Ever Obtained of the Current and Polarity of a Natural Lightning Stroke Hitting a Transmission Line Tower

19 representing the attenuation when the surge was applied to two line wires in parallel, and Fig. 20, representing the attenuation when the surge was applied to the three line wires in parallel. The higher rate of voltage attenuation with the surge energy supplied to the three line wires instead of one is readily noticeable from the shape of the curves.

The data from which the curves in Figs. 18, 19, and 20 have been plotted are actually indicated, and it will be

apparent that the curves which have been drawn to represent that data are rather broad averages. It is believed, however, that there is sufficient background

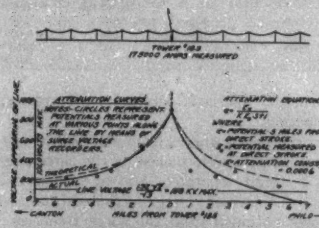



FIG. 14—ATTENUATION CURVE OF THE SURGE RESULTING FROM A DIRECT STROKE OF NATURAL LIGHTNING AS MEASURED BY THE SURGE VOLTAGE RECORDER

FIG. 15—RECORD OF THE DIRECT STROKE OF NATURAL LIGHTNING WHICH STRUCK TOWER NO. 159 OF THE PHILO-CANTON LINE ON AUGUST 25

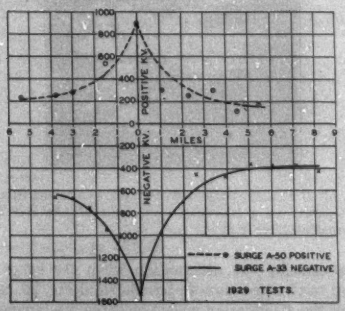



FIG. 16—ATTENUATION OF NATURAL LIGHTNING

Philo-Canton 132-kv. line No. 1—Bottom conductor—Phase 1

available for giving the curves the general shape that they have been given.

Referring again to Figs. 18, 19, and 20, it will be seen that with artificial lightning there is again a distinct difference in the rate of attenuation between positive and negative surges. For example, with a positive surge the crest voltage drops from 500 kv. to 200 kv. in nine miles when the surge from the lightning generator is applied

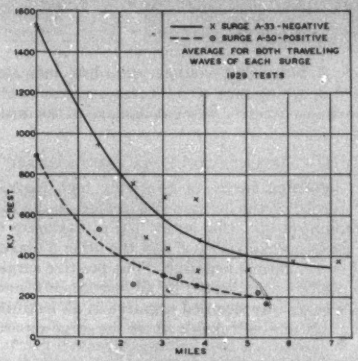



FIG. 17—ATTENUATION OF NATURAL LIGHTNING

Philo-Canton 132-kv. line No. 1—Phase 1

to one wire only; from 500 kv. to 200 kv. in six miles, when it is applied to two line wires; and from 500 kv. to 200 kv. in five miles when it is applied to all three line wires. When the surge is negative, the same relative difference on the rate of attenuation with one, two, and

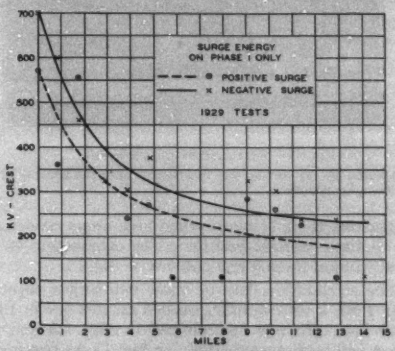



FIG. 18—ATTENUATION OF ARTIFICIAL LIGHTNING

Philo-Canton 132-kv. line No. 1—Phase 1

three wires appears, the drop from 550 to 250 kv. occurring in 8½, 4¾, and 4½ miles respectively.

The cathode ray oscillograph permitted the more precise study of attenuation and also the reflections taking place at the open and closed end of a line. Fig. 21 shows the repeated reflections from the open end of a

43-microsecond (7.96 mile) section of the line. Twice this time or 86 microseconds is required for the first reflection to return after traveling twice the length of the 7.96-mile section. A negative impulse of 427 kv. was applied in this case.

Fig. 22 shows the repeated reflections of a 427-kv. negative impulse from the closed end of the same length section of the line. Each reflection at the closed end is

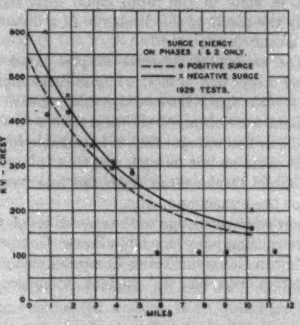



Fig. 19—Attenuation of Artificial Lightning

Philo-Canton 132-kv. Line No. 1—Phase 1

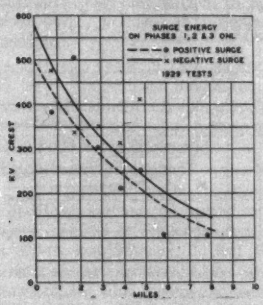



Fig. 20—Attenuation of Artificial Lightning

Philo-Canton 132-kv. Line No. 1—Phase 1

reversed in polarity, the second being of the same polarity as the original impulse, but lower due to attenuation along the line.

Referring to Figs. 23 and 24 previously mentioned, Fig. 23 shows plotted the two surges previously indicated in Fig. 9, these being the two surges on which attenuation data was obtained in 1929, and also three other surges obtained during 1928. It will be noticed that four of the surges are positive and only one was negative. It will be noticed first that only the two highest surges resulted in line tripouts. Further, it will be noted that one of the surges, although it reached a positive value of 1450 kv., did not cause line tripout. Again it will be very definitely noticed that the positive

Fig. 21—Cathode Ray Oscillogram Showing Attenuation of Reflections from the Open End of a Transmission Line

surges show a higher rate of attenuation than the negative surges. This is shown particularly well in Fig. 24, where all the positive surges have been combined and plotted as a single curve and the negative surge shown in Fig. 23 has been replotted. In Fig. 24 also are indicated the curves plotted according to Foust and Menger's formula and using an average value of $K$. It will be seen that the formulas fit the data obtained quite

Fig. 22—Cathode Ray Oscillogram Showing the Attenuation of the Reflections from the Closed, or Grounded, End of a Transmission Line

well. Further, the positive constant $K$ is almost twice that of the negative constant, the value of one being 0.000574 and of the other 0.000307.

## Conclusions

The field studies carried out during the last year on the Philo-Canton line and in the field laboratory indicate the following:

1. The lightning surges on the system are predominantly positive, indicating that they come from induced surges and are not direct strokes.

2. The maximum positive lightning surge recorded was 8.4 times normal; the maximum negative surge recorded was 14.3 times normal; the maximum de-energizing switching surge was 4.9 times normal and the maximum energizing surge was 2.7 times normal.

3. Records were obtained showing lightning

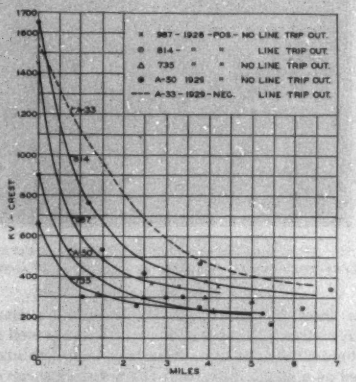



FIG. 23—ATTENUATION OF NATURAL LIGHTNING
Philo-Canton 132-kv. Line No. 1—Phase No. 1

arresters discharging current with correlated voltages, and fairly high voltages existing at lightning-arresters with correlated current discharges. No specific data were obtained to indicate the extent of benefit derived from lightning arresters functioning.

4. Data were obtained showing the attenuation different for positive and negative surges and the attenuation for both was shown to be rather steep. Constants of 0.000574 and 0.000307 for positive and negative surges respectively in the formula of Foust and Menger were obtained, indicating much more rapid attenuation for the positive surges.

5. Two direct strokes were recorded. Both were of negative polarity (negative cloud). Currents of 175,000 amperes and 100,000 amperes were measured in the tower. Induced voltages were simultaneously recorded on the phase conductors. Only one, however, produced a dynamic tripout of the line. The potential of this induced voltage surge attenuated rapidly and in accordance with the Foust and Menger formula.

6. Ten cathode ray oscillograms of induced natural lightning surges were obtained. All were of low voltage and of positive potential. Attenuation curves applying to these oscillograms could not be obtained since the voltages were too low to be recorded by the nearest surge voltage recorders. Oscillograms of the surges resulting from the two direct strokes could not be obtained since the direct hits occurred at too great a distance from the cathode ray oscillograph station.

7. Of the ten oscillograms of natural lightning obtained three were of steep wave-front (0.5 microsecond or less to 75 per cent of maximum voltage); four were of slow-wave-front (4 to 8 microseconds to 75 per cent); three of very slow front (10 to 13 microseconds). Since a slanting wave-front results from a slow cloud discharge and a slow cloud discharge cannot produce a high induced voltage, it is not surprising that these low voltage surges included seven having relatively slow fronts. The three steep-fronted surges were also of low voltage, in spite of the rapid cloud discharge, being probably the result of the discharge of a distant rather than of a near cloud.

8. *The average of the three steepest waves probably represents a type that is most likely to reach high enough voltages to cause spark-overs on high voltage lines.*

9. Data were obtained showing that a direct stroke can result in line outage; that it is possible for a direct stroke to cause no line outage; and that it is possible to have a direct stroke away from the line result in an outage on the transmission line.

Acknowledgment is due to the executives of the General Electric Company, the Ohio Power Company, and the American Gas and Electric Company who made this investigation possible; to various members of the

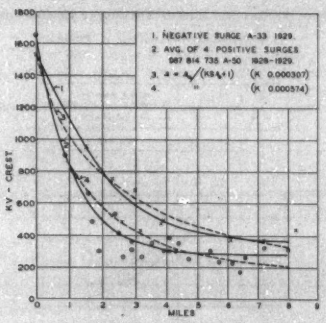



FIG. 24—ATTENUATION OF NATURAL LIGHTNING
Philo-Canton Line No. 1—Phase No. 1

General Electric Company, the Ohio Power Company, and the American Gas and Electric Company for their cooperation and help in the design, installation, and operation of the apparatus and equipment, and for their help in supervising, correlating, and working up the data; and in particular to Messrs. H. L. Rorden, J. C. Dowell, S. D. Day, and George Lippert, who actually carried out and were in charge of the various tests and field investigations.

## Discussion

For discussion of this paper see page 928.

# Lightning Investigation on Transmission Lines

W. W. LEWIS* and C. M. FOUST*
Member, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—The surge voltage investigations for 1926 and 1927 are briefly reviewed, and data given for 1928 and 1929. The cathode ray oscillograph has played a prominent part in the last two years work, and about 115 oscillograms have been obtained. New instruments were introduced in 1929 as follows: Lightning stroke recorders, field intensity recorder, and rate of change of field intensity recorder. A vast amount of progress has been made in the solution of the lightning problem. Personnel, equipment, and technique are available for the complete solution of the problem, by means of field and laboratory studies carried on simultaneously and supplementing each other.*

* * * * *

A *Symposium on Surge Voltage Investigation* covering mainly the work done in 1926 and 1927, was presented at the annual convention of the A. I. E. E. at Denver in June 1928.[1]

Tentative conclusions were drawn as to polarity and magnitude of surges, wave shape, and attenuation, and it was stated that in the coming year special efforts would be made to obtain data on wave shape, attenuation, effect of ground wires, and effect of lightning arresters and choke coils.

Two years' additional data have now been accumulated and we can answer some of the questions which were unanswered at the Denver Convention.

In 1928 work was continued on the Pennsylvania 220-kv. interconnected system, the Consumers Power Co. 140-kv. system, the Ohio Power Co. 132-kv. system, and the New England Power Co. 110-kv. system. The cathode ray oscillograph was introduced and a laboratory installed at Wallenpaupack to obtain oscillograms of the surges produced on transmission lines by natural lightning.

Mr. McEachron also began in 1928 his work on the Turners Falls 66-kv. transmission line, in the course of which he placed artificial lightning surges up to 400 kv. on the transmission line and studied their effects by means of the cathode ray oscillograph.[2]

In 1929 the work was discontinued on the New England Power system, but continued on the Pennsylvania, Consumers, and Ohio systems. A second cathode ray oscillograph was installed at Wallenpaupack and connected to a 300-ft. long antenna, 50 feet above the ground. A cathode ray oscillograph was installed at Newcomerstown on the Ohio system and connected to the 132-kv. line. Mr. McEachron continued his work with artificial lightning on the Turners Falls system and in addition conducted an extensive investigation with a 1000-kv. portable lightning generator on a 70-kv. line of the Consumers Power Co. in Michigan. The artificial lightning investigation is described in a paper at this convention.[3]

In the 1929 investigation new instruments were introduced as follows: Lightning stroke recorders, field intensity recorder, and rate of change of field intensity recorder.

In the present paper the 1928 and 1929 work will be discussed and an effort will be made to summarize the present status of the investigation and to outline the future work.

## I. Crest Values of Surge Voltages Due to Lightning and Switching

*Lightning.* In Table I are listed the maximum voltages due to lightning on three systems for the year 1926, 1927, 1928, and 1929, as measured by the surge voltage recorder. (The locations of the surge voltage recorders are indicated in diagrams in companion papers[4] and in the Denver papers previously mentioned.)[1] The voltages are given both in kilovolts and in the number of times normal crest line-to-neutral voltage. For comparison also are given the approximate insulator impulse flashover values as measured by the five-microsecond "Pittsfield Wave." This wave has the following general description:

Rises to its crest value in about ¼ microsecond, then decreases to 50 per cent crest value in about five microseconds.[5] The values given are for flashover on the tail of the wave.

In the case of the Pennsylvania Power & Light Company's system the line under investigation is that formerly known as the Wallenpaupack-Siegfried line, (now known as Wallenpaupack Tap and Siegfried-Roseland Line). The length is 65 miles.

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*Both of General Electric Co., Schenectady, N. Y.

1. *Symposium on Surge Voltage Investigation*, by W. W. Lewis, E. W. Dillard, J. G. Hemstreet and J. R. Eaton, P. Sporn, and N. N. Smeloff, A. I. E. E. Trans., Vol. 47, Oct. 1928, p. 1111.

2. *Cathode Ray Oscillograph Study of Artificial Lightning Surges on the Turners Falls Transmission Line*, by K. B. McEachron and V. E. Goodwin, A. I. E. E. Trans., Vol. 48, 1929.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 27-31, 1930.*

3. *Study of Traveling Waves on Transmission Lines with Artificial Lightning Surges*, by K. B. McEachron, J. G. Hemstreet, and W. J. Rudge, part of symposium on the subject of Lightning Investigation, see p. 885.

4. *Lightning Investigation on the Ohio Power Co. System*, by Philip Sporn and W. L. Lloyd, see p. 905; *Lightning Investigation on the 220-Kv. System of Pennsylvania Power & Light Co.*, by N. N. Smeloff and A. L. Price, see p. 895.

5. *Progress in Lightning Research in the Field and in the Laboratory*, F. W. Peek, Jr., A. I. E. E. Quarterly Trans., Vol. 48, April 1929, p. 436.



30-38

The conductors are horizontally arranged. Up to the year 1929 the insulation consisted of 14 disks spaced 5¾ in. with grading rings at the line end only. In the year 1929, two additional disks were added on the outside conductors for a distance of 40 miles from the Wallenpaupack end. The conductors are of 795,000 cir. mils, aluminum, steel reinforced. There are two overhead ground wires of 184,000 cir. mils, aluminum, steel reinforced. The ground wires extend for 20 miles from the Wallenpaupack end and five miles from the Siegfried end. They were installed during the year 1927.

On the Ohio Power Company's system the lines under investigation are the two circuits vertically arranged on the same towers, extending from Philo to Canton, a distance of 73 miles. The insulation consists of 11 disks on top and middle and 10 disks on bottom conductors, all spaced 4¾ in. The strings are equipped with grading rings at the line end only. The conductors are of 336,400 circular mils, aluminum, steel reinforced. Extending the total length of the line there is one overhead ground wire of 159,000 cir. mils, aluminum, steel reinforced.

On the New England Power Co. system there are two circuits, with all conductors horizontally arranged. The conductors are of 4/0 copper cable (212,000 cir. mils). Previous to 1928 there was one ground wire, and in 1928 a second ground wire was added. The ground wires are of 7/16 in. steel cable.

Prior to 1928 all conductors were insulated with eight disks spaced 5 in., with no grading rings. In 1928 the insulation was increased to 10 disks on the two outside conductors and to 9 on the conductors adjacent to the two outside ones, while 8 disks were retained on the two innermost conductors. Grading rings were added to all strings at both line and ground ends.

It will be noted from Table I that maximum voltages have been recorded which exceed the approximate impulse insulator flashover kv. This may mean that occasionally actual surges have required a much shorter time to reach flashover than with the Pittsfield wave on which the assigned impulse flashovers are based. However, the accuracy of voltage registration by means of Lichtenberg fixtures should be kept in mind in considering these extreme registrations.[6]

In Table II are given the height of line at tower and the average height of conductor, also the kilovolts per foot of height, as measured by surge voltage recorders in 1926-27-28-29.

On the special antennas used in connection with the field intensity recorder a potential gradient of 280 kv. per meter (85.5 kv. per foot) was measured. This is beginning to approach the figure of 100 kv. per foot, which it has been customary to use as the gradient possible in the worst case. It is probable that the gradient on the transmission line is set by the flashover of the line insulators, and that this gradient will increase as the line insulation is increased.

In Figs. 1, 2, and 3 are plotted the surge voltages caused by lightning during the years 1927, 1928, and 1929 respectively. The abscissas represent times normal crest line-to-neutral voltage, and the ordinates represent percentage of the total number exceeding the value indicated by the abscissas.

The curves for the Pennsylvania system show a much

TABLE I

MAXIMUM VOLTAGE CAUSED BY LIGHTNING, AS MEASURED BY SURGE VOLTAGE RECORDER

| System | Rated voltage (kv.) | Normal voltage crest (kv. line to neutral) | Approximate insulator flashover impulse (kv.)[1] | Maximum crest voltage caused by lightning (kv.) | | | | Number of times normal voltage | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1926 | 1927 | 1928 | 1929 | 1926 | 1927 | 1928 | 1929 |
| Pennsylvania Power and Light Co. | 220 | 180 | 1950<br>2210[2] | 2100 + | 2100 | 2700 + | 2400 + | 11.7 | 11.7 | 15.00 | 13.3 |
| Ohio Power Co. | 132 | 108 | 1180<br>1280[3] | .... | 1200 | 1640 | 1545 | .... | 11.1 | 15.2 | 14.3 |
| New England Power Co. | 110 | 90 | 1025<br>1150<br>1280<br>1400 [4] | 240 | 900 | 740 | .... | 2.7 | 10.0 | 8.2 | .... |

1. Based on 5-microsecond Pittsfield Wave.
2. Part of line changed from 14 to 16 disks (spaced 5¼ in.) in 1929.
3. Bottom conductor had 10 disks (spaced 4¾ in.), middle and top conductor 11 disks, for all years.
4. Up to 1928 all conductors had 8 disks (spaced 5 in.); in 1928 outside conductor had 10 disks and grading rings, next conductor 9 disks and rings, and inside conductor 8 disks and rings.

NOTE: Maximum voltage on Ohio Power system in 1927 recorded on middle conductor, in 1928 and 1929 on bottom conductor.

TABLE II

HIGHEST MEASURED VOLTAGE CAUSED BY LIGHTNING IN KILOVOLTS PER FOOT, BASED ON AVERAGE HEIGHT OF CONDUCTOR

| | Height of line at tower (feet) | Average height of conductor (feet) | Kv. per foot of height | | | |
|---|---|---|---|---|---|---|
| | | | 1926 | 1927 | 1928 | 1929 |
| Pennsylvania Power and Light Co. | 66 | 52 | 40 | 40 | 52 | 46 |
| Ohio Power Co. | 59* | 48* | .. | 20 | 34 | 32 |
| New England Power Co. | 49 | 41 | 6 | 22 | 18 | .. |

*Bottom conductor.

6. *Measurement of Surge Voltages on Transmission Lines due to Lightning*, by E. S. Lee and C. M. Foust, A. I. E. E. TRANS., Vol. 46, 1927, p. 339.

larger percentage of high surges than for the Ohio and New England systems. The tendency of the Pennsylvania system to record higher voltages may be due to some property of the line insulation and construction (the Pennsylvania line is more highly insulated than the others and has ground wires over only a portion of the

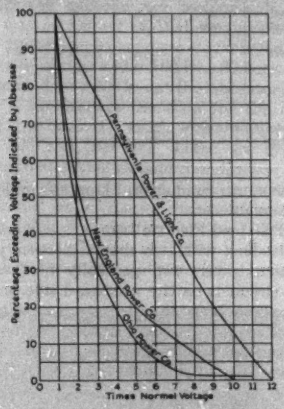



FIG. 1—VALUES OF SURGE VOLTAGES CAUSED BY LIGHTNING, 1927

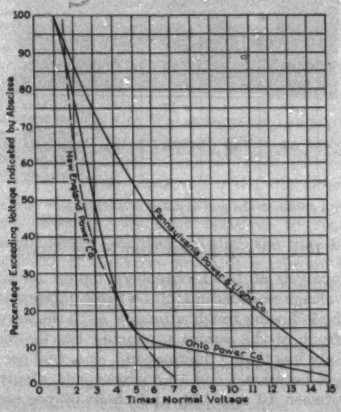



FIG. 2—VALUES OF SURGE VOLTAGES CAUSED BY LIGHTNING, 1928

line), it may be caused by the chance of more strokes and strokes of greater severity near the line, or it may be due to the fact that recorders are placed closer together over the entire line than on the other systems.

The year 1929 shows a tendency for the number of surge voltages of high magnitude on the Pennsylvania system to be much greater than in previous years. In fact, in the year 1929 there were 14 surges over 13.3 times normal (2400 kv.) out of a total of 45 surges which exceeded 300 kv. The indication from the measurements and from line operation is that this line is in an unusually severe lightning territory.

*Switching.* Table III gives the maximum voltage caused by switching, as measured during the years 1926, 1927, 1928, and 1929, also the approximate 60-cycle flashover of the line insulators.

In spite of the high values occasionally reached, the majority of all switching surges are less than 3.5 times normal. It is probable that slightly more than the 60-cycle flashover voltage is required to flash over during a switching surge (estimated impulse ratio 1.2). It is apparent from the data that the 60-cycle flashover of

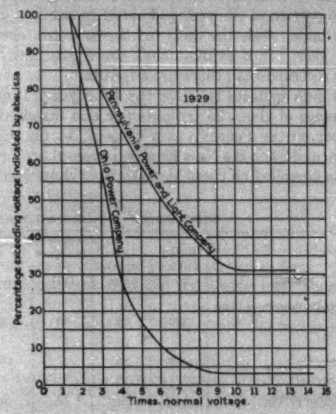



FIG. 3—VALUES OF SURGE VOLTAGES CAUSED BY LIGHTNING, 1929

line insulation cannot be neglected, especially if the insulators are liable to be subjected to rain at the time of switching.

In general it was noted that deenergizing was somewhat more severe than energizing. For example, on the Ohio system in 1929, there were measured 20 surges caused by deenergizing with a maximum value of 4.9 times normal, and only three surges caused by energizing with a maximum of 2.8 times normal. Switching load on and off gave a very mild overvoltage disturbance (of the magnitude of 1.2 times normal on the Ohio Power system).

## II. TRIPOUTS CAUSED BY LIGHTNING, AND FLASHED INSULATOR STRINGS

The number of surges caused by lightning, as measured by the surge voltage recorder, is given in Table IV for the years 1926, 1927, 1928, and 1929 for the three systems under discussion, also the number of line

TABLE III

MAXIMUM VOLTAGE CAUSED BY SWITCHING, AS MEASURED BY SURGE VOLTAGE RECORDER

| System | Rated voltage (kv.) | Normal voltage crest (kv. line to neutral) | Approximate insulator flashover 60 cycles (kv. crest) | Maximum crest voltage due to switching | | | | Number of times normal voltage | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1926 | 1927 | 1928 | 1929 | 1926 | 1927 | 1928 | 1929 |
| Pennsylvania Power and Light Co. | 220 | 180 | 1025<br>1150[1] | 630 | 720 | 845 | 450 | 3.5 | 4.0 | 4.7 | 2.5 |
| Ohio Power Co. | 132 | 108 | 650<br>700[2] | .... | 560 | 595 | 530 | .... | 5.2 | 5.5 | 4.9 |
| New England Power Co. | 110 | 90 | 565<br>510<br>565<br>615 [3] | 207 | 360 | 370 | .... | 2.3 | 4.0 | 4.1 | .... |

1. Part of the line changed from 14 to 16 disks (spaced 5½ in.) in 1929.
2. Bottom conductor had 10 disks (spaced 4½ in.); middle and top conductors, 11 disks, for all years.
3. Up to 1928 all conductors had 8 disks (spaced 5 in.); in 1928 outside conductor had 10 disks and grading rings, next conductor 9 disks and rings, and inside conductor 8 disks and rings.

tripouts. The data on the number of surges are given for the portion of the year indicated in the last column of the table, while the data for the tripouts cover the whole year. It is evident that there are many more surges recorded than there are tripouts.

The data indicate that for the four years there was an average of about 29 tripouts per one hundred miles per year on the Pennsylvania system, 14 on the Ohio system, and 24 on the New England system.

Data compiled on these systems also show that there are as many as 1 to 5 insulator strings or assemblies flashed over for each tripout. In other words, each stroke which causes a flashover usually affects more than one string or assembly, either on the same tower or on adjacent towers.

Statistics also indicate that where there are two circuits on a tower, from 5 to 25 per cent of the strokes affect insulator strings on both circuits.

In case of circuits with conductors horizontally arranged, or two circuits with some horizontal distance between them, statistics seem to indicate that the conductor or circuit on the side from which the storms generally approach suffer the greatest number of insulators damaged. For example, on the Pennsylvania Power & Light Co. 220-kv. line from Wallenpaupack to Siegfried, during the four years 1926, 1927, 1928, and 1929, there were 115 insulator strings flashed over on the west or storm conductor, 51 on the middle, and 97 on the east conductor.

On the Hartford Electric Light Co. system, a 66-kv. line 33 miles long with two circuits vertically arranged on the same towers ran generally northwest. The southwest circuit is on the windward side and the side towards approaching thunder storms. Three years operation of the line showed that trouble from insulator flashover and failure was more than twice as great on the southwest circuit as on the other or lee circuit.

TABLE IV

NUMBER OF SURGES AND NUMBER OF TRIPOUTS CAUSED BY LIGHTNING

| System | Rated voltage kv. | Line length miles | Number of surges caused by lightning measured by surge voltage recorders | | | | Number of line tripouts caused by lightning | | | | Period during which surge voltages were measured |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1926 | 1927 | 1928 | 1929 | 1926 | 1927 | 1928 | 1929 | |
| Pennsylvania Power and Light Co. | 220 | 65 | 33 | 48 | 28 | 45 | 16 | 7* | 14 | 38 | 1926 July 20–Oct. 4<br>1927 Mar. 12–Nov. 2<br>1928 April 15–Oct. 1<br>1929 April 17–Oct. 1 |
| Ohio Power Co. | 132 | 73 | .. | 166 | 46 | 31 | 15 | 4 | 12 | 11 | 1927 May 11–Oct. 16<br>1928 April 29–Oct. 20<br>1929 May 6–Oct. 1 |
| New England Pr. Co. | 110 | 74 | 14 | 104 | 47 | .. | 11 | 43 | 5 | 13 | 1926 July 28–Sept. 12<br>1927 June 6–Oct. 10<br>1928 June 23–Oct. 8 |

*Line out of service two months during lightning season, installing ground wires.

NOTE: Tripouts are given for the whole year while surges were recorded for only a portion of the year as noted in last column. Ohio Power and New England tripouts are for two circuits.

## III. Wave Front and Wave Shape

An analysis of 150 Lichtenberg figures obtained by surge voltage recorder in 1927 on three different systems gave the following rough summary as to the duration of wave front of the surges producing the figures: One surge only less than 1 microsecond, about 20 per cent of all surges between 1 and 10 microseconds, about 20 per cent between 10 and 100, and about 60 per cent over 100 microseconds.

A cathode ray oscillograph was installed in the lightning laboratory on the Pennsylvania System at Wallenpaupack (tower 1-3) during the latter part of 1928 season, and one oscillogram was obtained of a lightning surge.[7] The surge was positive in polarity, rose to

7. "Transmission Line Insulation and Field Tests Pertaining to Lightning," W. W. Lewis, *General Electric Review*, July 1929.

maximum in 8 microseconds, reduced to 50 per cent of that value in 17 microseconds and to zero in 35 microseconds. The crest voltage of the main wave was approximately 600 kv. At a point 17 miles from the laboratory a value of 2100 kv. was measured by surge voltage recorder.

In 1929 the cathode ray oscillograph installation (Fig. 4) was continued at Wallenpaupack and in the course of the season 95 surges were recorded. Of these, there were 50 surges under 100 kv., 30 between 100 and 300 kv., and 15 over 300 kv. at the laboratory.

Table V summarizes the data for the oscillograms taken up to August 11, 1929, with voltage magnitudes between 100 and 300 kv. These are typical of all surges recorded in this voltage classification.

The oscillograms obtained indicate that the surges have various wave shape characteristics. For this reason, in Table V under the heading, "Time in Microseconds," four columns are given: First, the time consumed in the initial voltage rise. In several cases

FIG. 4—INTERIOR VIEW OF WALLENPAUPACK LABORATORY

Showing two General Electric portable cathode ray oscillographs

this is given between zero and a definite time value, the portion of the wave previous to this time not being recorded. Second, the time required to reach the maximum voltage recorded. Third, the time between the beginning of the surge and half maximum voltage value on the tail of the wave, and fourth the time duration of the first loop of the wave.

In Table VI are summarized the data for the 15 oscillograms with voltage magnitude exceeding 300 kv. It will be noted that the voltage magnitudes in this classification range from 330 to 1260 kv. The wave front ranges from 1.6 to 36 microseconds. Two of the oscillograms obtained could not be analyzed for wave front, because of improper adjustment in the oscillograph arrangement. The total duration varied from 4 to 75 microseconds. Approximately 60 per cent were positive and 40 per cent negative for the first loop. Within the time range of the oscillograms obtained, two-thirds of the waves were oscillatory and one-third unidirectional.

In considering the magnitudes of these waves, and their front and duration, it should be remembered that all of the waves were measured at the terminal of the transmission line, and the voltage values recorded were influenced by reflection. In most cases the waves originated on the line many miles from the terminal.

TABLE V

PENNSYLVANIA POWER & LIGHT CO. CATHODE RAY OSCILLOGRAMS 100 TO 300 KV., YEAR 1929, UP TO AUGUST 11

| Oscillogram number | Kv. max. | Polarity of first loop | Nature of wave | Time in microseconds to reach: At least 75% of max. voltage recorded | Max. voltage recorded | 50% max. on tail of wave | Zero of first loop |
|---|---|---|---|---|---|---|---|
| 901178 | 245 | Pos. | Uni. | 0–1.2 | 0–1.2 | 22 | 33+ |
| 179 | 160 | Pos. | Osc. | 0–1 | 5 | 13 | 24 |
| 183 | 180 | Pos. | Osc. | 5 | 8 | 23 | 32 |
| 187 | 260 | Pos. | Uni. | 0–1 | 5 | 26 | 45+ |
| 189a | 180 | Pos. | Uni. | 0–1.5 | 5 | 20 | 45+ |
| 189b | 140 | Neg. | Uni. | 0–1.5 | 10–28 | 45+ | 45+ |
| 190 | 280 | Pos. | Osc. | 4 | 4 | 11 | 20 |
| 191b | 250 | Pos. | Osc. | 0–1.3 | 3 | 5.5 | 9.5 |
| 197 | 180 | Pos. | Osc. | 0–1 | 6 | 27 | 35 |
| 198 | 150 | Neg. | Uni. | 0–1.5 | 4 | 45+ | 45+ |
| 199 | 180 | Pos. | Osc. | 2.5 | 4.5 | 18 | 26 |
| 200 | 260 | Pos. | Osc. | 5 | 5 | 27 | 36 |
| 201a | 130 | Pos. | Osc. | 3 | 3 | 11 | 33 |
| 203 | 260 | Pos. | Osc. | 2 | 5 | 25 | 35 |
| 204 | 170 | Pos. | Uni. | 0–1 | 20 | 43+ | 43+ |
| 214 | 135 | Neg. | Osc. | 0–2 | 0–2 | 6 | 10 |

Osc. = Oscillatory.
Uni. = Unidirectional.

The waves therefore have been subjected to considerable attenuation in magnitude and change in form. Taking this into account and the extremely high magnitudes measured on the line by surge voltage recorders, it is reasonable to assume that many of the waves at their

TABLE VI

PENNSYLVANIA POWER AND LIGHT CO. CATHODE RAY OSCILLOGRAMS OVER 300 KV., YEAR 1929

| Oscillogram number | Kv. max. | Polarity of first loop | Nature of wave | Time in microseconds to reach: Max. voltage recorded | 50% max. on tail of wave | Zero of first loop |
|---|---|---|---|---|---|---|
| 901180 | 1260 | Neg. | Osc. | 3.3 | 3.7 | 4 Flashover |
| 185 | 360 | Pos. | Uni. | 4 | 45+ | 45+ |
| 186 | 330 | Pos. | Osc. | 1.6 | 16 | 29 |
| 188 | 530 | Pos. | Osc. | 7–8 | 18 | 24 |
| 191 | 600 | Neg. | Uni. | 4 | 14.5 | 45+ |
| 193 | 740 | Pos. | Osc. | 7 | 16 | 22 |
| 194 | 810 | Neg. | Osc. | 36 | ? | 37 Flashover |
| 201 | 740 | Neg. | Uni. | 6.5 | 43+ | 43+ |
| 229 | 330 | Neg. | Uni. | ? | 12 | 75 |
| 231 | 330 | Pos. | Osc. | ? | 18 | 25 |
| 249 | 390 | Pos. | Osc. | 6 | 14 | 18 |
| 251 | 390 | Pos. | Osc. | 6 | 35 | 55 |
| 272 | 600 | Neg. | Uni. | < 7.5 | 69+ | 69+ |
| 275 | 500 | Pos. | Osc. | < 8 | 32 | 45 |
| 285 | 630 | Pos. | Osc. | 11 | 20 | 29 |

Osc. = Oscillatory.
Uni. = Unidirectional.

origin have fronts steeper than those measured by the cathode ray oscillograph.

A cathode ray oscillograph was installed in 1929 on the Ohio Power Company system at Newcomerstown. Ten lightning surges were recorded, of which only three

were equal to or greater than normal (108 kv.). All the recorded surges were positive and all unidirectional. The wave fronts varied from 4 to 30 microseconds and the total duration from 45 to 60 + microseconds.

In the Consumers Power Co. investigation for 1929[8] seven cathode ray oscillograms of lightning surges 200 kv. and above were obtained. The wave front varied from 0.5 to 7 microseconds. The total duration of the first loop varied from 0.7 to 40 + microseconds. Four of the surges were of negative polarity and three positive. Five of the waves were unidirectional and two oscillatory.

## IV. Attenuation

In 1927 plots were made of two surges which appeared at more than one station on the Pennsylvania Power & Light Co. system and six surges on the New England Power Co. system, with distance from an assumed origin as abscissas and voltage as ordinates.[9] An average curve was drawn and equations determined for the variation

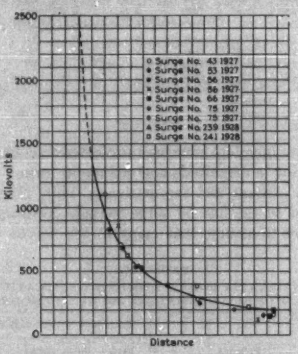



Fig. 5—Curve Showing Variation of Voltage with Distance for Various Surges

Occurring on the New England Power Co. system in 1927 and 1928. Factor $k$ from curve = 0.00016

of voltage with distance and the rate of change of voltage with distance, or attenuation. These equations are as follows:

$$e = \frac{e_o}{k\,s\,e_o + 1} \qquad (1)$$

$$A = -\,k\,e^2 \qquad (2)$$

in which

$e_o$ = initial surge voltage at the point where the surge originated.

$k$ = a proportionality factor which is found empirically.

$s$ = distance in miles from the origin of the surge.

$e$ = voltage at any distance $s$.

$A$ = the attenuation in kilovolts per mile.

The factor $k$ for the surges investigated was found to be 0.00016.

The curve referred to has been replotted with the two surges from the Pennsylvania system omitted, thus confining the data to the 6 surges found on the New England Power system in 1927, together with 2 additional surges obtained on this system in 1928 (see Fig. 5).

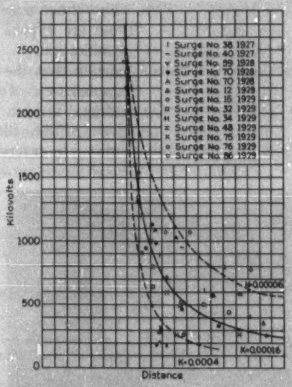



Fig. 6—Curve Showing Variation of Voltage with Distance for Various Surges

Occurring on the Pennsylvania Power and Light Co. system in 1927, 1928, and 1929

Surges on the Pennsylvania system for 1927, 1928, and 1929 have been plotted in Fig. 6 and surges obtained on the Ohio Power system for 1928 and 1929 have been plotted in Fig. 7.

These data all tend to confirm the validity of Equations (1) and (2) derived in 1927.[9] There is, however, considerable difference in the factor $k$ for the various systems. This factor from the New England surges is 0.00016. On the Pennsylvania system there is a considerable range in the points of the various surges, but a fair average curve through these points again gives a factor $k$ of 0.00016. On the Ohio Power Co. system an average curve drawn through the points of the surges for 1928 and 1929 has a factor $k$ of 0.00057. The last named system thus shows a much faster attenuation than the other two.

A few tests were made on the Ohio System with surges from a 1000-kv. lightning generator. The potentials at various points were measured by means of surge voltage recorders. The results are plotted on

8. *Lightning Voltages on Transmission Lines*, by R. H. George and J. R. Eaton, part of symposium at this convention on the subject of Lightning Investigation. See p. 877.

9. *Surge Voltage Investigation on Transmission Lines*, by W. W. Lewis, A. I. E. E. Trans., Vol. 47, No. 4, 1928.

Fig. 8, the full curve representing an average of the various test points. The dotted curve is taken from Fig. 7, and represents the average attenuation measured with natural lightning surges.

Unfortunately, the surges placed on the transmission line from the lightning generator were not of sufficient amplitude to permit the checking of attenuation over

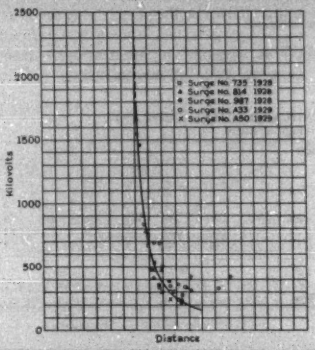



Fig. 7—Curve Showing Variation of Voltage with Distance for Various Surges

Occurring on the Ohio Power Co. system in 1928 and 1929. Factor $k$ from curve = 0.00057

the voltage range of most interest in connection with natural lightning surges. However, in the limited range of these tests, the attenuation of the artificial surges appears to be of the same order as that of the natural surges.

Mr. McEachron in his work in Michigan[8] found factors $k$ of the order of 0.00039 to 0.00049 when an artificial surge was placed on three conductors in

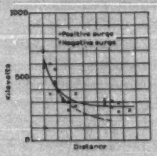



Fig. 8—Curve Showing Variation of Voltage with Distance for Artificial Surges Produced by Lightning Generator

Ohio Power Co. system, 1929. Dotted curve is from Fig. 6

multiple. With natural surges it is probable that three conductors in multiple are also involved, so that attenuation factors should be compared on this basis. Mr. McEachron also found it necessary to introduce an exponent to modify the distance $s$ in the denominator of formula (1). This exponent, however, does not differ greatly from unity, and for practical purposes it can probably be neglected.

It was found in the Michigan tests that $k$ varied with steepness of wave front, was different for positive and negative surges, and was different for a line with overhead ground wires and for a line without overhead ground wires.

A factor $k$ of 0.00069 was found on the Turners Falls 66-kv. line when artificial surges were placed on a single conductor.[8]

While the attenuation factors from the various systems indicate that the wave attenuates faster with smaller conductors, it appears that other line and wave characteristics, such as those mentioned in connection with the Michigan tests, have considerable influence in affecting this factor $k$.

## V. Effect of Overhead Ground Wires in Reducing Surge Voltages

*Ohio Power Company System.* In 1927 approximately 50 surges were measured simultaneously on top, middle, and bottom conductors of the vertically arranged circuits; in 1928 five surges were recorded, and in 1929 one surge. This line is a double circuit line with one overhead ground wire above and midway between the two circuits.

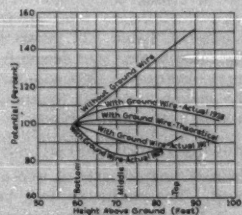



Fig. 9—Curves Illustrating Ground Wire Protection

Ohio Power Co. system, 1927, 1928, and 1929

In Table VII is given the theoretical potential of the three conductors without ground wire, expressed in per cent, on the assumption that the bottom conductor is 100 per cent and that the other conductors have potentials proportionate to their heights above ground. Then there is given the theoretical potential with ground wire, still assuming that the bottom conductor is 100 per cent and using the protective ratios 0.42, 0.52, and 0.62 for top, middle, and bottom conductors, respectively.[10] Finally, is given the average of the surge voltage recorder readings expressed in per cent, with the bottom conductor as 100 per cent.

In case of the top conductor two figures are given under the column of measured potential; the first is a comparison of the surges on top and middle conductors and the second of the surges on top and bottom conductors. The results are illustrated graphically in Fig. 9.

10. *Relation between Transmission Line Insulation and Transformer Insulation*, by W. W. Lewis, A. I. E. E. Trans., Vol. 47, No. 4, 1928, p. 992.

TABLE VII

EFFECT OF OVERHEAD GROUND WIRE, OHIO POWER COMPANY

| Conductor | Approximate height at tower (feet) | Theoretical potential without ground wire (per cent) | Theoretical potential with ground wire* (per cent) | Measured potential with ground wire average of readings (per cent) | | | |
|---|---|---|---|---|---|---|---|
| | | | | 1927 | 1928 | 1929 | Weighted average |
| Top | 85 | 143 | 97 | 83–89† | 99–116† | 92 | 83 |
| Middle | 72 | 121 | 102 | 91 | 110 | 83 | 93 |
| Bottom | 59 | 100 | 100 | 100 | 100 | 100 | 100 |

*Calculated by means of tables in Footnote reference (10).
†First figure is comparison of top to middle, and second figure comparison top to bottom conductor.
1927 figures average of 51 to 54 surges.
1928 figures average of 5 surges.
1929 figures are one surge only.

TABLE VIII

EFFECT OF OVERHEAD GROUND WIRE, NEW ENGLAND POWER COMPANY

Surge Voltages Having Their Highest Voltage at Barre

| | 1927 | | | | | | 1928 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | G | | | | | | G | | G | |
| Conductor position | 1 | 2 | 3 | 4 | 5 | 6 | 1 | 2 | 3 | 4 | 5 | 6 |
| Average of surge voltages (number of times normal) | 4.8 | 3.1 | 4.2 | 3.3 | 4.4 | 6.4 | 4.2 | 6.4 | 2.7 | 2.1 | 3.4 | 4.3 |
| Surge voltages in per cent (assuming conductor 6 as 100 %) | 75 | 49 | 66 | 52 | 69 | 100 | 98 | 146 | 63 | 49 | 79 | 100 |
| Theoretical protective ratio* in per cent | 74 | 64 | 64 | 74 | 89 | 100 | 100 | 84 | 72 | 72 | 84 | 100 |
| Insulator flashovers | 22 | 16 | 21 | 17 | 17 | 23 | 5 | 4 | 4 | 1 | 4 | 6 |
| Lightning storms | 22 | | | | | | 20 | | | | | |
| Insulator flashovers | 116 | | | | | | 24 | | | | | |
| Tripouts | 43 | | | | | | 5 | | | | | |

*From Footnote Reference 10.
$G$ = Ground wire.

The last column of Table VII gives the weighted average for the three years. On account of the large number of surges recorded in 1927 compared with two later years, the weighted average figures give a curve practically the same as the 1927 curve.

## New England Power Company's System

This transmission line consists of two circuits horizontally arranged. The conductors may be designated 1, 2, 3, 4, 5, 6. In 1927 there was one ground wire above and between conductors 2 and 3. Instruments were installed on all six conductors at two places, Griswoldville and Barre. The readings on these instruments did not necessarily indicate the potential due to the conductor position at that point, because the conductors were frequently transposed. The fairest attempt to evaluate the effect of the ground wire was to select those surges which had their highest values at one of the stations, and therefore, presumably originated near that station. For this purpose five surges which had their highest values at Barre were studied. The average values of the surges expressed in times normal are given in Table VIII.

In 1928 a second ground wire was placed above and between conductors 4 and 5. The average values of two surges having their highest values at Barre are given in Table VIII.

Fig. 10 illustrates graphically, the effect of overhead ground wires for the years 1927 and 1928.

The number of insulator flashovers, storms, and tripouts for 1927 and 1928 are also given in Table VIII.

In 1929 there were 13 tripouts on this line, and a total of 38 flashovers, divided among conductors 1 to 6 respectively as follows: 7, 7, 7, 2, 6, 9.

On Fig. 11 are shown the number of insulator string flashovers for each conductor, for the years 1924 to 1929.

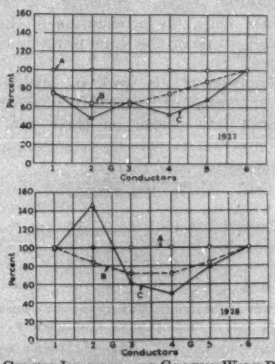



Fig. 10—Curves Illustrating Ground Wire Protection

New England Power Co. system, 1927 and 1928

A. Without ground wires
B. With ground wires (estimated)
C. With ground wires (measured by surge voltage recorder)

In this connection it must be remembered that in addition to adding the second ground wire in 1928, the line insulation was also considerably improved, being increased from 8 disks on all conductors to 10, 9, 8, 8, 9,

10 disks. Grading rings were also added at both line and ground ends of all strings.

*General.* A similar improvement was shown on the Ohio Power Co. system previously discussed. In 1925 there were 88 tripouts. In 1926 a ground wire was added and grading rings at the line ends of all strings. The tripouts, as shown by Table IV, have not exceeded 15 per year since that time. There is no doubt that the ground wire should be credited with some of this improvement in operation.

Some data were secured on antenna at Wallenpaupack during a lightning stroke. An antenna 50 feet

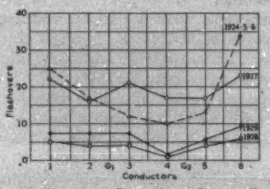



FIG. 11—CURVES SHOWING INSULATOR STRING FLASHOVER ON NEW ENGLAND POWER CO. SYSTEM, 1924 TO 1929

Ground wire $G_2$ was installed in 1928

from the ground with a grounded conductor 10 feet above, registered a potential approximately one-half that recorded on a similar 50-foot antenna without ground wire.

The Overhead Systems Committee of the Great Lakes Division, National Electric Light Association,[11] made a study of the operation of high-voltage transmission lines during 1927. The lines without overhead ground wires (728 miles) had 12.2 interruptions per 100 miles due to lightning, while the lines with overhead ground wires (1511 miles) had 5.9 interruptions per 100 miles due to lightning.

A similar study was made for 1928 operation.[11] The lines without overhead ground wires (719 miles) had 16.8 interruptions per 100 miles, and the lines with overhead ground wires (1576 miles) had 8.1 interruptions per 100 miles. The data for the two years indicate approximately twice as many interruptions per 100 miles on lines without ground wires as on lines with ground wires.

The Texas Power & Light Company in 1925 operated 726 miles of 60-kv. line with overhead ground wire. On these lines they had 28 interruptions or approximately 4 interruptions per 100 miles. During the same year they operated 491 miles of 66-kv. line without overhead ground wire. The interruptions were 75 or about 15 per 100 miles. In 1926 they had 800 miles with ground wire, and the interruptions were 64 or 8 per 100 miles. In the same year they had 784 miles without ground wire. The interruptions were 220 or 28 per 100 miles.

11. Report of Overhead Systems Committee, Great Lakes Division, National Electric Light Association, Sept. 1928. Also report of same committee Oct. 1929.

All these data, though incomplete, give corroborative evidence of the value of the overhead ground wire in improving the continuity of service.

## VI. LIGHTNING STROKE RECORDERS

In 1929 lightning stroke recorders were placed in service on 284 of the approximately 300 towers of the Wallenpaupack-Siegfried line and on about 20 towers of the Philo-Canton line.

Fig. 12 is a view of the recorder. This recorder is a small Lichtenberg camera, which is placed across a portion of a leg of a transmission tower. The development of the instrument and its application are due to Mr. W. L. Lloyd of the Pittsfield High-Voltage Laboratory.

The film for this instrument consists of two sheets separated by tinfoil and wrapped in treated paper, the whole forming a lightproof and water proof packet, so that the instrument can be readily loaded in the field. The film is inserted in the camera and pressure is applied till the film is held firmly in place, with the electrodes against the outside wrapping of the packet.

The theory of the device is that a direct stroke hitting the tower or flashing over an insulator will cause sufficient current to flow down the tower leg to give an appreciable drop, and consequently a Lichtenberg figure on the film. The current flowing when an insulator flashes over due to an induced stroke will not be sufficient to cause enough drop in the tower leg to give a figure on the film.

Four figures were obtained, two on the Wallenpaupack-Siegfried line and two on the Philo-Canton line.

The first Pennsylvania record was obtained on August 27 at tower 26-2 (Siegfried-Roseland Section).

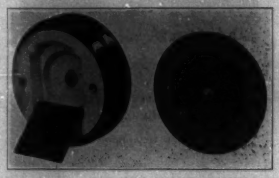


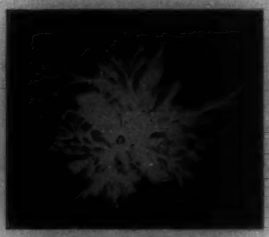
FIG. 12—VIEW OF LIGHTNING STROKE RECORDER

This record was interpreted to indicate about 60,000 amperes negative polarity. At the same time the surge voltage recorder at this tower indicated a positive surge of 2400-2800 kv. (13.3 to 15.5 times normal). An oscillogram of low-voltage amplitude was taken of this surge at the lightning laboratory (about 40 miles from origin of surge). Tripout 33 was associated with this surge.

The second Pennsylvania record was obtained Sept. 10 at tower 12-5 (Wallenpaupack Tap section). This tower is at High Knob, in the section of line equipped with a counterpoise.[4] The record was interpreted to

indicate about 100,000 amperes negative polarity. There was no surge voltage recorder at this tower and the recorder at the next tower, 12-6, was out of service. The recorder at tower 10-2 (the nearest recorder north) indicated a positive surge of 350 kv., which it is thought correlates with the surge indicated by the lightning stroke recorder. The surge voltage recorder at tower 17-1 (the nearest recorder south) gave no indication. No tripout accompanied this surge.

The first Ohio record was obtained on July 25 at 3:20 p.m. on tower 185 and indicated approximately



Top Film

Bottom Film

Fig. 13—Figure Obtained with Lightning Stroke Recorder on Ohio Power Co. System

July 25, 1929, Surge A-50

175,000 amperes negative polarity. (Fig. 13.) At the same time, the surge voltage recorder on the transmission conductor on this tower indicated a positive surge of 8.4 times normal (surge A-50). There was no tripout. A good attenuation curve was obtained of this surge by means of surge voltage recorders, (Fig. 14).

The second Ohio record was thought to have been obtained on August 23 at 2:58 a. m. This was at tower 159. The recorder indicated a surge of approximately 100,000 amperes negative polarity. At the same time, the line surge voltage recorder indicated a positive surge of 6.5 times normal at this tower (surge A-72). This surge was accompanied by a tripout.

There is a large field for an instrument of this sort, but the records obtained so far are too few to establish any conclusions as to the value of the instrument for the purpose intended. It is planned to continue the operation of these instruments for another year.

## VII. Field Intensity Recorder and Rate of Change of Field Intensity Recorder

Two instruments were built and placed in operation at the Wallenpaupack laboratory, in an effort to obtain some measurements with regard to electric field conditions to which transmission conductors might be subjected. These instruments are called respectively a field intensity recorder and a rate of change of field intensity recorder.

The instruments were developed and applied under the supervision of Mr. H. L. Marvin of the General Engineering Laboratory, Schenectady, and the data obtained were analyzed by Mr. Marvin.

The purpose of the field intensity recorder is to obtain a photographic record on motion picture film of the vertical component of electric field intensity (voltage gradient) versus time. The purpose of the rate of change recorder is to obtain a photographic record of the vertical component of the time rate of change of electric field intensity. The adjustment is made so that only relatively large values such as occur during thunder storms are recorded. The data so obtained are expected to be helpful in two ways: (a) to acquire further knowledge of the nature of lightning storms; (b) in measuring the relative severity of thunder storms.

Instruments were installed in a small building near the lightning laboratory at Wallenpaupack and began operating on May 28, 1929, and continued operation

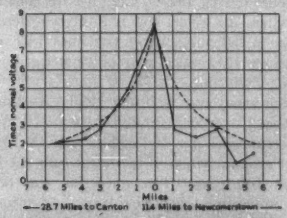



Fig. 14—Attenuation of Surge A-50, which Occurred on Ohio Power Co. System July 25, 1929

(See Fig. 13 for lightning stroke recorder registration.) Dotted curve shows attenuation calculated from Equation (1), with $K = 0.0006$

throughout the lightning season. During that time the recorders went through more than 33 storm periods. Each recorder used approximately 1400 ft. of motion picture film. The field intensity recorder operated satisfactorily from the first, but the rate of change recorder produced blank records until after August 5, at which time changes were made in the instrument to increase sensitivity and adjust for slower rates of change. Following these changes records were obtained on this instrument also.

Fig. 15 shows a view of the field intensity recorder and Fig. 16 shows a typical record taken with this instrument, also a record obtained at the same time with the rate of change of field recorder.

Records obtained from the field intensity recorder were measured, and the data plotted for each storm on cross-section paper, the abscissas representing time and the ordinates kilovolts per meter. Fig. 17 shows the data for the storm of June 19, 1929.

A study of the records indicates that the readings for any one storm are usually of one predominant

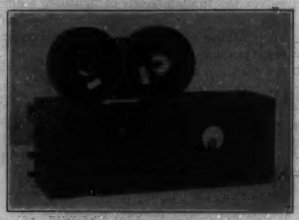


Fig. 15—View of Field Intensity Recorder

polarity, which may be either positive or negative. Of 33 storm periods studied, about 40 per cent gave readinas predominately positive, about 40 per cent predominantly negative, and about 20 per cent mixed positive and negative.

In Fig. 18 are plotted as abscissas kilovolts per meter against number of strokes as ordinates, as measured by the field intensity recorder.

In Fig. 19 an attempt is made to correlate the potential gradient with distance of the stroke from the laboratory. The distance was determined roughly by an

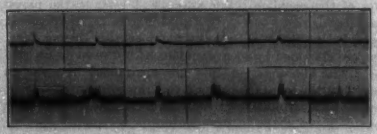


Fig. 16—Typical Record Obtained with Field Intensity Recorder (Upper) and with Rate of Change of Field Recorder (Lower)

observer in the cupola of the laboratory, with the assistance of a stop watch and a device for sighting on the stroke. Of 253 strokes over 15 kilovolts per meter recorded, it was possible to correlate in this manner only 81 strokes or 32 per cent of those occurring. The other strokes were too uncertain in correlation or else no satisfactory distance measurement was obtained. It will be noticed that the correlation is very rough but that there is a tendency for a curve showing greater field intensity with shorter distance from the laboratory.

Up to the time of writing this paper it has not been possible to determine the meaning of the records obtained from the rate of change of field intensity recorder, and their discussion will be left until a later date.

## VIII. Conclusions

A vast amount of progress has been made in the

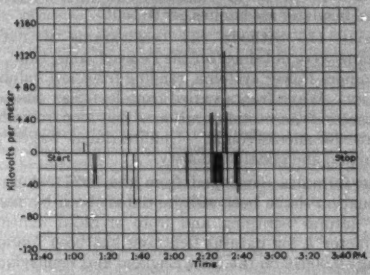



Fig. 17—Field Intensity Data Obtained by the Field Intensity Recorder during the Storm of June 19, 1929

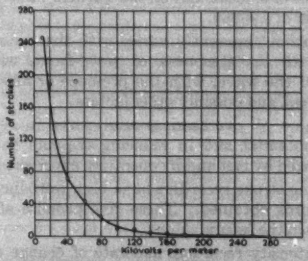



Fig. 18—Curve Showing Field Gradient against Number of Strokes, as Obtained by the Field Intensity Recorder During the 1929 Season

Ordinates represent number of strokes giving intensity greater than specified value

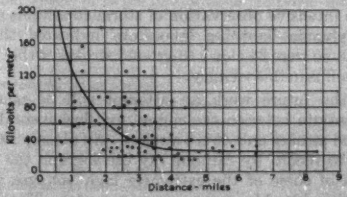



Fig. 19—Correlation of Potential Gradient with Distance of Stroke from Wallenpaupack Laboratory, Season of 1929

study of the effects of lightning on transmission lines in the past two years.

Upper limits of 15.2 times normal voltage for light-

ning surges and 5.5 times normal for switching surges have been reached.

Gradients as high as 52 kv. per foot of height have been recorded on transmission lines, and 85 kv. per foot on special antenna.

Tripouts have occurred on the lines under investigation as high as 29 per 100 miles per year, with 3.6 flashed insulator assemblies per tripout.

About 115 cathode ray oscillograms of natural lightning were obtained on the Pennsylvania, Ohio, and Consumers Power systems, ranging from low values to 1260 kv. Wave-fronts varied from less than one to 36 microseconds and total duration of first loop from about one to 75 microseconds. Unidirectional waves predominated and positive polarity.

The formulas developed from the 1927 results for attenuation[9] have been substantiated, both by results from natural lightning and from artificial lightning. The factor $k$ for natural lightning has been found to average 0.00016 on the New England and Pennsylvania systems. For Ohio the factor is 0.00057. Artificial lightning surges on the Michigan system gave a factor of the order of 0.00044 and on the Turners Falls system of the order of 0.00069.

Attenuation apparently varies with the size of conductor, with the steepness of wave-front, with the polarity of the wave, with the presence or absence of ground wires, and possibly other factors.

The value of overhead ground wires in reducing induced potential and in reducing tripouts has been demonstrated by test and by operating experience.

Lightning stroke recorders have been introduced and a few records obtained. These give promise of much usefulness in the future.

Field intensity recorders and rate of change of field intensity recorders have been used and data of considerable value obtained. Gradients as high as 85 kv. per foot have been recorded. These instruments promise to yield a good deal of information about the habits of storms.

The intensive observation of storm conditions at the Pennsylvania lightning laboratory indicated that in 1929 there were 24 cloud-to-ground strokes within a one mile radius in this vicinity.

In the future work an attempt will be made to differentiate between the surges and flashovers due to induced strokes and direct strokes. An attempt will be made to record by cathode ray oscillograph the wave shapes of some of the extremely high voltages which have been found by surge voltage recorder. The effects of counterpoises or grounded conductors under the transmission line will be studied. Attenuation will be further studied both with natural and artificial lightning. Devices to prevent flashover (line type arresters) will probably be tried out experimentally during the coming year.

# Discussion

## PAPERS ON LIGHTNING INVESTIGATIONS

(Cox and Beck, Torok, Conwell and Fortescue, George and Eaton, McEachron, Rudge, and Hemstreet, Smeloff and Price, Sporn and Lloyd, Jr., Lewis and Foust)

New York, N. Y., January 29, 1930

**A. E. Silver:** Of the unsolved transmission problems today, lightning is outstanding. Bringing it under intelligent control is an economic necessity in power system development.

The outstanding item of progress reflected by the very valuable group of papers comprising this symposium is the arrival at that state of mind where the accepted goal is to conquer natural lightning in its worst effects on transmission lines. It is evident that investigators have now firmly resolved, and with confidence, to discover the fundamentals of lightning sufficiently to enable designing practical transmission lines whose service will be immune to lightning effects, *i. e.*, lines proof against direct as well as induced strokes.

Contrast this with five years ago, when transmission engineers and the few others who were then studying lightning effects accepted direct strokes as being of a magnitude beyond practical control, thinking that when they occurred service interruptions must be endured. Even two years ago only the most optimistic had the courage to resolve that the problem of withstanding direct strokes on transmission lines must be solved.

Again, large progress is reflected in determining propagating and terminal effects of lightning surges once established on the line. Many data have already been obtained, the necessary equipment and technique seem to be well in hand, and present interest seems to assure carrying on until sufficient data have been gathered and analyzed to establish laws and formulas for these phenomena. It is already well established that the insulator spillover interrupting service usually occurs very close to the point where the lightning surge originates on the line.

It is essential that progress in this branch of the problem be not confused with the far more fundamental and difficult task of discovering the mechanism and laws of the lightning stroke in its origin and in its establishment on the transmission line. In part, distinctly different equipment and technique are required, and these are not yet out of the development stage although now yielding some of the necessary data.

Thus far, in analyzing data obtained, major weight has been given to the factors of surge propagation on the line with a tendency in the papers to overlook segregation between the two phases of the problem. For example, I refer to the paper by Messrs. Lewis and Foust. In Tables V and VI, 31 surges of the 95 recorded at the Wallenpaupack Laboratory during the 1929 season are classified by measurements at the cathode ray oscillograph. The classification does not distinguish between waves measured at the point of origin on the transmission line and those measured at a distance from the origin. Rapid attenuation and change of wave shape in propagation is accepted. Clearly, to take the average of any substantial number of these waves as a conception of the characteristics of natural lightning surges, as they exist at the point of origin where they must be controlled to avoid service interruption, is misleading, and tends to wrong working assumptions.

If waves measured at the origin were segregated, then of the 31 listed in Tables V and VI, it is probable that not a single wave could be so classified. This is impressive as an index of the inherent slow rate of gathering the necessary fundamental data, at least until the factor of distance can be incorporated in measuring devices. Also, it should be an incentive to expediting the obtaining and analysis of propagation data to deduce the laws for correcting surge measurements back to the origin wherever along the line they may have been recorded, provided this proves to be a practical procedure.

I repeat, for emphasis, the caution that throughout our investi-

gation work, we all keep clearly in mind as the main objective the protection of service from lightning spillover, which, in general, does not result from the lightning surge after it has traveled away from the point of its origin on the line.

In the matter of transmission line design to render harmless the effects of lightning surges, valuable aid is made available in the papers by Messrs. Conwell and Fortescue, and Messrs. McEachron, Hematreet, and Rudge. These not only present valuable data but lay the ground work for even more valuable results as the field tests are continued. Laboratory methods so applied in the field on actual lines, together with the experience to be gained from thoughtful trial of improved types and observation on the part of operating men, give definite promise of rapidly bringing the application of overhead ground wires and their efficient connection to earth from the realm of conjecture to that of intelligent design.

Prevailing theory, field experience, although confused, and experimental results, already afford ample grounds for the belief that when lightning-proof transmission lines have been reduced to a basis of scientific design, the effective application and proportioning of overhead ground wires and earth connections will be a major factor in at least one method of solution.

**D. W. Roper:** In connection with our investigations on 2400-volt lightning arresters, we have found such informal discussions very desirable and valuable.

In the several papers presented, there is a number of conflicting opinions and theories and all these points must be ironed out and some agreement reached before the proper conclusion can be obtained.

The Transmission Distribution Committee, of which Mr. Woodrow is chairman, and the subcommittee on Lightning and Insulators, of which Mr. Sporn is chairman, are to be congratulated on this very excellent meeting and for the results which are here presented. If they care to arrange for further informal discussions to summarize and digest the information that has been presented, I assure them in advance of the cooperation and support of the Commonwealth Edison Company and affiliated companies.

**E. P. Peck:** All of these lightning studies are made for the purpose of furnishing data which will permit the reduction of interruptions to service due to lightning. An attempt has been made to correlate the results of these tests and of additional information on circuit characteristics, and arrange the data in a systematic way to permit the predetermination of the probable number of interruptions due to lightning on any given transmission line. A chart has been prepared which purports to show the anticipated number of trip-outs due to lightning per 100 circuit miles per year, when the electrical characteristics of the transmission line and the lightning characteristics of the territory through which the line runs are known. All of the reports of tests made throughout the country that were available, were analyzed to determine the effect of different characteristics on the line performance. The chart was prepared from the data obtained by this analysis.

The method is not expected to give results which have engineering accuracy, but rather the order of accuracy expected from rain fall or stream run-off records. The answers should not be considered useless, even though they are supposed to furnish average results over a long term of years. Since the charts are based on data which were available in the early part of 1929, and which data were somewhat inaccurate and incomplete, it must be expected that the charts will require revision after better data are obtained. Even in its present state, however, this method appears to offer one of the best means of determining the effect of changing any of the characteristics of the circuit, such as number of insulators, height of conductors, or number of ground wires.

To use the charts, it is necessary for the investigator to have records on his own system or in his territory, of the number of lightning flashovers per year. Data are also needed on the voltages impressed on the line by lightning impulses and the number of times these voltages occur. With this information and the charts, we believe it possible to determine with reasonable accuracy the improvement that may be obtained in interruptions per year due to lightning by making any definite change in the number of insulators or others characteristics of circuits.

**L. V. Bewley:** I wish to discuss the characteristics of traveling waves caused by induced strokes. This discussion will be based on the principles established in my paper *Traveling Waves Due to Lightning*, A. I. E. E. Trans., Vol. 48, July 1929, p. 1050. By studying these inherent characteristics we are in a much better position to decide whether the observed traveling waves originated from induced or direct strokes. The shape of a traveling wave due to an induced potential depends upon four factors. First and most important, the law of cloud discharge; second, but not nearly so important, the distribution of bound charge; third, the distortion and attenuation which the wave suffers due to losses as it moves along the line; and fourth, the change in wave shape caused by its behavior at a transition point. The cloud discharge may be divided into two stages. The incipient or preliminary stage, probably lasting for several hundred microseconds, during which time there is undoubtedly an intensification of the field gradient, and a migration of the bound charges held by adjacent cloud fields toward the center of disturbance. Possibly, therefore, the actual field gradient at the instant of rupture is much greater than under static equilibrium conditions. The final stage of cloud discharge probably lasts up to a hundred microseconds. The corresponding distribution of bound charge is therefore also divided into an initial stage corresponding to the static field prior to discharge, and a transient stage caused by the migration of adjacent bound charges towards the center of disturbance. Line distortion is caused by corona, and to a much less extent by skin effect. If you will refer, for instance, to Figs. 5, 6, and 7 of Conwell and Fortescue's paper, you will see that, in the short course of a few miles, there is noticeable distortion in the traveling wave, although such excessive distortion is rather unusual. But the point is, when picture of a traveling wave on a transmission line is taken with a cathode ray oscillograph, it is not known, as a rule, how far it has traveled, and therefore it is impossible to determine whether the wave shape under observation is the same as that at the point of origin. This is very important when drawing conclusions from the wave-front.

The following criteria of induced strokes are of interest:

1. If a wave has not suffered distortion or elongation due to reflection at a transition point, then its length in microseconds is equal to the length of the bound charge in thousands of feet plus the time of cloud discharge in microseconds.

2. The front of the traveling wave is equal to the length of the bound charge, or to the time of cloud discharge, depending upon which is the lesser.

3. The general outline of a traveling wave is established by the law of cloud discharge rather than by the distribution of bound charge and, therefore, a rectangular bound charge may be assumed for estimating purposes.

4. The *rate* of rise of potential under the center of disturbance is practically double that due to the passage of a traveling wave front, although the maximum potential is only a few per cent higher than the crest of the traveling wave. This is an important point because it has a bearing on the arc-over characteristic of the insulator at the point of disturbance.

5. The longer the time of cloud discharge the more depressed the crest. If, for instance, a 1000-ft. bound charge released instantaneously gives a 100 per cent crest, then a 10-microsecond discharge gives only about a 10 per cent crest.

Now consider a few of the oscillograms given in this group of lightning papers, in the light of the above criteria. Take, for instance, the lower right hand surge in Fig. 7 of the paper by Cox and Beck. This surge has approximately a 6-microsecond front and an effective length of around 35 microseconds. If

that wave is just as it was at its origin, and has not suffered distortion as it developed, then it can be accounted for as follows: 5000-ft. bound charge, exponential cloud discharge to practically zero in 30 microseconds, and an initial gradient of 25 kv./ft. The 5000 ft. bound charge probably is exorbitant. It does not seem intuitionally reasonable to talk about bound charges of that extent, but on the other hand there is no definite proof known to the writer that such long charges are impossible. However, it is more probable that this wave which they give has experienced considerable slowing up of its front between the point where it originated and the point where it was measured. On such a basis it could be accounted for by a much shorter bound charge released in about 35 microseconds, but in that case a field gradient of from 50 to 75 kv./ft. would correspond.

The highest record obtained by George and Eaton is shown in their Fig. 9a. That wave could have originated from a 3500-ft. bound charge released in 22 microseconds, and an initial field gradient of 50 kv./ft. Here again, the wave has probably been distorted on its front, and no doubt came from a much shorter bound charge. In the oscillograms obtained by these authors there is a little flat place just back of the crest in all of them. This same characteristic has been found by other investigators. It would be of interest to know whether the authors assign any sound reason for this peculiarity.

McEachron, Hemstreet, and Rudge describe some interesting tests with traveling waves to determine the protective ratio afforded by ground wires. It is rather interesting that the same protective ratio is found with fully developed traveling waves, as by the purely static methods, such as the conventional calculations, tests on model transmission lines, and tests on antennas. Within a short time a paper will be submitted to the Institute in which it will be shown that the protective ratio provided by ideal ground wires is entirely independent of the law of cloud discharge, of the distribution of bound charge, and of the formation of traveling waves; and that the protective ratio found by traveling waves is theoretically identical with that found by Petersen's method or tests on models and antennas. It is worth remarking that ground wires are distinctly beneficial whether the trouble is due to induced or direct strokes, although there is some difference in the most efficient way to employ ground wires, depending upon whether the protection is for induced or direct strokes. As far as the use of ground wires for direct strokes is concerned, good grounds are essential, for, as the pioneer work of Cox, Slepian, Fortescue, and Atherton, of the Westinghouse Company, has shown, the lower the ground resistance the lower the voltages on the ground wires, line wires, and across the insulator strings; and the fewer the number of spans subjected to dangerous voltages.

**H. S. Randall:** The papers covering the intensive Lightning Investigation on Transmission Lines carried on during the last year recall to mind one of the first surge investigations made on an actual transmission line with a surge generator at one end and a Dufour cathode ray oscillograph at the other.

In 1927 the Duquesne Light had a two circuit 22-kv. line approximately 5 miles long and of standard Duquesne Light construction consisting of 37-kv. insulator, 4/0 copper mounted on wooden poles, and crossarms which was temporarily out of service.

Permission was given the Westinghouse Company to install a surge generator at one end and a Dufour cathode ray oscillograph at the other. The set-up was in operation during the summer. It was hoped to obtain a few actual lightning surge records but two things prevented: first, the present method of tripping the cathode-ray oscillograph, getting it onto the firing line at the right time, was not developed, and, second, there was no lightning in this district during the test period.

Up to this time many calculations had been made on the reactions occurring on a transmission line when subjected to surge voltages and laboratory tests had been made on laboratory circuits with lumped constants only. It was hoped to be able to obtain a direct check on the results obtained in the laboratory.

Among the phenomena predicted by these theories which were observed during this pioneer surge test were:

1. Traveling waves move with the velocity of light.
2. Traveling waves on reaching open end of the line reflect back on the line with same polarity.
3. Traveling waves on reaching grounded end of the line reflect back on the line with reverse polarity.
4. The surge impedance for a single conductor is in the order of 400 to 500 ohms.

An attempt was made to determine the effects of lightning arrester, choke coils, capacitors, and resistors, on the surge voltages. A 40-kv. surge was applied to the open line and there were many repeated applications of the surge due to the reflections. With a 3-kv. lightning arrester at the end of the line, the surge was limited to a much lower value and the arrester absorbed sufficient energy so that there were only two impulses.

A choke coil was inserted ahead of a transformer at the end of the line and steep surges applied to the line. The tests showed that although the voltage on the transformer was not reduced, the wave-front was sloped off. No attempts were made to go further with this study but at the present time several thorough studies have been made on the effect of choke coils.

A capacitor was installed at the end of the line and this modified the surge due to the time it took to charge the capacitor. A 40-kv. surge was applied but the voltage across the capacitor rose to only 6.5 kv. with a sloping wave-front. There was a number of reflections as the capacitor does not absorb the energy of the surge.

With a resistance equal to the surge impedance of the line installed at the end of the line there was no reflection or folding back on itself. With the resistance greater than the surge impedance a wave of same polarity was reflected—with a smaller resistance the reflection was of opposite polarity.

The amount of absorption depends on the relation of resistance to surge impedance, there being no absorption when the line is open or grounded through zero resistance.

Compared with the last year's surge investigations the report of this one reads like a school primer, "but we must learn to creep before we walk" and getting started in the right direction has been a big help in arriving at the present point in surge investigations.

**L. A. Terven:** Thanks to the engineering investigations which have been possible through improved equipment for which the manufacturing companies in the United States are so largely responsible, the West Penn Power Company has been able to make several practical applications of the principles of lightning protection to the solution of specific problems. As an example, a case might be mentioned where a short 2300-volt line feeding a manufacturing establishment was subject to numerous induced surges from a 25,000-volt line which paralleled it on the same pole structure for about 670 ft. The 25-kv. line then crossed the river adjacent to the manufacturing plant at a rather high elevation above the ground plane.

From actual klydonograph measurements, the quantitative values of the surge were learned. Additional lightning arresters were then installed and all ground connections were improved. In fact, the ground for the lightning arrester at the consumer's premises was extended into the river bed. An idle line was used as a grounded system of shield wires between the 25-kv. line and the 2300-volt line. The shield wires also extended across the river, which was outside of the parallel, and a branch followed the 2300-volt line for some 200 ft., after the latter had left the exposure. Subsequent investigations showed a marked reduction in the amplitude of the surges experienced and service over this line has been quite satisfactory since the work was done in 1927.

**R. N. Southgate:** It has been very gratifying to view the progress which has been made during the past year in studying the attenuation of real and artificial surges along transmission lines.

Before proceeding with a discussion of attenuation a distinction should be made between attenuation, as a reduction in the magnitude of the surge, and distortion as a change in shape of the surge. Both attenuation and distortion of wave shape are brought about by the same factors: namely, the series resistance of the line and the shunt leakage such as corona or leaky insulation. These factors are perhaps too interlinked to be segregated definitely into two different groups.

Considering first the effect of series resistance, a transmission line having an appreciable resistance to transients may be represented by an ideal transmission line having no resistance divided into segments by small series resistors. A surge on such a line will behave as follows: The wave travels over the first segment of line unaltered until it strikes the first resistor, then a change in surge impedance causes a reduction in the magnitude of the wave passing through the resistor, as a positive reflection will travel in a reverse direction. This process is repeated when the next resistor is reached but the reflection from the next resistor must pass through the first resistor. Thus we can see that an original wave of definite length will be replaced by a composite of backward and forward reflections added to the remaining portion of the original wave. Therefore, in addition to a reduction in magnitude, both the front and tail of the wave will be distorted as the wave is propagated along the line.

The effects of shunt leakage resistance may be treated similarly so as to show the continuous leakage to ground of the surge and the reflections on the original wave. However, when the voltage impressed upon the line is raised to a certain point a much more important factor, called corona, appears for consideration. The formation of corona or breakdown of air takes place when the electrostatic stress about the wire reaches a value at which extensive ionization by collision takes place. The effect is to move the charge to a specific distance out from the wire and concentric with the wire. The formation of this space charge though rapid is not instantaneous so that in a schematic diagram this effect may be drawn as follows: A condenser is connected to each incremental length of line conductor through a sphere-gap and a resistance. When the traveling wave reaches a definite voltage these gaps break down and charge the condenser through the resistance. Initially the current delivered to these condensers will be rather large, then as the condenser comes nearly to the potential of the line the current will diminish and finally at the crest of the wave only the leakage current will flow. As the voltage of the line diminishes, the charge in this condenser will flow back into the conductor when the difference in potential between the condenser and the conductor is sufficiently large to cause the gap to break down, again completing the discharge process. It is noted that the effects of corona are to slope off the front of the wave, reduce the crest of the wave, increase the tail, and lengthen the entire surge.

It is interesting to observe the general agreement in the papers presented with regard to the greater attenuation of positive surges and surges having steep wave-fronts. Also the greater part of the attenuation is charged to corona loss rather than to resistance, which accounts for the fact that it varies greatly with the original voltage and polarity of surge.

At the midsummer convention in Denver in 1928, Mr. W. W. Lewis presented a formula derived by Messrs. Foust and Menger which seems to express fairly satisfactorily the general law of attenuation on a given line. In the light of additional data, it now appeared necessary to modify the factor $k$ or introduce other variables to conform with the condition, size, and spacing of the conductors as well as the nature of the weather and shape of the surge. Any formula that will accurately express attenuation under all conditions promises to be quite a complex function.

However, some of the general laws or characteristics controlling the attenuation of a surge will be useful in determining the protection features that must be incorporated at terminal points. While there is some indication that the attenuation of surges may be materially different under ground wires, it may be possible to apply greater protection to lines near substations so a surge originating at remote points on the system will be attenuated to a harmless quantity by the time it reaches the substation. It therefore becomes necessary to pay particular attention to the origin of surges on the line next to the substation in order to coordinate the apparatus insulation with that of the line. The reverse corollary to this statement is that attenuation makes it possible to over-insulate remote portions of the line which are particularly susceptible to disturbances and decrease the outages per year.

**E. E. George:** It seems that a new field is opened up by equipment to record and measure direct lightning strokes. In the past research has been pretty well confined to induced strokes. Some of the operating and transmission men have had an idea that a good deal of damage on high-voltage systems, particularly the burndowns, was caused from direct strokes.

About a year and a half ago attention was particularly directed to this again in making arc tests, because it was never possible to get any very extensive damage to insulators or conductors for the currents that would be on the system in any reasonable time, that is, the time we used to consider good relaying. There is nothing to indicate that, if the kv-a. could be doubled or trebled, the conductor and insulators would be injured, yet it was known that, in many of the burndowns, although the line apparently relayed instantaneously, the insulators were shattered and the conductor was badly burned.

It is hard to reconcile this with the fact that lightning is supposed to be a matter of microseconds. Currents of the order of a hundred thousand amperes were never mentioned at that time, but it did seem that there must be some enormous melting or mechanical effect there. If the stroke of lightning could tear up an oak tree or set a barn on fire from top to bottom, certainly it ought to do some damage to copper conductors the size of one's little finger.

The evidence of burndowns from this time on was followed very closely and it was never possible to find any case in which the damage was attributed to a power arc. In other words, the burning down of the line seemed to be due to the initial shot of lightning.

One thing to keep in mind in such a system is the relative seriousness of trip outs and burndowns. A line 100 miles long may be out twenty times a year. The total duration of outs will be twenty minutes. Six of those outs may occur in the worst lightning months, say July. This means that for six minutes the customer has been interrupted. If from those twenty outs five per cent of burndowns, say one burndown a year, occur in the country where it is difficult to patrol and repair trouble, the line will be out from two to twenty hours. It may be a radial transmission line, affecting a good many customers. So the prevention of burndowns is of particular interest.

It has been said if a lightning proof line can be made customers will receive perfect service. This statement should be qualified somewhat. A record of all the cases of trouble for the past year discloses that about 55 per cent are due to causes external to the system—wind, weather, natural phenomena, floods, and things of that kind, and in no way associated with the system or its operation. About 45 per cent are due to personnel failures, poor operation, poor design, equipment defects, poor maintenance, etc. Of the 55 per cent due to external causes a reasonable portion is due to lightning. We believe it is a fair statement to say that if lightning could be eliminated entirely the interruptions to customers probably could not be cut by 40 per cent.

In studying lightning one of the things to keep in mind is the limitations of the protective scheme. Phase-to-phase faults are hard to relay. It may not be so always. At the present time, the ground faults can be very well cleared up. If more than one phase is involved, clearing up is a little more difficult. If the fault involves three phases, it is still more serious. For that

reason, some operating men are opposed to horizontal construction, if it means closer spacing between phases and higher insulation to ground.

The only other point in connection with direct strokes is that this device permits measuring strokes on steel towers. Maybe some day somebody can devise equipment to be put on wood poles. (Perhaps such a device ought to be pretty well insured beforehand.) The belief exists that it will be possible to decide soon whether or not wood construction is worth while on high-voltage lines.

**E. J. Wade:** A set of three oscillograms is shown in Fig. 9 of the Conwell and Fortescue paper which show no oscillations. I know from experience that obtaining such oscillograms is difficult where the impulse generator is close to the oscillograph. It is important to be sure that they have thought of all factors in the divider and connections which would make it absolutely certain that these oscillograms represent the actual conditions.

The importance of careful study of the potentiometer schemes which are in use should be emphasized. When a capacity potentiometer is used there is little question but that all the oscillations are reproduced which are important. Possibly additional oscillations are introduced if care is not taken, but when a resistance potentiometer is used, especially if it is of high resistance value, the oscillations are likely to be suppressed and result in error, not only in the calibration but in the time it takes the wave to reach maximum.

The cable resistance type potentiometer used in these tests is very convenient and if one can be sure that it is accurate, it is the proper thing to use. However, the capacities at each end which can be considered as in parallel with the resistances have a considerable effect on the front of the wave. We have been using in the laboratory for several years a resistance potentiometer without the cable in which the capacities are controlled so that it is like a capacity bridge. The capacities are adjusted to have the same ratio as the resistances. In this manner the ratio is controlled to a known value from the resistance measurements. The capacities are then balanced so that it is accurate for all wave-fronts.

The manner in which the capacities are balanced is interesting. Volt ampere curves are taken on a test piece which is known to be of constant resistance and the capacities are adjusted until no loop is obtained between the rising and falling current. A description of this laboratory potentiometer is given in *Electric Light and Power* for May, 1929.

Concerning Messrs. Conwell and Fortescue's paper, I should like to say something about the surge impedance measurement which they made. In speaking particularly of the tower impedance measurements, they apparently have combined what they call the surge impedance of the tower with the resistance of the ground. No attempt is made to separate them. If they are separated we can consider the ground resistance as either constant or falling slightly with increasing currents.

Mr. Beck made some tests in the laboratory, reported in the *Electrical World* in March, 1928. These tests were made on earth in a box, and he found no change due to impulse currents. Other tests were made on driven grounds, some by Towne, noted in the *General Electric Review* of November, 1928, and others which were made last summer in Michigan, indicate a reduction in resistance for high impulse currents. The reduction is not very great. These tests by Messrs. Conwell and Fortescue show an increase in impedance for impulses. Based on the tests just referred to this increase must be ascribed not to the ground resistance, but to the tower itself. It would seem that the impedance of a tower would depend on the design of the tower, contour of the ground around the tower, and the resistivity of the soil and ought to be nearly the same for different towers.

In Table I is shown an increase of from 15 to 55 ohms over the low-voltage resistance. This seems to be quite a wide variation for the different towers. I also wonder whether it is accurate to use the term "surge impedance" to describe these tests, because the height of the tower is very short compared to the length of the wave front, and there is time for a number of reflections while the voltage is rising so that the actual surge impedance of that short section of tower might not have much effect. Perhaps they can explain their tests so that it will clear up this matter.

On the surge impedance of the transmission line, Fig. 10, the two upper points at 200 kv. seem to be the only supporting data which indicate a falling off of impedance for high voltages. It is doubtful whether such data provide sufficient justification for saying that the surge impedance is lower for high voltages due to corona.

In Mr. Torok's paper, Fig. 17, the impulse breakdown at slow impulses, 20 microseconds, does not show a constant impulse ratio. For instance, at a setting of two times the diameter an impulse breakdown 25 per cent higher than the 60-cycle breakdown is found, while at seven times the diameter it is only 5 per cent higher. This is not only contrary to expectation, but the different curves are somewhat erratic. Is this due to an uncertain calibration or is it a characteristic of the sphere-gap?

**W. J. Rudge:** The oscillograms shown in Fig. 1 herewith,

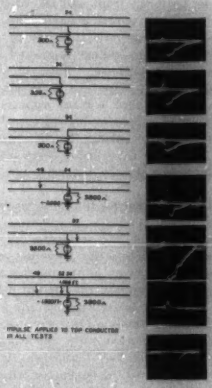



Fig. 1—Measurement of Induced Voltages for Various Conditions of Grounding

were taken to supplement the measurements given in the paper by McEachron, Hemstreet, and Rudge. The oscillograph was located 5.5 miles from the Croton end of the S-19 line and the impulse generator; 30 miles of line extended beyond the point of measurement.

The negative wave shown by the bottom oscillogram, Fig. 1, was applied to the top conductor, the other conductors being insulated except for the measuring devices. Voltage which was induced on the middle conductor by the wave traveling on the top conductor is shown by the top oscillogram. A positive rise in voltage may be noted at the beginning of the wave. On the next oscillogram the line was opened and measurement of induced voltage made on the section near the impulse generator. The wave shape is essentially the same as before. The third oscillogram was taken on the section of line removed from the generator. It is to be noted that the positive rise in voltage is absent.

Comparison of these oscillograms indicates that where one conductor carrying a wave is paralleled by an insulated conductor, upon which an induced wave is traveling, the shape of the wave will be dependent on the position of measurement.

Fig. 2 shows a series of oscillograms which were taken with one

conductor of the line used as a ground wire. Arrows are placed at the position where measurements were made.

The applied waves traveling on the bottom conductor are shown by the upper middle and right oscillograms. Voltage induced on a span of the ground wire by the wave shown on the upper oscillogram is shown by the oscillogram below.

An analysis of these oscillograms shows that a value of resistance which gives a damping decrement corresponding to that of the oscillations found on the middle oscillogram was nearly the same as the resistance obtained by taking the sum of the tower footing resistances at each end of the span on the ground wire.

The frequency of the oscillations checks up with the time which is required for a wave to travel twice the open length.

While these measurements are limited in scope they will serve as a guide to any one making a theoretical study of the ground wire problem.

**O. Ackerman:** Messrs. McEachron, Hemstreet, and Rudge state that "some difficulty has been experienced in measuring the surge impedance of the transmission line conductors."

Similar difficulties have been encountered in the transmission line experiments about which Mr. Conwell has reported. These difficulties are not only of an experimental nature as might be expected from the use of sphere-gaps, but they are rather fundamental.

The surge impedance was measured by surging the line over a resistance $R$ and the voltage was recorded from both ends of this resistance to ground. The voltage drop across the resistance is proportional to the surge current. According to our conventional conception of surge impedance, this is the ratio between

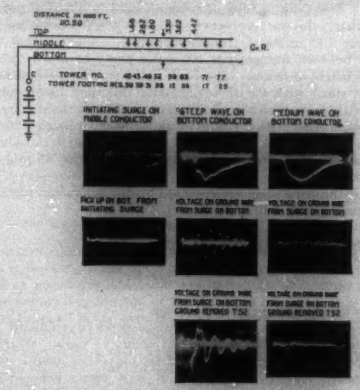



Fig. 2—Measurements on Ground Wire

voltage and current at any point of the surge and this ratio should be constant.

A glance at the oscillogram in Fig. 3 shows that this is not the case. If the ratio were constant, the two curves ought to be similar. Figuring the ratio $E/I$ at various points, it varies from 300 ohms to infinity. We were therefore at first quite at a loss as to how to calculate the surge impedance from such an oscillogram. We owe the solution of the problem to Dr. Slepian.

Obviously, resistance and corona play a big part in the problem. The effect of the line resistance as outlined by Mr. Southgate is nicely illustrated in this oscillogram. Reflected by the line resistance part of the surge current is flowing backward, spreading the wave over a longer stretch than that given by original impulse. Therefore, the current flow through the resistance comes to a stop and may even reverse before the voltage becomes zero.

This is part of the facts which necessitate dropping the simple term "surge impedance" for the term "impedance function" known from the operational calculus. The impedance function for a line with constant $L$, $C$, $r$, and $g$ is given by the term under the radical sign. The sign $p$, can be considered as a parameter although it has a more definite meaning in operational calculus. Here we can take it as standing for the fact that $Z$ is not a constant but depending on some variable $p$.

The impedance function of a transmission line with complicated corona characteristics and skin effect is not necessarily given by the term under the radical sign, but it is always equal

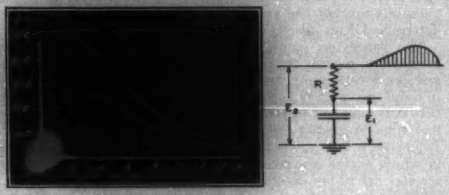



Fig. 3

$$Z_{(p)} = \frac{\int V_{(t)}\, e^{-pt}\, dt}{\int I_{(t)}\, e^{-pt}\, dt} = \sqrt{\frac{L\,p + r}{C\,p + g}}$$

Measuring Impedance Function $Z_{(p)}$ and Surge Impedance of Transmission Line with a Cathode Ray Oscillograph

to this quotient of integrals which has been derived by Dr. Slepian. Leaving aside the exponential term, we obtain the impedance function by dividing $\int V\,dt$ by $\int I\,dt$. Instead of taking $V/I$ at any particular point, we take an average in some way. The method yields satisfactory and consistent results. For large values of $p$, $Z$ approaches $\sqrt{\frac{L}{C}}$. Knowing $\frac{L}{C}$ we can gain information about $r$ and $g$ out of relations such as under the radical sign, and thus will be able to tell more about attenuation and wave distortion not only in an empirical manner but from a more scientific standpoint.

**F. W. Peek, Jr.:** Of importance in these investigations are the results of the work of the investigators with the operating companies cooperating with the General Electric Company. On one line alone, a 220-kv. line of the Pennsylvania Power and Light Company, over 150 cathode ray oscillograms of natural lightning were obtained during the year. Other oscillograms of natural lightning were obtained on other lines, particularly on the lines of the Ohio Power Company. Next to the cathode ray oscillograms, the most important factor that has entered the investigation this year is the direct stroke indicator. Although this work was not started until late in the season a number of records was obtained of direct strokes of lightning on towers. Direct-stroke currents of the order of 175,000 amperes were recorded. These measurements are of extreme importance because a knowledge of actual current values will permit us to calculate the lightning voltages that appear across a tower or between ground wire and earth during a direct stroke. With this information it is possible to determine the tower design and conductor configuration necessary to make a transmission line lightning proof against direct strokes.

Next in importance are the data obtained on ground wires and rods described by Mr. Smeloff. You will remember some years ago we made measurements of the protective ratio of the ground

wire in the laboratory on small models. The protective ratios obtained by this method indicated a greater effect from the ground wire than calculations. It thus appeared that ordinary calculations did not take into account all of the factors. This year these tests were repeated in the field with natural lightning and full size towers. One span or antenna arrangement was erected without a ground wire while an adjacent span was erected with a ground wire. Simultaneous measurements on these two spans or antennas during thunder storms showed a protective ratio of approximately the same value as that obtained on the miniature models in the laboratory. Apparently a factor usually neglected in calculations is the corona which effectively increases the size of the conductor. Gradients as high as 85 kv. per foot were measured by these antennas. This value approaches the gradient of 100 kv. per foot which was determined in an entirely different manner.

The papers on lightning arresters already presented at this convention record two important steps forward in lightning arrester development, first, the size of the new arrester has been so reduced that it is now possible to place it near the apparatus that it is intended to protect; second, it is now possible for the first time to predict the performance of the lightning arrester. Reference is here made particularly to Mr. McEachron's paper in which curves are given from which the performance of the arrester can be pre-determined for any condition.

While progress has been made on transmission lines the improvements have been going forward in the factories in making transformers more highly resistant to lightning transient voltage. Perhaps the outstanding achievement in this direction is the non-resonating transformer. During the year 150 or more natural lightning waves were measured on transmission lines. An examination of the oscillograms shows that the waves vary over a considerable range as would be expected. In most cases they were evidently caused by storms some distance away. In this connection it is important to determine from these measured free traveling waves the character of the voltage during the formation of the wave at the point of origin. This is particularly important because the voltage will always be much higher at that point and arc-over is more likely to occur there. Calculations show that for a range of cloud sizes and rates of discharge to be expected, the voltage at the source or origin reaches maximum in from one-half to one-third of the time indicated by the front of the free traveling wave. The effect at the point of origin would thus be that of a wave about twice the steepness and of a higher voltage value than those measured. A study of the measured waves shows that 50 per cent reach crest voltage in less than 3 microseconds and 90 per cent in less than 8 microseconds or, at the point of origin, 50 per cent of these transients would reach maximum voltage in less than 1½ microseconds and 90 per cent in less than 4 microseconds. Insulator spark-over, if it occurs at all, is likely to occur on the rising front of these waves. The laboratory tests show that the spark-over voltage in 4 microseconds on the uniformly rising wave has an impulse ratio of approximately 1.6, and for spark-over in 1½ microseconds, an impulse of 1.9. Thus, from an examination of these waves one would expect 50 per cent of the insulator arc-overs to have an impulse ratio of 1.9 or greater, and 90 per cent of them to have an impulse of 1.6 or greater. Measurements with the surge voltage recorder during the past few years have given approximately these same results. For this reason also it would seem desirable in making laboratory tests to use a wave giving an impulse ratio of 1.9. It so happens that the standard laboratory waves adopted a number of years before these measurements were made give these results.

A further examination of the oscillograms shows that some of the waves have a front of 10 microseconds or more. The front of a wave is usually shorter than the time that it takes for the cloud to discharge. The induced voltage that can occur on a transmission line depends upon the rapidity of the cloud discharge. For a cloud discharging in 10 microseconds and a cloud 1000 ft. long, the maximum voltage that could occur would probably be in the order of 500 kv. with a front of two or three microseconds. This would not be high enough to cause arc-over on a 110-kv. line. From this it appears that induced voltages high enough to cause arc-over on lines 66 kv. and above must have steep wave fronts and thus high impulse ratio. For lines 66 kv. and below it would appear that induced voltages caused by slow discharging clouds might be sufficient to cause arc-over. Accordingly, the average impulse ratio measured for lower voltage lines would probably be less than for higher voltage lines.

An examination of the waves indicates that voltages sufficiently high to cause arc-over on 220-kv. lines could be induced with clouds of a reasonable size and a reasonable rate of discharge. It also appears, however, that the induced voltage would cause a greater number of outages on the low-voltage lines and as the voltage and thus the insulation is increased, the direct stroke would become more and more important as the cause of outages. Voltages caused by direct strokes would be quite steep and thus have high impulse ratio.

During the past year we have made further mathematical and laboratory studies on the possibility of using ground wires to prevent outages from direct strokes as well as induced voltages. The results are very promising. One important factor brought out is the necessity of very low ground resistance at the tower footings for direct stroke protection.

A statistical study of lightning outages on transmission lines in various parts of the country has been completed. Since different voltages, heights of line and insulation obtain, an attempt was made to reduce the data to a common insulation basis by dividing the number of insulator units in the string by the tower height. Since the number of storms varies in different parts of the country, the outages were reduced to a 100 storms per year basis per 100 miles of transmission line. A curve was then plotted between outages per 100 miles per year and insulators per foot height of tower. The curve indicates that outages would be very small with 0.8 of an insulator unit per foot height of tower without ground wires. With ground wires the outages are of the same order with 0.4 of an insulator per foot height of tower. This means that $0.4 \times 40 = 16$ units for a 40 ft. conductor height should give a very small number of outages, all probably due to direct strokes.

This is the same conclusion reached by our laboratory methods. For example, with a 40 ft. line

$$V = g\,h = 100 \times 40 = 4000 \text{ kv.}$$

With ground wire

$$V = \frac{4000}{2} = 2000 \text{ kv.}$$

which is the maximum induced voltage.

By referring to the lightning spark-over curve (standard ½/5 Pittsfield wave) this corresponds to about 15 units. Thus, 16 units should give negligible outages for induced voltages, which was checked statistically above. It now seems economically feasible to design a line with ground wires so located that direct stroke outages may be greatly reduced or even eliminated.

Mr. Torok has given a very interesting paper on the test results of a certain type of wave. A rectangular wave such as he is attempting to produce, would give results of theoretical interest. It does not appear, however, the wave used really gives this effect or eliminates the variable due to wave-front. In fact, it seems to be a wave with front reaching crest in between 1 and 2 microseconds and decreasing to half value in about 40 microseconds. In making spark-over tests it is desirable to use a wave giving an impulse ratio of about 1.9. Unless this is done, the effects are little different from those caused by the 60-cycle arc-over. The high impulse ratio is a more severe test because it subjects the solid insulation of the insulator to much higher stresses. This follows because of the high arc-over voltage.

It is of interest to find that Mr. Torok now checks the results

which we had obtained on the grading shield. His tests show that for the high impulse ratios the arc-over voltage of the string is materially increased, when the grading ring is used. The tests also show that better results are obtained with the hoop type of ring.

**A. S. Brookes:** In addition to the paper by Messrs. Conwell and Fortescue there are some further points about the surge impedance of grounds which should be considered at this time. Previous investigators have measured the surge impedance of grounds and found that a ground may be considered as pure resistance. One thing they have not considered is that the transmission engineer is not primarily interested in the ground impedance but in the impedance of the ground plus a tower. Consider the action of a tower footing in lowering the voltage of a surge on a ground wire. The tower may be considered as a conductor of appreciable length connecting the footing to the ground wire. When a traveling wave hits the top of the tower, a reduction in voltage takes place and a surge travels down to the ground taking a finite time to reach it. If the footing is of lower surge impedance than the tower, a negative reflection takes place. When this reflected wave strikes the junction, it causes an increase in current and a reduction in voltage. This process of wave reflection continues back and forth until a steady state condition is established some time after the original wave reached the tower.

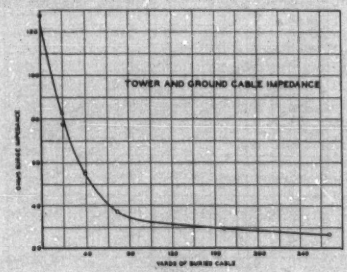



Fig. 4

Tests were made at Stillwater to determine the effective surge impedance of the tower and footing combined. These were made by measuring the reduction in voltage of a surge passing the tower on a conductor of known surge impedance grounded to the tower. Tests were made at different times and as close agreement found as could be expected with the amount of variation present in the moisture content of the soil. The surge impedance seems to be about twice the meggered resistance but the agreement is not close enough to be of much significance.

The method of using a buried footing tie or "counterpoise" is of interest as the action of such a cable is unlike that of a ground concentrated at one point. The cable may be considered for purposes of analysis as connected to the ground through a number of high resistances. When the resistance of such a combination is meggered, a low value is obtained, as might be expected because a steady state condition is reached and all the resistances carry practically equal current. Under surge conditions, a finite time is required for the reflection from each assumed resistance connection to travel back to the top of the tower and it might be expected that only the part of the cable near the tower would be effective, due to the long time required for reaching the steady state condition. This analysis considers the cable only as a path to ground and neglects any "counterpoise" effect. Further tests are really needed to determine if the latter effect is of importance.

Table I in the paper by Messrs. Conwell and Fortescue shows that the cable does reduce the tower surge impedance very greatly. The relatively small effect on tower 41 may be explained by the fact that here the cable ran along the top of rocks for about a hundred feet before entering the ground. Tower 39 showed the impedance with the cable to be about half of that with the cable disconnected. Evidently the cable lying in the earth near the tower footing exerted some effect, even when disconnected, because tower 40 showed an impedance of 115 ohms when the cable was disconnected from the base of the tower and when the entire cable was actually removed from the earth, an impedance of 128 ohms. On this tower the improvement in surge impedance effected by the buried cable was in the order of 6 to 1.

Tests were also run at Stillwater to check the belief that it was only the first part of the cable which was effective. Measurements were made with various lengths of cable and the curve of the surge impedance plotted against length of cable used is shown in Fig. 4. This shows that with surges of the duration used in the tests, the first 80 yards of the cable are by far the most effective portion.

These tests indicate that the use of a cable buried six or eight inches and extending about two hundred feet from a tower footing parallel to the line conductors is a very effective means of improving high resistance grounds, and such a cable is probably cheaper and easier to install than a concentrated ground of equal impedance. Data are insufficient to attempt a complete theoretical analysis of the value of low impedance grounds but a partial analysis and some operating data seem to indicate that a transmission line with low impedance footings does have better ground wire protection and is more free from flashovers.

**A. C. Monteith:** The beneficial effect of ground wires on reducing outages has been demonstrated on a large number of lines throughout the country. There is some discussion as to how this gain is secured.

If it is accepted that all surges on high-voltage lines producing outages are caused by direct strokes, the line construction employed will be different from that used if surges arising from induced strokes are considered of major importance. Data gathered both in this country and in Germany indicate that the effect of direct strokes should be given first consideration in line and tower construction to build a line which will have a minimum of outages due to lightning. This point of view emphasizes the fact that ground wires should be located with respect to the line wires so as to attract and receive the lightning stroke. It further means that the ground wires will be placed above the line conductors and spread out so as to shield the line adequately. This point of view also stresses the importance of securing the lowest tower and footing resistance economically possible.

Two ground wires will usually give good protection for a twin circuit line with vertical configuration or a single circuit line with horizontal configuration provided the above mentioned factors are recognized.

Work of a theoretical nature has been done by Messrs. Fortescue, Atherton, and Cox and presented in their paper entitled *Theoretical and Field Investigations of Lightning* before this society last year. Based on this work and the results of the work done by Professor Matthias in Germany together with data on probability of frequency of lightning occurrence obtained from klydonograph records, curves have been prepared to show the effect of ground wires and tower footing resistance on the probability of outage of a transmission system equipped with various numbers of insulator units assuming that the line is adequately shielded.

In Fig. 5, Curve $A$, the assumption has been made that the maximum voltage in a direct stroke to the ground wire at the tower will be ten million. If the frequency of occurrence of the ten million volt stroke is taken as unity the probabilities are that $N$ squared times as many surges of $1/N$ times this value will be

experienced. Unity may be one or more. Curve *A* intersects the voltage line at ten million with the probability of occurrence as unity. The slope of the curve is such that the probability of a 5-million-volt surge is four times unity and of a one-million-voltage surge 100 times unity.

From Fig. 6 which is Fig. 24 published in the Fortescue, Atherton, and Cox paper, the values of voltages across an insu-

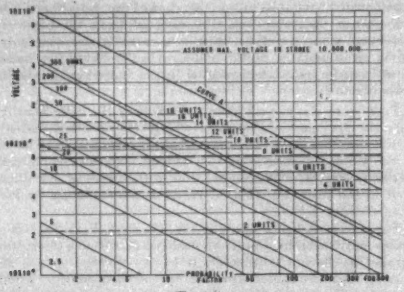



Fig. 5

lator were secured due to a direct stroke on the ground wire at the tower for various values of tower and footing resistance in ohm. The Curve *V* indicates the potential on the ground wires, in terms of ground impedance, for a stroke to the ground wire at the tower and in the mid-span. Those of *V* indicate the potentials on the line wire for the same conditions. Those of $V_2 - V_1$ indicate the potentials across the insulator string also for the same conditions. These curves show that next to placing the ground wires so that they receive the direct hit, the value of tower and ground resistance is the most important factor. The percentage reduction accomplished by ground wires in the case of direct strokes, even with reasonably low ground impe-

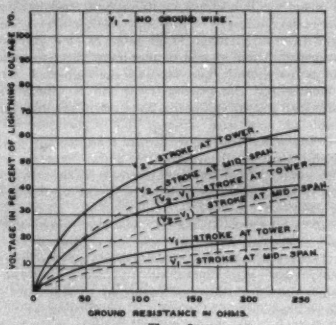



Fig. 6

dance, is very much greater than that in connection with induced strokes.

The family of curves for various values of ground impedance are shown in Fig. 5 and give the relationship existing between crest voltage of the stroke at the tower and the voltage across the insulator string as well as the probability of such voltages occurring. The horizontal lines give the impulse flashover value of the various strings of standard 10-in. insulators at 15 microseconds when subjected to a flat topped wave similar to the Trafford wave.

The curves show that the probability of outage for a line having a 10-insulator string is ten times as great with 200 ohms surge impedance as compared to a line with 25 ohms surge impedance. Also the probability of outage for a line having 6-insulator and 25 ohms surge impedance to ground is 5 times as great as if fourteen units were used. These curves show very strikingly the large gain in utility of insulation made by keeping the tower footing resistance to a minimum. The values of surge impedance referred to are of the tower and footing measured without the interconnecting ground wire in place.

In Fig. 5 the assumption that 10,000,000 volts is the maximum that can be secured from a lightning stroke is open to question as no direct data are available to substantiate this assumption. However, theoretical work together with results, obtained in Germany, of current measurements in a stroke, indicates that this assumption is fairly reasonable. Fig. 7 is identical, in every respect, with Fig. 5 except that the assumption of maximum magnitude of the surge has been increased to 15,000,000.

The data presented in these figures are meant to present the picture of the value of ground wires and low ground impedance

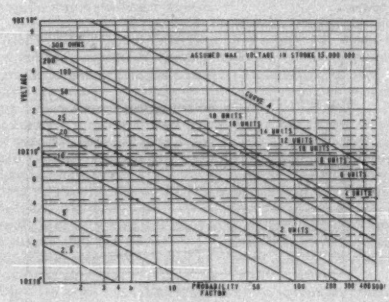



Fig. 7

from a qualitative standpoint rather than from presenting quantitative results of actual data.

With the tests already under way in the field and those contemplated for the next lightning season some very interesting data should be obtained to establish definitely the validity of the theories which have been advanced. The direct proof of the theories will have marked influence on the considerations that should be given weight in laying out the types of tower construction that should be used. If the theory of the direct stroke is further substantiated the curves in Figs. 5 and 7 indicate very strongly that extensive work is yet to be done before the designer can predict with certainty a lightning proof line.

**Edward Beck:** The paper by McEachron, Hemstreet, and Rudge, presents some data on the impulse characteristics of driven grounds, indicating that the apparent resistance of a ground when subjected to impulse voltages is somewhat less than the resistance as measured by the usual means such as by a megger, for instance. The writer has made similar tests on driven grounds and these are in rather good agreement with the results secured by Towne and McEachron, Hemstreet, and Rudge. The writer found in his test that grounds which indicated high resistance when measured by means of instruments showed a much greater reduction in apparent resistance when subjected to surge voltages than grounds which measured low in resistance. The results of these tests have been published in the proceedings

of the Signal Section of the American Railway Association for March 1929.

The investigations of lightning phenomena on transmission lines have increased our knowledge of this subject and have already caused us to change some of our ideas, in some instances quite radically. Although it is not among the most important strides towards the solution of the lightning problem, one of the most radical changes in established practise brought about by the lightning research involves the choke coil. For some time past many people who have studied the choke coil theoretically have held that the type of coil in general use is of no benefit as an aid in lightning protection because it is too small and that if it is made sufficiently large to exert an appreciable influence on a lightning transient it is likely to produce secondary effects which may be harmful to apparatus unless taken care of by auxiliary protective equipment. Although this view was held by many, the lack of complete test data restrained the industry from accepting this opinion and from discarding the choke coil as a protective device because there naturally lurked in the background the thought that the theorists might have overlooked something. The lightning investigations have shed light on the general shape of lightning waves to be expected and on the behavior of choke coils. It quickly developed that the type of choke coil usually applied is in general neither beneficial nor harmful, in other words it is not economically justified. Thus a direct economic benefit to the operator has already resulted

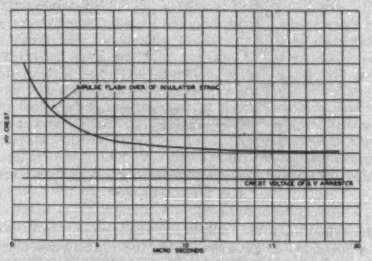



Fig. 8—Comparison of Lightning Arrester Voltage and Impulse Flashover of Insulator String

from the work done by the various investigating groups. In certain specific cases the application of choke coils is sound practise but where they are used they must be designed for the particular installation.

The choke coil situation represents one of the changes in ideas which the lightning research has brought about. With data now available on the performance of insulation and protective devices when subjected to impulse voltages and on the general nature of the lightning transients to be expected it appears to me that the time is ripe to reconsider another phase of the lightning problem. During the past few years much thought has been devoted to the proper coordination of line and apparatus insulation purely as an expedient to safeguard apparatus against damage by lightning. It has been proposed that an insulator string be used as a standard for this coordination and for this proposal there is a sound background. However, the impulse data now before us bring out the shortcomings of the insulator string for this office. The Torok paper presents data on the impulse characteristics of insulators. We see from it that the flashover of a string is not a fixed quantity but that it varies with the nature of the applied impulse (Fig. 8). If we say that the flashover or impulse ratio of a string or a gap is thus and so, we must also specify the wave for which this holds, and this gives us no data on the flashover of the string for another wave unless we have before us the entire impulse flashover curve. Thus we have a standard which is a variable and which, by the nature of its high flashover on steep waves may pass on voltages which can be dangerous to apparatus. Also it is known that other insulation does not necessarily parallel the characteristics of a string preserving the same margin; on the contrary, the characteristics of the various types of insulation that enter into system design and must be considered in the coordination may even cross each other. It would be desirable that the standard chosen have a fixed characteristic independent of the wave shape. The value to which modern valve type lightning arresters will limit lightning voltages is practically a constant quantity for the range of waves that occur. This is known from tests on arresters ranging to the largest yet installed. Moreover arresters will limit the voltages to lower values than the proposed insulator strings. The arrester is the most efficient voltage limiting device that is available and the one that must be considered. With standard voltage class insulation in a station and modern valve arresters of that voltage class properly applied it is immaterial to what degree the lines may be overinsulated, the voltage which reaches the station is limited to a definite value by the arrester.

Hence the writer would propose that in the coordination of insulation serious consideration be given to a standard based on the impulse characteristic which has the advantage of being a constant and of being the base, namely that of a lightning arrester as it is used today.

In the projection of a system one of the first things that is determined is the operating voltage. This fixes the ratings of the arrester to be used which in turn fixes the transient voltages that are permitted at arrester locations. The insulation employed on the system can then be based on this.

It may seem somewhat early to suggest the use of lightning arrester characteristics as basis for the coordination of insulation as there still exists some scepticism of their performance and reliability. However, with actual test data before us it appears to the writer that the characteristics of lightning arresters present features which make them more suited as basis than insulators and I am confident that as the lightning research progresses and data continue to be published, the difference between the two will become universally apparent. Moreover the arrester is proposed merely as a basis for coordination. If insulator string or gaps are preferred as protection in some cases there is no reason why they should not be used. This is a matter of economics. However, I would suggest that they be coordinated with the other insulation through the medium of the arrester characteristic.

**Harald Norinder:** I have read with great interest the paper of J. H. Cox and Edward Beck on the subject of *Cathode Ray Oscillograph Studies on Lightning on Transmission Lines.*

I was particularly interested in seeing whether the records of lightning surges on transmission lines in the United States would show some difference in their general structure from those of surges recorded with similar instruments at the research station of the Royal Board of Water Falls, in Sweden. From theoretical considerations I was unable to discover any reason for a difference in the structure of the surges experienced on transmission lines in Europe and in America. The general physical state of a thunder cloud must be the same in regions not included in the equatorial belt, where the conditions are probably quite peculiar.

However, it does not follow from this that we might be able to use a few records as a basis for a "standard" lightning surge. Physical structures and conditions during thunderstorms are too variable to produce some uniform type of lightning surge.

In Sweden at the research station of the Board of Water Falls during the summer of 1929 two cathode ray oscillographs were connected to transmission lines of either 20 or 80 kv.

A comparison of the records secured at the Upsala station with those presented in the paper by Messrs. Cox and Beck show good

agreement. The general duration of the surges and the time to reach their crest values are of the same order.

The absolute crest values in kilovolts are higher in the case of those described by the Cox and Beck paper than our own. This difference is brought about by the difference in insulation on the respective lines. We have recorded our surges on moderately insulated transmission lines of 20- and 70-kv. systems and all

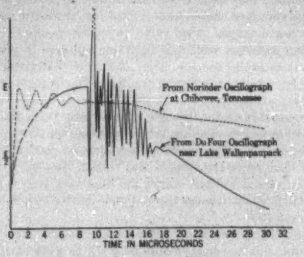



Fig. 9—Lightning Waves

surges with higher amplitudes have been lost because of the flashovers they produced.

Detailed results of our lightning surge records in Sweden during the season of 1929 will be published in the *I. E. E. Journal*, London, 1930, and the *Bulletin de la Société Francaise des Electriciens*.

**C. L. Fortescue:** There are two things we want to avoid in an investigation of this character. First is jumping at conclusions, and second is wishful thinking.

Mr. Peek makes a plea for the short wave, of 20 microseconds on the basis that it is close to the average of the waves observed.

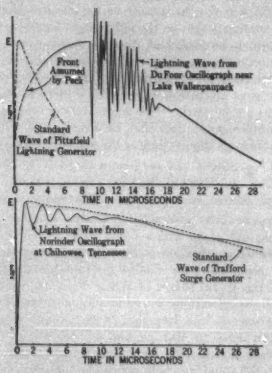



Fig. 10

I might say that if we wanted to design a battleship to withstand gunfire, we wouldn't take the average battery; we would take the largest guns built and would try to design our armor to withstand the impact of those guns. When we are designing transmission lines, what we want to do is to make that transmission line as nearly as possible immune from lightning and therefore we ought to consider the most severe type of wave that is possible due to lightning.

These waves shown in Fig. 9 were taken during the season of 1928. In the first waves the front was indeterminate but you will notice the Tennessee wave here is of considerable length. After 30 microseconds it is only reduced to about 80 per cent of its original value. This other wave, the Wallenpaupack wave, rises to a very high value and then drops off. It is admitted that for that wave there was a flashover of an insulator on an adjoining line. The result of a flashover on an adjoining line is to dissipate part of the surge in this other line. Consequently, the probability is that if it hadn't been for the flashover that wave would have been of about the same character as the Tennessee wave.

Fig. 10 shows the Tennessee wave, the Wallenpaupack wave, the 5 microsecond wave, and the Trafford wave. The wave we are using in our laboratory follows very closely the outline of the Tennessee wave.

Some of the waves we obtained at Stillwater can be seen in Fig. 11. This first wave, obtained on the Wallenpaupack line, went up to an exceedingly high value flashing over the insulator. You will notice there that in spite of that flashover there is so much energy left that the voltage is maintained for a considerable time. This other lower wave you see follows closely the same characteristic, and it is only reduced to 80 per cent of its value. So you can't say that the ordinary lightning wave is a short wave.

I am under the impression from the paper by Mr. Smeloff that a large number of those waves cause flashover some distance

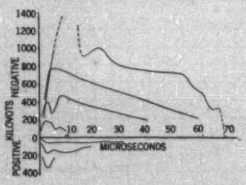



Fig. 11—Typical Lightning Surges Recorded with Cathode Ray Oscillographs

before they reach the cathode ray oscillograph. In such cases they are chopped. You can't define them as an actual lightning wave after they are chopped. What we really want is an actual lightning wave as it appears on the line at the point where it happens without any interference due to flashover of insulators or anything else. That is the reason why we seized the opportunity of doing work on the Stillwater line, which is the highest insulated steel tower line in the United States.

Just a few words about some of the other papers. In Mr. McEachron's paper he mentions the attenuation with ground wires. He says in his conclusions that if that is general, it is an important thing to know that the effect of ground wires is to reduce attenuation, but I don't think that is general. I think that the attenuation will depend a good deal on the surge impedance of the ground.

I drew the conclusion a year or so ago that the effect of the ground wire would be to increase the attenuation. However, the effect of it in the decrease in attenuation, if it is there, is not serious as far as the operation of the line is concerned.

I think the lightning stroke recorder is a good idea. We should use it without jumping to conclusions. I think our friends have jumped to conclusions. I don't think that the method of using it will give the value or even an approximate value of the lightning surge current.

As regards the question of direct stroke versus induced stroke, there is no real controversy there at all, except in this respect, that as far as high-voltage lines are concerned, the group with which I am working has disregarded the induced stroke as a cause of outage, and we are concentrating on trying to find what the

maximum value and wave form of direct stroke is. However, there is some evidence in Messrs. Lewis and Foust's paper which seems to show that a considerable number of the voltages producing outages are due to direct stroke, possibly all of them, I don't know. The fact that the transmission line on the storm side gets more outages I think is very positive evidence that the large number of the outages are due to the direct stroke.

**F. E. Andrews:** I wish to discuss the four papers which had to do with the investigations of actual lightning on transmission lines. The experience which has been obtained on the lines of the Public Service Company of Northern Illinois I believe should add some weight to the information which has already been given in these papers, and in some respects may be considered somewhat more conclusive than some of the data which is given in these papers.

I will refer to three 132-kv. lines originally constructed without ground wires. They are insulated with unshielded strings with a 60-cycle flashover of approximately 570,000 volts r. m. s. These three lines operated for two and three years, depending upon the line concerned, without ground wires, and during that time of operation without ground wires there were 115 outages due to lightning. In other words, with 174 year miles of operation, we had 115 outages, or 66 outages per 100 miles per year. After the installation of the ground wires on these same lines, the record was approximately 1.2 per 100 miles per year; 163 year miles with 2 lightning outages. During the year 1929, for 297 miles of lines operated we had 3 lightning outages, or approximately 1 per 100 miles per year.

The approximate value of lightning surge voltage gradient which we estimate would cause flashover, when the lines were without ground wires, was 20 kv. per foot. That is based on an impulse ratio of 1.8. The estimated voltage which will give flashover with ground wire is about 37 kv. per foot. I therefore believe that we can assume most of the 115 outages due to lightning were caused by lightning surge voltages between approximately 20 and 37 kv. per foot. The performance after the installation of ground wires indicates that the lightning surge voltages exceeding 37 kv. per foot on these lines are of the order of 3 per 100 miles per year.

This brings up the question of the extent to which it pays to go to voltage gradient such as 100 kv. per foot, ordinarily spoken of as the maximum gradient which may be expected. It is a question whether the small number of outages occurring at voltages above the flashover values which I mentioned justifies the expense of insulating, or otherwise designing, to withstand such voltages.

The question of induced strokes versus direct strokes is pertinent. To us it doesn't make very much difference whether the strokes which caused the outages on the line before the ground wires were installed were induced or direct. It appears that voltages were experienced of such a character that they would flashover an insulator string of approximately 570 kv., 60 cycle flashover value. After the ground wire was installed the protective ratio and character of the lightning were such that we did not get flashover except in rare instances. We feel that this experience gives us a reasonably satisfactory basis for the design of our lines.

**H. L. Melvin:** Referring to the section of the paper by Mr. Torok dealing with wood insulation, I am of the opinion that the dashed portions of the time lag curves should show decreasing values to 8 or 10 microseconds similar to those for other types of insulation and even to a greater degree for wet wood. It is also believed that the failure to obtain breakdown with the longer durations might be accounted for by the limitations of the laboratory lightning generator, or with the longer durations, breakdown may have occurred within the wood section rather than along the surface, thus not being observable. However, if a cathode ray oscillograph was used in making the tests, these results are very interesting.

During the past two years several lines, utilizing the impulse insulation of wood in an experimental way to a greater degree than any lines heretofore constructed, have been under special observation and test. Considerable damage has been done to unprotected sections of poles and crossarms, indicating terrific power in the lightning discharges. These flashovers probably occurred on the front of the wave, in many cases at least, as voltages in excess of 200 kv. per foot of length of wood were recorded a number of times by surge voltage recorders. We are also of the opinion that most of them were due to direct strokes and side flashes. These lines, some of which are insulated as high as an estimated equivalent of 25 to 30 suspension units, do not hesitate to flashover and it is common experience to find 40 to 50 ft. of pole flashed, which, based on the test data, would be the equivalent of more like 50 units or about 20 ft. of air. These values interpreted in times of normal crest voltage to ground are, of course, greatly in excess of the commonly discussed values of 10 to 15 times normal. For example, on a 13-mile section of 66-kv. line in Kansas utilizing the impulse insulation strength of 7 ft. of pole, values of the order of 1800 kv. or 35 times normal were recorded four or five times in 1929.

It is hoped that with another year's experience on these lines and others which have been constructed, that enough will have been learned about wood as insulation and its protection to use it intelligently, though it may not be possible to estimate with any degree of accuracy the relative value of such increased impulse insulation as reflected by improvement to service.

In comparing the data given by Mr. Torok with that in the paper by the speaker, which was presented at the Pacific Coast Convention, it will be noted that spark-over voltage values for time lags of between one and two microseconds compare quite closely with the values obtained on a variety of samples of wood under various conditions of moisture and contamination for tail of wave flashover using the so-called Pittsfield 20-microsecond test wave.

Regarding many of the data contained in the other papers, I wish to enter a plea that lightning voltages be expressed in actual kilovolts rather than times normal. It might also be emphasized that unless the recorder was at the point of origin of the surge and unless spark-over did not occur, the reading obtained is not necessarily a record of the maximum voltage appearing on the line for a given lightning discharge. Whenever insulator spark-over does occur the reading is really a measure of the strength of the insulation to lightning voltages. It therefore follows that the curve between frequency of occurrence and magnitude of lightning voltages cannot be plotted with any degree of confidence on account of the limited ranges of insulation and instruments used in recording the voltages.

**H. B. Vincent:** We have been hearing a lot about direct strokes. Mr. Fortescue said there was no controversy. So that there will be no confusion in some of our minds I should suggest that various authors using that word give us a definition.

**H. K. Sels:** In summarizing the results that have been obtained to date at the several field lightning observation stations it might be well to consider the knowledge which is needed to develop the maximum ability of transmission systems to withstand lightning. The three phases of the problem as stated by Messrs. Cox and Beck should be restated to include another important factor, the characteristics of lightning storms. Broadly speaking the three fields which must be covered are:

1. The mechanism of lightning and its influence on a transmission system whether by conduction, induction, or both.
2. The characteristics of the greatest electrical forces which may be imposed on transmission systems and the behavior of such forces on the system.
3. Remedial measures which may be used to protect, relieve, or withstand these forces without interruption to service and damage to the system.

About four years ago there was proposed a research committee between a group of operating companies and manufacturers

similar to that now existing in Germany but unfortunately it was not organized. As a result and with some duplication several independent investigations have been initiated and while considerable knowledge regarding the characteristic wave forms and propagation of lightning surges on a few existing lines has been gained, many of the fundamental ideas are purely speculative and theoretical. Actual knowledge therefore appears limited to a relatively few isolated and specific cases and so it is felt that coordination of the investigations has not been of the best. A certain amount of duplication may be excusable to bring out all the facts.

Up until the past year practically nothing had been done to investigate the mechanism of a cloud discharge except for a few simple mechanical observations with rotating or swinging cameras. Even this simple means shows that a cloud discharge may be composed of several lightning flashes occurring for periods up to 0.6 second or more. During the past year greater activity has been evidenced in studying storm movements and characteristics by a systematic recording of weather data in one local area, installation of electrostatic devices for measuring field intensity, and rate of field change and direct stroke recorders. These investigations show that lightning storms are extremely local, that several individual storms may be in progress over a line at one time and that the present practise of using less than 100 microsecond sweep circuits on oscillographs will register only a small part of the phenomenon. Therefore, a great deal more remains to be done to improve the technique and give a complete record. It has been suggested that more attention be paid to both electrostatic and electromagnetic fields, particularly their directions, intensity, and rates of change correlated with the location of the lightning discharges. What happens below the ground plane should not be neglected. A sufficient number of stations should be used to determine the distribution of these various factors giving a complete picture of the magnitude, rate, and extent of a cloud discharge. Practically nothing is known of the sphere of influence of the main stroke and whether lightning is conducted upon the transmission line by the main or a branch stroke or is induced. At present many favor the conduction theory but the data are not conclusive and the deduction may be wrong when applied to all cases. The mechanism of the lightning getting on the line should be determined, particularly when ground wires are used. In this connection a simple device is needed to record flashovers differentiating if possible between surge and power current as the correlating of flashover, surge voltage, and trip-out records has been very difficult and doubtful.

Next to knowing how the lightning gets on the transmission line comes the measuring of its characteristics. The key of this situation seems to be to locate the field observation station so that the lightning can be measured and observed at the point where it strikes the line. After the surge gets on the line comes the ability of the line to hold and propagate the wave. It has been shown that the behavior of a surge on the system can be studied in the laboratory or the field with artificial surges, particularly after the characteristics of the lightning discharges have been determined. Volumes of surge voltage recorder data have been collected and oscillograph records of waves are becoming common but at present the characteristics of the greatest electrical forces that can be imposed upon the system is not known at its source. This is partly due to the location of the measuring instrument but also to the shortcomings of the potentiometer coupling devices and shielding of recorder leads. Mention is made in the papers of questionable recorder operation due to stray fields, corona, or leakage currents so that some part of the data at the higher voltages may be misleading. It is imperative that improved methods and technique be developed to eliminate existing discrepancies as the most accurate instrument in the world is worthless with an uncontrollable multiplying ratio.

Various remedial measures may be applied to the transmission system to improve its performance. The method of using artificial surges in studying the characteristics of different transmission line and apparatus designs has been successfully demonstrated. On this account there has been considerable agitation for the adoption of standard test surges based on the meager data now available. There is also considerable controversy as to whether system insulation fails on the front or tail of a wave. Whatever assumptions are adopted it should be recognized that they should be used as such for uniformity of tests and they may be changed annually to conform with each year's developments. In the last analysis whatever remedial measures such as ground wires, counterpoises, routing of lines around storm centers or paths, additional insulation, arcing and protective devices, improved grounding, line type arresters, etc., are adopted as the result of field or laboratory tests, the actual performance over a period of years should be carefully recorded and considered the final criterion. What the operating engineer ultimately desires in this problem is sufficient design data so that he can survey the storm and physical characteristics of the territory to be covered and design a system to give a predetermined service in the most economical manner.

In conclusion the authors and companies represented deserve every credit for the initiative and thoroughness in conducting this season's investigation which under the program outlined here may take several more years to complete satisfactorily.

**A. H. Schirmer:** A rapid review of the papers indicates that many of the conclusions of past years will have to be revised in order to bring them in agreement with the more complete data now available.

It may be of interest to outline briefly some of the lightning investigations which have been carried out on telephone lines. In the past, the surge recorders principally used were two-electrode machines with stationary plates and a number of four-electrode machines using a slow moving film. With these recorders we could not be certain after an electrical storm whether the figures were the result of a single stroke of lightning or whether they were the composite effect of several strokes.

In order to overcome these difficulties, a surge recorder was designed early in 1929, which employed a motion picture film which could be made to pass under an electrode at a relatively high speed so that individual figures could be obtained for each lightning flash. In order to permit direct comparison between films from different recorders, all films were started and stopped simultaneously by means of relays operated on a (common) telephone circuit. In order to prevent flashover at the electrode, the dielectric was made considerably wider than the film. The film was driven by 24-volt motor operated by two 12-volt storage batteries.

As originally designed, the film speed was 5 ft. per minute. Later on this speed was reduced to 2 ft. per minute. As the film magazines have a capacity of 200 ft., each surge recorder could be kept in operation for at least an hour and a half.

Six of these new type surge recorders were connected to antennas erected at right angles to a telephone line in Western Maryland. Each antenna was 135 ft. long and approximately 20 ft. above the ground. These antennas were located at intervals of one and a half miles. The purpose of the test was to obtain an indication of the area affected by an individual lightning stroke. The recorders were in service during 14 storms in that location. A number of these storms did not give any figures on the film. The interesting feature, however, is that in no storm did a single stroke of lightning give a figure on more than one surge recorder although several of them showed figures from a single storm.

It is planned to construct several more of these new type surge recorders and to continue the tests on antennas and also to make tests on various types of telephone plant to determine the magnitude and attenuation of lightning surges.

**E. W. Boehne:** (communicated after adjournment) In

several of the papers presented considerable interest was shown in the use of a conductor imbedded in the ground between tower footings. The exact function of such a counterpoise in reducing line flashovers is not known; however, we have two interesting facts on record which, it is believed, will help our understanding of this new protective agent.

We learn from a reliable operating company who preserves an accurate record of their line flashovers, that a section of one of

Fig. 12

their 66-kv. lines which parallels a railroad has had only a very few flashovers in a period of several years, whereas a section of this same transmission line which is not near the railroad suffered many times as much grief in the same period. On measuring the tower footing resistances it was found that the average resistance of the section near the railroad was 4 ohms in contrast with an average resistance of 25 ohms in the section remote from the rails. The line in question was equipped with ground wires.

A similar case is on record in which one of the 220-kv. lines in the East which parallels a large river has never had a flashover.

The action of the steel rails and the river in the above examples is believed to be a counterpoise action. They both reduce the tower footing resistances enabling the ground wires to be closer to ground potential. A second advantage is that they undoubtedly

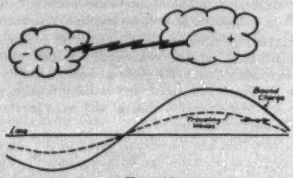



Fig. 13

raise the effective ground plane, increasing the capacity of the conductors to ground.

It is the firm belief of the writer that similar cases are on record which have never been investigated. Additional information would be valuable in building up our knowledge concerning this phenomenon, and the writer wishes to take the initiative in requesting that any data similar to the above mentioned cases if sent to Institute Headquarters will be duly appreciated.

The last lightning season has been particularly fruitful in actual records of lightning surges. On investigating these records one will find many oddly shaped waves, some with reversed polarity, (Figs. 9 and 10 of Mr. Smeloff's paper) others with two unidirectional humps in the same wave.

Fig. 14

Fig. 15

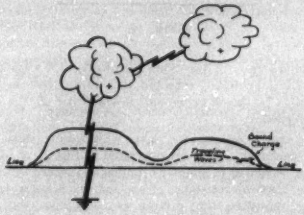



Fig. 16

It is the purpose of this brief discussion to suggest three possible ways to account for these queerly shaped waves.

The first and most probable explanation is that they have their origin, both of magnitude and shape, in the lightning dis-

charge. We have all observed lightning flashes between clouds without observing a simultaneous discharge to ground. Such a discharge, an example of which is shown in Fig. 12, must be due to the presence of both positively and negatively charged clouds in the atmosphere. Consider the case of Fig. 13. Here the presence of the positively and negatively charged clouds produced a bound charge of reversed polarity on the conductor. When the discharge between the clouds takes place a traveling wave of half this magnitude travels in both directions on the line.

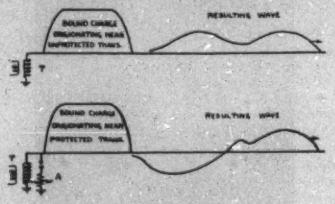



Fig. 17

Figs. 14 and 15 show two pictures of lightning discharges, the latter being taken in Japan. These show that the lightning phenomenon is not always a simple discharge. Consider, however, the simple case of Fig. 16 in which two positively charged clouds discharge either separately or in series to ground.

In a similar fashion the bound charge is released and in this case gives rise to unidirectional waves having two peaks.

In Fig. 17 is shown a single bound charge which originated near a line terminal. Here, on the release of the charge the

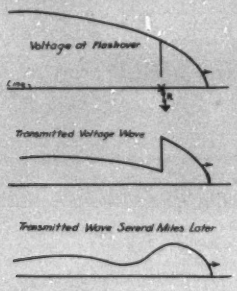



Fig. 18

waves disburse in both directions. However, the wave traveling to the left is immediately reflected, depending upon the terminal impedance. In this way we can account for all the types of waves recorded.

A third way to account for waves with double peaks is by an insulator flashover. It is demonstrated in Fig. 10 of Mr. Smelloff's paper as well as in another example mentioned by Mr. C. L. Fortescue, that the resistance of such an arc is not always zero. Assuming, therefore, that a large wave originates on the line, Fig. 18, and that a flashover occurs having a definite resistance, this resistance to ground will form a transfer impedance allowing a portion of the remainder of the wave to pass the arc. The evolution of such a wave is shown in Fig. 18. These voltages are undoubtedly strengthened by induced waves from traveling waves on conductors which did not discharge.

**J. K. Hodnette:** (communicated after adjournment) The field investigation of lightning reported in the symposium on lightning investigations has shown with engineering precision the shape of surges existing on transmission lines, both with respect to the front or rate of rise and the duration or length of tail, and the magnitudes resulting from natural lightning. This information is invaluable in making laboratory tests, since with it the conditions experienced in service can be simulated in the laboratory and the performance of apparatus determined under practical conditions. This reflects immediately in the tests on transmission line insulation as the line and substation structure are most susceptible to lightning strokes and their insulation is relied upon to limit the surge voltage on the system. By assuming the worst conditions for a particular case as indicated by the field tests, the safe performance of insulation can be predetermined from laboratory tests as Mr. Torok has demonstrated for line insulation using a steep front and long tail surge.

Of no less importance is the effect on the study of substation apparatus and particularly transformers which comprise the most valuable substation apparatus subject to line surges. It is essential here to coordinate and correlate field investigations and laboratory tests on transmission line insulation with the tests on the terminal apparatus, because the surges impinging upon the latter are derived from those existing on the line. An investigation of this nature was made last year and reported in a paper before the Institute under the title *The Effect of Surges on Transformer Windings*. In this paper it was predicted that the maximum voltages expected from lightning were 14 to 15 times normal and of short duration and the longest lightning waves were in the order of or less than 60 microseconds to half value. It is a pleasure to have these statements in my paper confirmed as to the magnitude and duration of lightning surges and that, therefore, the magnitude of the voltages resulting from them within the transformer winding will be of the order previously estimated. This further indicates that modern transformer design can progress along sane and logical lines, in step with our increased knowledge of the stresses to be encountered.

**E. J. Amberg:** One phase which has not been mentioned in either the paper or the discussions is the collection and systematic recording and analysis of statistical data by individual power companies in regard to frequency and general movement of lightning storms and also data in regard to line outages and insulator flashovers due to lightning. As far as the latter are concerned, most companies keep some kind of a record and I am sure that with very little additional work such records could be put in a form in which they will be very valuable later on.

With the progress which has been made in the last two years in lightning investigations, it is quite evident that within a few years concrete recommendations can be made for the construction and operation of lines which will be practically lightning proof.

The important question then will be to what extent can these recommendations be applied economically to new and existing lines, and in order to obtain the greatest benefits for the smallest amount of money it will be necessary to have reliable statistical data as to lightning storms in general and as to performance of existing lines during lightning storms.

As far as new lines are concerned, many of the recommendations for a lightning proof line can be incorporated in the original design at little extra expense; whether such new lines should be made lightning proof for the entire distance will depend entirely on service requirements.

When it comes to improving conditions on existing lines, the problem will be more difficult because the necessary changes will nearly always be expensive. Economic consideration will make it necessary in most cases to confine reconstruction for lightning protection to short sections of the line.

**C. A. Jordan:** The results of the 1929 lightning investigations have materially advanced understanding of lightning surges and wave propagation on aerial transmission circuits.

In fact, it seems apparent that the progress last year in this branch of study, at least, has been greater than in any previous year. Particularly encouraging is the excellent agreement in the findings of different groups of investigators employing artificial surge generators to study the various factors governing the propagation of traveling surges. While the advance in knowledge of lightning itself has been less satisfactory, the new instruments and technique which have been and are being developed offer promise that in relatively few years enough additional information will have been secured from field studies of natural lightning to make lightning control merely an economic problem.

The measurements at Croton Dam, Michigan, indicate that the transient impedance of tower footings may be of the order of 67 per cent of the steady state impedance. At Stillwater, New Jersey, other investigators using a different method found that transient impedance of towers and footings combined exceeded the steady state impedance by 90 to 187 per cent. The presumption is that this difference in results is due, at least in part, to tower impedance. In view of the fact that most power companies are limited to steady state methods in measuring tower footing impedance, and can make no determination of tower impedance, it is important that the relation between transient and steady state values of footing impedance be established clearly.

While on this subject, it may be well to point out that while tower footing impedance undoubtedly has a very important influence on what happens when towers or ground wires intercept a direct stroke, if the dimensions of the intercepting metallic path are great enough to contain one-half the front of the resulting surge, the metallic path will exhibit characteristic surge impedance to the lightning discharge. In this case, the impedance of the nearest grounding point or tower footing will have no effect on the crest value of potential to ground which will occur. Thus, if on a transmission line equipped with ground wires and having an average span length of 1000 ft., lightning struck a ground wire in the middle of a span and the discharge current rose to its maximum value in one microsecond or less, the potential from ground wire to earth at the point of contact of the stroke would become $0.5\ i\ Z_o$ before the effects of low impedance at the neighboring towers could become apparent.

It is hoped that during 1930 it will be possible for the various investigators to gage more closely the lightning discharge currents which may occur and their rates of change with time. I believe these two factors, together with the coupling between ground wires and line conductors (about which the Stillwater and Michigan investigations furnished some information), contain in large measure the key to the question of whether lightning-proof lines are economically feasible.

I have some difficulty in reconciling the theory on the second ground wire effect outlined in the McEachron, Hemstreet, and Rudge paper with the results of the coupling measurements at Stillwater, New Jersey. This theory is based on the assumption that a traveling wave in one wire will induce a traveling wave of opposite polarity in an adjacent wire, whereas the Stillwater measurements show that the original and induced waves have the same polarity. In measuring surge potentials with sphere-gaps as was done in Michigan, it is of course not possible to determine polarity. However, the accuracy of the numerical results should not be affected. If this is the case, the information obtained in Michigan regarding the effects of ground wires on free traveling waves indicates that some of our previous conceptions were incorrect, and offers considerable food for thought in connection with the installation of discontinuous ground wires adjacent to terminal stations.

While progress in the studies of natural lightning has of necessity been slower, the various groups have been fortunate in obtaining a number of oscillograms of lightning surges. Although, due to the limitations of line insulation, it does not seem probable that the extreme lightning potentials can be recorded on transmission lines of existing types, these oscillograms represent an encouraging start in the investigation of surges which may be imposed on terminal apparatus.

However, all the present records are of surges which originated at some distance from the oscillographs. These surges were at lower voltage levels than are known to have appeared on the respective circuits on which the oscillograms were recorded, and undoubtedly in their travel to the recording stations they were considerably modified in shape. There is every reason to believe, from the evidence at present available, that at the point of surge origin the amplitude and steepness may both be much greater than any recorded to date. I wish, therefore, to emphasize the note of caution expressed in the closing paragraphs of the Cox and Beck paper and in the preceding discussions. Present knowledge of possible lightning surge wave-shapes is too limited to make it advisable at this time to standardize wave shape or shapes for testing insulators and apparatus.

**K. B. McEachron:** (communicated after adjournment) The paper by Mr. Torok is, I feel, a very valuable contribution to the subject of flashover of insulation under impulse conditions. In approaching this subject, we have to distinguish between two very different conditions. One is the breakdown of insulation on the front of the wave, and the other is the breakdown on the tail of the wave. This wave tail may be nearly horizontal, or it may be sloping, which will, of course, give rise to somewhat different results.

There can be no question that flashovers in practise do occur on the front of the wave, and therefore it seems to me that it is very desirable that a study of flashover of insulators be made on the front of the wave as well as on the tail. Work of this character was done as early as 1915 by Mr. Peek but should be repeated and extended now that the cathode ray oscillograph is available. Such a study was made for two and three suspension units, and for various ratings of pin type insulators, by Wade and Smith, and reported in the August 18 issue of the *Electrical World* for 1928. These tests should be extended for still higher voltages so that the insulator flashover values on the front of the wave may be well established. In general, the agreement between the Wade and Smith results and those as shown by Torok, is quite satisfactory when it is remembered that one is based on the front of the wave breakdown and the other on the tail of the wave.

On the first page of Mr. Torok's paper, he states that the time lag is measured from the point where the voltage first exceeds the 60-cycle crest breakdown value. I do not agree that this is the proper point for measurement, for if breakdown occurs on the front of the wave a certain amount of confusion is likely to arise. For instance, with a rise of voltage equivalent to the 60-cycle rate of rise, the time lag will be zero, whereas with an infinitely steep wave the time lag will also be zero, which gives an unfortunate relationship and does not express very accurately what is meant by the term "time lag." It seems to me that this confusion can be avoided by not using the word "time lag" at all, but instead refer to "time to breakdown," in which case the time is always measured from the beginning of the wave rather than from some arbitrarily established flashover value. Furthermore, the 60-cycle flashover value of insulation is not a fixed quantity. It depends upon a variety of conditions, such as humidity, etc., whereas the impulse flashover is less dependent upon such factors. The 60-cycle flashover value in the case of insulators which have different shaped terminals such as pin type insulators, depends on polarity which introduces a variation in the basis for determining the beginning of the time measurement if the 60-cycle flashover potential is used.

I would like to propose that a method of referring to waves be established, in which the time to reach crest voltage and the time to reach half value, be stated. For instance, a 5-60 wave would be a wave which rises to its crest value in 5 microseconds, and decays to half value in 60 microseconds—in each case time being measured from the beginning of the wave. If the crest voltage is stated in kilovolts, the wave is pretty well defined by such a characterization. This method, of course, assumed a

straight line rise and a straight line decay when, as a matter of fact, both of these may be exponential or some other form, but at least it gives an average measure of the front and the tail and the crest value, which are the three factors in which we are most interested. Such a designation would avoid much of the confusion which now exists.

It is gratifying to note that the results obtained by Messrs. Conwell and Fortescue check so well with those we have obtained ourselves in Michigan.

In Fig. 5 of their paper, an oscillogram is shown giving the effect on wave form of the travel of an impulse along the line. I should like to ask the authors if they have any explanation for the change of wave shape as the wave passes along the line. One gets the impression from reading the paper that this wave shape change is due to the action of corona.

In Fig. 11 of the paper by Messrs. Smeloff and Price, is shown an oscillogram which was taken at the time the line was not energized, and shows the flashover of an insulator on the front of the wave in about 36 microseconds. Since this is "front of the wave flashover," the flashover potential should not be far from the 60-cycle flashover value based on the cathode ray oscillograph studies of Wade and Smith. In Table II this surge is shown as having a value of 1360 kv. at or near the point of inception. This represents an impulse ratio of about 1.2 above the 60-cycle flashover value of the line insulation. This oscillogram is very interesting as it does give fair agreement with the laboratory results of insulator flashover on the front of the wave.

In the investigation in the paper by Messrs. Sporn and Lloyd among other data, some information was secured concerning the performance of lightning arresters. The current through one leg of the arrester was measured, and also the voltage across the arrester. In the discussion, the following statement appears, "The data in Table IV show that the lightning arrester, in the case of switching surges has discharged a current of 226 amperes per leg at 450 kv. Since it is known that switching surges do not exceed some 550 kv. on these lines, there are no definite data to show that the arrester has held the voltage down appreciably on switching surges." It is interesting to point out in this connection that whenever a lightning arrester draws current from a transmission line, the voltage is necessarily reduced by the action of the surge impedance of the line. It is true that in arrester operation it is necessary frequently to distinguish between breakdown and $I\,R$ drop through the arrester. However, it is worth while to find out what the voltage reduction would be as a result of drawing a current of 226 amperes. The authors have not stated whether these results come from the end of the line or from an arrester located at a junction point on the line. It is therefore necessary to distinguish the two cases.

The first case is for the arrester at the end of the line. The equation for this condition is:

$$2\,E_1 = E_a + Z\,I_a$$

When $E_a$ is the potential across the arrester, $E_1$ is the potential of the traveling wave on the line which is half that at the end of the line with no arrester. $I_a$ is the current through the arrester, while $Z$ is the surge impedance of the transmission line. Using 226 amperes for $I_a$, 500 ohms for $Z$, and 450 kv. for $E_a$, $2\,E_1$ becomes 560 kv. This shows a reduction of 113 kv. as the result of arrester operation.

For the second case in which the arrester is tapped to a transmission line, the equation is:

$$2\,E_1 = 2\,E_a + Z\,I_a$$

Using the same figures as in the previous substitution, we arrive at a value of 506 kv. for the voltage of the traveling wave, which voltage has been reduced to 450 kv. by the operation of the arrester. It is interesting to note that 450 kv., which is the voltage measured across the arrester during the discharge, is slightly less than 2.5 times the arrester rating. Referring to the two papers presented earlier at this convention dealing with lightning arresters entitled *Development of the New Auto-Valve Arrester*, by Messrs. Slepian, Tanberg, and Krause, and *Thyrite—A New Material for Lightning Arresters*, by K. B. McEachron, it will be found that a voltage of 2.5 times normal is a very satisfactory voltage for the arrester to go into operation, and is about as good as can be expected at the present time.

**A. O. Austin:** The fact that lightning strikes near the line without producing a serious disturbance does not necessarily prove that a transmission line will not be subject to flashover due to induced surges. If there is a cloud-to-cloud discharge, the resulting low resistance path may permit a final discharge to ground at relatively low gradients. If this assumption is correct, a lightning discharge could take place near the line without necessarily inducing a high potential on the line. Conversely there are some conditions where the gradient was such that a discharge could be obtained from a metal point held up in the air. On one occasion, the brush over a mountain side has been seen to discharge. Certainly the gradients in these cases were very high and a lightning stroke in the vicinity of the line would produce a high voltage on a transmission line in the field. Apparently there is no question but that a direct stroke is likely to be far more severe than an induced one, particularly where a negative charge is placed on the conductor.

While the general theory of the ground wire in lowering maximum voltage through increase in the effective capacitance of the power conductors has been generally accepted, it would seem that the energy dissipating properties of the ground wire should be given more attention. This is particularly true where it is desired to protect the station equipment and for the application to very long lines where it may be desired to dampen out a disturbance which might otherwise cause an arc to ground over reduced insulation sections. There is probably some ground resistance which will produce the maximum attenuation. In considering the effect of ground resistances, it is essential that the varying height of the conductor be taken into account at the same time. A high ground resistance may not be a disadvantage, but if the effective height of the conductor is increased with the high ground resistance, a higher effective voltage may result. With a high effective ground resistance the potential of the tower may be raised by the charge from the ground wire, causing the ground wire to act as a counter potential wire, thereby permitting the maximum voltage across the insulators.

**J. H. Cox:** The mechanism of the production of surges by lightning on transmission lines, that is whether produced by induction or direct hits, has been mentioned either directly or indirectly in a number of papers at this meeting. I wish to emphasize the importance of this question as it has a vital bearing on the methods used to protect lines against lightning phenomena. In the past the opinion was quite general that practically all troublesome lightning surges were the result of induction and were more or less amenable to protection, and that the few direct strokes which occurred were so severe that they were entirely beyond control. This opinion is still somewhat prevalent. If this is true the natural conclusion is that any protection accomplished is only relative and that the idea of a lightning-proof line is hopeless since we will always have direct hits with us.

I do not wish to be understood as stating this to be an established fact, since the data are far from conclusive and it is possible that this belief may have to be reversed, but a number of factors brought out by both test and analytical work in investigation of lightning phenomena has led the group with which I have been working to believe that there is no sound foundation for the above opinions and that the only lightning surges which are high enough to give trouble on high-voltage lines are caused by direct strokes. Furthermore, we believe that many methods of protection which are or may be employed at the present time are quite effective in keeping all but the most severe direct strokes within a safe value. Fortunately most of the methods used to protect against direct strokes are also effective against induced strokes if such exist.

I will not take up the space to discuss in detail the factors which have led us to the conclusion that all important surges on

high-voltage lines are the result of direct strokes but will merely state the factors as follows: (1) our present knowledge of rate of growth of streamers in relation to the speeds necessary to cause large induced stroke surges; (2) a consideration of the differences between the energies involved in induced and direct strokes; (3) klydonograph data which showed the small number of surges occurring; and (4) observations in field tests where strokes striking the earth very near the line were found to cause no surges. Incidentally Simpson in England and Matthias in Germany working on this phenomenon have independently come to the same conclusions.

Direct stroke surges vary from very weak to the very destructive transients sometimes observed. Therefore, if all important surges are caused by direct hits and since protective measures now being employed protect against the majority of these, protection becomes only a matter of degree and certain measures may need only some modification to make them completely effective. With this conception the problem of a lightning-proof line does not seem hopeless. It should be stated here that actual observations are of great value in the determination of this problem and the operating engineers being in a particularly favorable position to supply this data could contribute materially by reporting such cases as they happen to observe. However, caution should be exercised in reporting observations as it is very easy to draw false conclusions and to appear to see things in lightning phenomena which actually do not happen.

Regarding the wave-fronts as reported in some of the papers, I believe that many of these are misleading as well as some of the conclusions drawn from the data as presented. For instance, several of the papers present tables of wave-fronts varying in time to reach maximum value from as short as zero to one microsecond. It is true these have been indicated as approximate values but I feel that it is misleading to state them at all when they are the result of pure guess work. As a striking example take that in the Sporn and Lloyd paper where the time to 75 per cent is given as 0.2 microsecond and to maximum value as one microsecond. When these values are compared with the oscillograms shown in Fig. 10, which we may assume were the best obtained, it would seem that considerable courage is required to measure times of this order from the blot shown at the beginning of these oscillograms. In this connection the time of wave-front is still considerable of an unknown factor. Complete oscillograms have been obtained and wave-fronts of the order of one microsecond have been obtained; however, it must be admitted that the exact location of these strokes was not known and that it is probable that a surge has not been recorded at the point of inception. It also seems quite probable that wave-fronts of the original surge may be considerably steeper than any of those recorded and the maximum values considerably greater. There is great need for records of surges at the point of inception and on a line of insulation value above the maximum surge voltage.

It should be mentioned here that oscillograms of surges on lines, even though they may be of induced origin, are not measures of cloud field gradients due to the time lag of the stroke and the opportunity for redistribution of the bound charge on the line. This is evident from the great difference in the ease of obtaining oscillograms on antenna and on lines.

Regarding the attenuation of traveling waves on lines we are glad to note that Mr. McEachron's data agree with ours and indicate that attentuation is decreased with a larger number of wires. This also checks theoretical considerations which in this case are based on known factors. It is to be noted that the data given in the Sporn and Lloyd paper indicate the reverse and that attenuation is least rapid on only one conductor. The data in this case were obtained by means of the klydonograph and the curves drawn mean very little as the points given are too scattered. The principal conclusion to be drawn from these latter curves is that the klydonograph is not a sufficiently accurate instrument for this kind of measurement.

In the paper by Messrs. McEachron, Hemstreet, and Rudge data were presented which show that on a particular line equipped with ground wires attenuation was less rapid than on a line without ground wires. In a paper of which I was an author, published in the *Electrical World* about a year ago, from theoretical considerations the opposite conclusion was stated. However the two compensating effects mentioned by Mr. McEachron were pointed out and it is possible that with different configurations the balance might be the reverse from Mr. McEachron's case. In either case the difference is not large and even if it were it is of no great importance in transmission line performance. This is because if a surge is high enough to flash over the line insulation it will do so at the point of origin and after a flashover is produced the only importance of the rate of attenuation is the magnitude of the surge which might be impressed upon terminal apparatus. In this connection it is felt that the last sentence states the important part of Mr. McEachron's conclusion 7, in that the value of additional ground wires near the station is because of the protection they afford against surges originating at that point and I definitely feel that from this standpoint they are more than justified since their cost is low and we are always in danger of a stroke at that point. There can be no question regarding the desirability of continuing the line ground wires into the station structure.

**J. H. Cox and Edward Beck:** Mr. Sels has presented a comprehensive outline of the lightning problem in general, particularly that part still remaining unsolved, and pointed out the breadth of scope of the program necessary. Mr. Roper has mentioned the value of cooperative and coordinative effort so far as it has been accomplished in his particular lightning problem and has indicated that such collective effort is the shortest path to results. On various occasions in the past we have expressed the desirability of a comprehensive cooperative program and we feel that there is still need for such a program and that it would greatly accelerate the final solution of the problem.

Mr. Silver has pointed out that the recorded waves as reported in this symposium were probably all recorded at some distance from their origin and that this voltage is relatively unimportant since if a flashover occurs as a result of a lightning surge it does so at the point of origin where the voltage is obviously the maximum. This point is well taken and for this reason, as well as the determination of the fundamental nature of lightning, it is desirable to obtain records at the origin. However, apart from their importance as causes of line flashover and their indication as to the nature of lightning surges, records obtained at points distant from the origin are valuable because they give data on the voltages to which station apparatus may be subjected.

Mr. Bewley has presented an interesting discussion of the mechanism of cloud discharge which contains theories which may prove useful. However, we believe that further amplification would be desirable since part of his theory is not quite clear to us. For instance, Mr. Bewley states that during the incipient period of the cloud discharge there is a migration of the charge towards the center of disturbance. Mr. Bewley's idea of the incipient period does not seem clear since there can be no migration of distant charges without a change in field to cause such migration. Such change in field would be caused only by the removal of charge from cloud to earth in the lightning stroke and to be appreciable surely must involve a considerable part of the discharge. All of Mr. Bewley's discussion pertains to induced stroke surges and although according to his calculation such surges may reach appreciable proportions we disagree with the conclusions reached. In the near future Mr. Fortescue will present a mathematical analysis of the induced stroke which we believe will be conclusive proof that high induced voltages are improbable.

In connection with Mr. Peek's comments, tests on models in the laboratory indicate only approximately the protective ratio of ground wires since the difference in size of certain elements cannot be corrected for. Also, potentials measured on

antennas in the field are not indicative of the surges which would be induced on transmission lines unless such antennas are connected to ground at their terminals with resistances equal to the antenna surge impedance.

I cannot agree with Mr. Peek's statement that if the insulator flashes over at all it is likely to occur on the front of the wave, since from the point of view of line flashover the minimum wave which just flashes over the insulator is the most important and for such waves the flashover undoubtedly occurs on the tail of the wave. Furthermore, Mr. Peek still mentions impulse ratios for lightning waves of 1.6 to 1.9 and again, except for the magnitude of the chopped wave which enters the station, the important waves are those which just flash over and, as shown conclusively in Mr. Torok's paper, such waves have an impulse ratio of the order of 1.2.

Mr. Boehne discusses the nature of surges induced by cloud to cloud discharges. In this connection the operators of the lightning laboratories in the field have frequently observed intense cloud to cloud lightning activity immediately above the station, both parallel to the line and at right angles to the line, but have never recorded an overvoltage as a result of such activity.

**J. J. Torok:** Mr. Wade has questioned the results shown in Fig. 17 of my paper. The apparatus used in making this test was the same as that in all the other impulse tests and a very careful calibration was made of all parts. It is believed that this calibration is quite accurate and therefore that the curves show the actual characteristics of the sphere-gaps tested. I do not see that these curves are contrary to expectation since it is known that the characteristics of sphere-gaps change between close spacings at which they are ordinarily used and long spacings of several times their diameter such as used for the upper curves.

Mr. Peek has criticized the wave used in the tests presented in my paper. This wave was as nearly flat-topped as it was possible to obtain with laboratory equipment and without oscillations. It is felt that the deviation from a true rectangular wave is not sufficient to modify the results materially except at the short time lags and these are of the least importance in connection with their application. Mr. Peek states that the wave used should give an impulse ratio of 1.9 but gives no reason and I see none. He also states that the results of a flat-topped wave are little different from those caused by a 60-cycle arc-over. It is quite obvious from the curves presented that this is not the case and that any desired impulse ratio can be obtained by varying the magnitude of the impressed wave. Regarding the results obtained with arcing rings, the tests do not show that the hoop type of ring is necessarily better but that it is sufficiently adequate for the usual line and that the larger, and better, ring, is not economically justified.

In connection with Mr. Melvin's comments, all measurements made in this work were taken with the cathode-ray oscillograph. I do not believe that the shape of the curves for wood insulation were the result of lightning generator limitations as this was not indicated by the oscillograms.

Mr. McEachron comments that tests with the flat-topped wave which give only flashovers on the tail of the wave are incomplete, and that tests giving flashovers on the front of the wave are needed. Such tests would require a definition of the wave and introduce again the third variable and since undoubtedly the flashover involves energy it is believed that flashover on the front of a sloping wave can be readily predicted from curves obtained with the flat-topped wave.

Mr. McEachron also comments on the limitation of these curves when carried to the 60-cycle crest breakdown value and states that the time lag at 60 cycles would be zero. This does not seem correct since the length of the 60-cycle wave is several thousand microseconds and the time during which the voltage slightly exceeds the steady state breakdown is probably over 100 microseconds. Also, I do not feel that the variability of the 60-cycle breakdown is very appreciable since the amount of this variation is not large when considered in connection with the accuracy possible in impulse tests.

**C. L. Fortescue:** Mr. Rudge questioned the appropriateness of the term "surge impedance" as applied to tower and tower footing resistance, in the paper entitled *The Lightning Laboratory at Stillwater, New Jersey*. In investigations of this character we must consider in what form the results will be most useful. It will be obvious that the actual wave propagation through the tower into the earth is quite a complex phenomenon, involving reflections at the tower footing and change of impedance in the tower from its top to tower footing. Formulas taking all these factors into account will be of very little use in estimating the protective value of ground wires against lightning strokes. The obvious solution therefore will be to obtain an equivalent surge impedance which will apply to the most extreme case, that is to say, to waves having very steep front and long duration. The tests were made with a great deal of care, a resistance type potentiometer which has been verified very carefully in our laboratory, and the steepest wave-fronts and the longest wave which it was possible to obtain by the surge generator available being used. The results, we believe, will be fairly indicative of what may be expected in the case of a lightning stroke.

I should like to state that throughout these tests we exercised the utmost care to verify our results and we found at first that test results using the ordinary type of capacitive potentiometer were inconsistent. We at once changed to the resistance type of potentiometer which, on account of the fact that this line was not energized, could be used. The results then obtained checked up with repeated measurements and were always consistent.

It is pleasing to note that the data obtained by us on attenuation check up very well with those obtained by Mr. McEachron, by entirely different methods.

Referring to Mr. Amberg's remarks on the economics of this situation I wish to assure him that throughout these investigations we have kept our feet on the ground and have not lost sight of the economic significance of the various protective factors we have discussed. Elsewhere in the discussion it is pointed out that a buried counterpoise is only effective for a short percentage of its length. This suggests at once that it may be more effective to run out radial feeders from the tower than to use a long counterpoise extending from tower to tower. Naturally, when driven grounds are effective they are preferable to buried cable or counterpoise and should be used but where it is impossible to drive a ground or where they are not effective I feel sure that some form of artificial ground such as buried cables extending radially from the tower may be made very effective and will prove economical.

Considering now the practical results that will be derived from these lightning investigations I wish to point out that all the measures proposed might be classified as defensive measures. We have three lines of defense. The first line of defense is the proper design and construction of transmission lines which includes such measures as liberal spacing between conductors, ground wires so placed that they will dissipate any stroke of lightning and prevent it from reaching the line wires, adequate spacing between the ground wires and conductors so that whatever surge potential is produced on these ground wires as a result of the lightning stroke the spacing will be sufficient to prevent the stroke from extending down to the line wires, effective grounding of the tower footings so that the full value of the ground wires as a protection against strokes will be realized. By these means properly applied it is hoped that we will be able to obtain transmission lines practically immune to lightning; however, in case an exceptionally severe stroke should cause an outage we still have a second line of defense to fall back on.

Other devices which have been considered are the spacing of lightning arresters at short intervals along the line and the placing of spillover gaps with fuses to interrupt the dynamic

arc at frequent intervals along the line. Where flashover takes place on an insulator string not provided with any device to blow out the arc, quick-acting circuit breakers will prevent the outage from resulting in any instability provided the system is properly designed with respect to stability so that the quick-acting circuit breaker may be considered as one of the second lines of defense. If in addition to this we have combined with this quick-acting circuit breaker a quick-acting automatic reclosing device, we shall have gone a long way towards designing a model system.

This second line of defense will consist of such measures as the use of properly designed arcing rings which will prevent flashover, if it takes place, from cascading over the string and fracturing the insulators or puncturing them. Thus even though a flashover should take place the insulator string is still in perfect condition to perform its proper function. In addition we may have other means combined with the arcing ring such as that discussed by one of the previous speakers which, by means of a fuse or other device, will prevent the continuation of the dynamic follow-up arc and thus the line will flash over and come back into service without an outage.

This third line of defense consists in careful design of the system taking all conditions of stability into account. In other words, it is included under the heading of system designing which has been discussed in a previous session. The factors which determine the stability of a transmission system have been pretty well established so that there is little difficulty in determining whether a system will stay in operation after a fault has occurred and has been cleared. The high-speed breaker has been a tremendous step in advance in facilitating the design of system which will be stable under fault conditions. Furthermore, it permits the use of higher levels on existing systems and enables the designer to make use of means of obtaining economical power transmission over long distances, such as the Baum system. The Baum system heretofore has suffered from the fact that with the slow speed breakers in vogue before the advent of the high-speed breakers, the synchronous condensers required to maintain stability under transient conditions were large and costly. The high-speed breaker enables us to use standard designs of condensers which will hold up the voltage under the transient conditions until the circuit is cleared. The combined result obtained by the use of high-speed breakers and the Baum system will permit an economic transmission of power over long distances so that the power may be generated at the points where coal can be obtained cheaply, with the minimum of handling and where there is adequate condensing water, and transmitted to the load centers for distribution. Obviously if we can insure against interruption of service due to lightning we can operate all transmission lines at a much higher power level thus effecting a great economy.

I wish to say that it has been very gratifying to me to see how all the various bodies working on this investigation are gradually approaching each other in their conclusions and it is hoped that this season will see a still closer agreement.

**R. H. George:** In Mr. Bewley's discussion of our paper, attention was called to the flat place in the waves just beyond the crest, and the question was asked as to whether we could assign any reason for it.

Although this peculiarity of wave shape has received much consideration, no sound reason has been found for its occurence. Checks on the potentiometer and cathode ray oscillograph made by means of the surge generator, described in the paper by Messrs. Hemstreet, McEachron, and Rudge, showed the recording apparatus to be free from distortion. Also the fact that waves coming into the oscillograph station from either the north or the south possessed the same flat characteristic would indicate, since no terminal apparatus was located at Croton, that the wave shape was not due to the contour of the land which the line traversed.

It is very interesting and important that Mr. Bewley's theory of traveling waves apparently offers an explanation for the wave shape of natural lightning surges.

The tests reported in Mr. Schirmer's discussion show that the telephone companies are in a position to obtain very valuable information relative to areas affected by lightning strokes and should be encouraged to make as extensive an investigation as possible.

Mr. Schirmer's results with recorders located one and one-half miles apart, check results obtained at Purdue University last summer. These results indicate that a single stroke does not usually affect a very large area. While taking cathode ray oscillograms of lightning surges on a 140-ft. antenna, a record was kept of the time which elapsed between the lightning flashes and the resultant thunder, where possible, and these data correlated with the surges on the antenna.

Although the results were subject to considerable error they indicated that strokes occurring more than one-half-mile away rarely produced appeciable surges on the antenna.

The lightning investigation will be continued at Croton, Michigan during the 1930 season, with the aid of improved apparatus, and it is hoped that surges may be recorded which have their origin in the immediate vicinity of the oscillograph station. Until a number of such surges has been recorded the data must be considered incomplete.

**K. B. McEachron:** I agree with Mr. Silver that it is very desirable to be able to reconstruct the original impulse at the point of inception from the oscillogram taken at some other point. To acquire the ability to do this is one of the objects of the study which we have conducted with artificial transients on transmission lines.

The picture which Mr. Southgate gives of the action of corona in changing wave shape, in which he suggests an equivalent circuit consisting of a gap with series resistance and capacitor would, it seems to me, be more accurate if the condenser was also shunted by a resistor of proper value. It does not seem likely that much energy is returned to the conductor from the corona formed around it when the voltage begins to decrease; however, it may later be shown that the amount of energy returned to the conductor is greater than now appears possible. I do not believe that very much is known about the formation and disappearance of corona under the transient conditions encountered during the travel of short time impulses along transmission lines. It would be very helpful indeed to have this information and it is to be hoped that the investigations now in progress will give some clew to the laws of corona formation and disappearance under transient conditions.

The results of tests to be presented at the Summer Convention, relating to further studies in Michigan, indicate that there is little measurable change in the form of traveling waves if the potential is kept below the corona voltage. This seems to indicate that the effects which Mr. Ackerman describes as changing surge impedance are dependent, to a considerable degree at least, on the effects of corona. If and when the effect of corona at different voltages on the surge impedance is evaluated by actual test, it will become possible to take these factors into account when making calculations relating to the travel of waves on lines. Tests involving the measurement of current and voltage need to be carefully made not to invalidate the relatively small differences which may result due to corona. Much more evidence under a variety of conditions must be obtained before any conclusion with regard to values of surge impedance can be stated with assurance.

Mr. Fortescue suggests that the resistance of grounds may have considerable effect on the attenuation of surges on conductors protected by ground wires. In this connection it is important to know if the effect of the ground wire on attenuation, found in Michigan, may be applied generally. The effect of the ground wire should be determined both for the case of high resistance

grounds and low resistance grounds, so that the effect of the ground wire on the attenuation of surges becomes known for all conditions.

It would seem from Mr. Andrews' experience that quite a high percentage of the outages on the circuits described by him were caused by induced discharges, since the ground wire appeared to reduce very greatly the number of outages. This possible conclusion is based on the proposition that the ground wire as usually installed is in the most efficient location for induced discharges, but is not, in general, in the best location for direct strokes and I assume that the ground wire installation referred to by Mr. Andrews is in the usual location.

Mr. Jordan refers to the fact that if direct strokes occur in mid span that low tower footing resistance will be of little avail if the length of wave front is less than the span length. This again emphasizes the idea that some form of protection other than the usual ground wire is required for protection against direct strokes in mid span. If flashover does not occur in mid span so that power current follows, low tower footing resistance will be helpful in preventing a flashover of the insulator string at the tower.

**A. L. Price and E. Bell:** Considerable discussion has taken place as to whether induced or direct strokes are responsible for the greater number of service interruptions. We wish to emphasize one bit of information included in the paper by Smeloff and Price relative to this subject, namely the fact that during the 1929 lightning season 24 cloud-to-ground strokes were observed within a one mile radius of the Wallenpaupack Lightning Laboratory.

Mr. Peek has given the dimension of the protected area of a lightning rod as a radius equal to four times the height of the rod. Considering the transmission line conductors as protecting an area of four times their height on either side of the line gives an area protected by the 65 miles of line of about 5.7 square miles. On the basis of 24 strokes per 3.14 square miles and assuming equal storm conditions throughout, we should expect about 43 direct strokes to the Wallenpaupack Tap-Siegfried Roseland Line during the course of the 1929 season. Actually 37 trip-outs occurred during the period when lightning stroke observations were being made. These data would indicate that there is a reasonable expectation of a sufficient number of direct strokes to account for all circuit interruptions.

Fig. 18 (profile of flashed insulators per mile on the Wallenpaupack Tap-Siegfried Roseland Line over a period of years) shows that considerable benefit would accrue if some practical means could be found of measuring storm intensities over proposed transmission line rights of way and thus avoid routing lines through localities where storms are particularly numerous and severe.

While there is considerable evidence that direct strokes are the major cause of line trip-outs on high-voltage lines, induced strokes also cause numerous and often high voltages. During 1929 some surge voltage recorder measurements were made on a wood pole line, and on a telephone line beneath, both lines being supported by the same poles. Voltages exceeding 330 kv. were recorded on the telephone line on several occasions. Of particular interest, however, was the large number of small surges recorded during lightning storms. The telephone line appeared to act as a very long antenna, despite the fact that it was grounded at either end through drainage coils. None of the surges did any damage and their only apparent effect was to make the line noisy.

The average conductor height was 20 ft., hence the voltage gradients measured ranged from zero to about 17.5 kv. per foot maximum. It is therefore apparent that induced strokes do cause very appreciable voltages on aerial conductors, and that on low-voltage lines which are not highly insulated, both direct and induced strokes should share the onus of being responsible for line flashovers and trip-outs.

**Philip Sporn:** Referring to the question of continuity of service and its relation to the solution of the lightning problem, Mr. George has stated that on a system that he is familiar with 55 per cent of the trouble is due to causes external to the system, such as wind, weather, and other phenomena. On the 132-kv. system of the American Gas & Electric Company subsidiaries the record over four years has indicated that 75 per cent of the outages have been due to lightning. In general where the construction of the line is of a high order, and the line is located in a territory where lightning is prevalent, I believe that a far greater percentage of outages is due to lightning than has been indicated on the system quoted by Mr. George.

Regarding the comments of Mr. Andrews and his experience with some 132-kv. lines before and after ground wires, the reduction in outages obtained on these lines after the installation of ground wire would lead one to conclude, first, that the lines were rather low lines, and that the ground resistance must have been unusually low,—in other words, that the ground wire must have been particularly effective; and second that the intensity of the lightning in that territory is not particularly heavy. On the system with which I am connected our experience before and after the installation of ground wires showed a marked reduction in the number of outages after the ground wire was installed, but the reduction was not nearly as great as indicated by Mr. Andrews. Also from analyses made regarding the relative number of outages of top, middle, and bottom wires we came to the conclusion that voltage gradients as high as 50 to 60 kv. per foot were quite common.

The point discussed by Messrs. Cox and Fortescue with regard to the relative importance of induced and direct lightning strokes on the higher voltage lines is one still open to a wide difference of opinion. There are definite data available to show that both direct and induced strokes are important and one cannot be neglected in favor of the other. I am confident that on this matter a final conclusion can be drawn only after more data are obtained.

Mr. Cox's point with regard to wave-fronts shown in our paper is of course slightly exaggerated in that the data with regard to wave-front steepness are not guesswork but are based on laboratory test of the time taken for the initiating gaps to function and put the oscillograph in operation. While there may be some error in the estimated time of the wave-fronts as given, it is believed that it was better to give approximate values rather than to give nothing at all. The weakness encountered in measuring this portion of the wave has been fully realized and it is expected that in the set-ups used in the coming year's investigation the initiating gap will be speeded up sufficiently to determine more completely the front of the wave.

# A Self-Compensating Temperature Indicator

BY I. F. KINNARD[1] and H. T. FAUS[1]

Member, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—The following paper describes a unique adaptation of the temperature sensitive magnetic alloys known as "calmaloy" to the cold junction compensation of thermocouple temperature indicators. It has been known for some time that certain specially prepared copper-nickel alloys possess the property of changing permeability linearly with temperature over very wide ranges. This peculiar function of permeability has been advantageously used for effecting temperature compensation on different devices, particularly watthour meters. The need has recently arisen of providing suitable compensation for millivolt meters used in connection with thermocouples for determining the temperatures of air cooled aircraft motors. It is shown that by employing the restoring torque on the instrument produced by a small vane of calmaloy in addition to the usual restoring torque of the spring, a very satisfactory compensation results. Curves are shown which illustrate the accuracy of compensation obtained and a detailed explanation of just how it is accomplished is also given.*

* * * * *

THE development of air-cooled airplane motors, in which the operative temperatures are rather high as compared with those of water-cooled motors, has made it expedient to find means of measuring these temperatures. For laboratory measurements where the weight and cost of apparatus are not important, and where high accuracy is desirable, the type of pyrometer utilizing a thermocouple and a potentiometer has proved very useful. For permanent installation on an airplane where a direct reading instrument of fairly small size is required, it has been the practise to use a millivoltmeter with an iron-constantan thermocouple, the cold junction being made at the instrument. A mercury thermometer is used to indicate the cold junction temperature. This method has the very serious disadvantage of requiring calculation to determine the temperature of the hot junction.

Various methods of cold junction compensation are successfully used on thermocouple type pyrometers now on the market. In general, they may be divided into two types, electrical and mechanical. The former type uses an e. m. f. derived from a battery and an adjustable portion of this e. m. f. is added to the thermocouple e. m. f. to correct for the change due to the difference between the actual cold junction temperature and that for which the instrument was calibrated. The latter type uses a bi-metallic spring which, for a given change in temperature, will move the pointer by an amount sufficient to compensate for the error caused by the change in cold junction temperature.

The battery method is not considered suitable for aircraft use on account of the weight, and because of the effect of very low temperature on the e. m. f. of the battery. Since the instrument should have a scale range from 100 to 650 deg. fahr., and should give reasonably accurate readings at any cold junction temperature from + 105 to − 40 deg. fahr., it was believed that it would not be practicable to use a bi-metallic spring capable of supplying a correction equal to 27 per cent of the full scale reading of the instrument. This problem is made much more difficult by the small size of the instrument required.

In a previous article, mention was made of a series of temperature sensitive magnetic alloys.[2] These alloys have been manufactured for some years under careful control for use in meters and instruments. Some

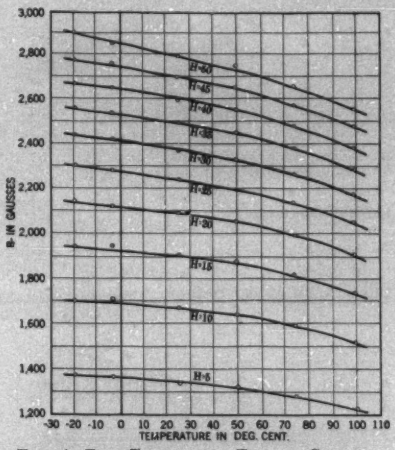



FIG. 1—FLUX TEMPERATURE TESTS ON CALMALOY

Composition: Cu 9.5 per cent, Ni. 88 per cent, Fe. 2.2 per cent
Heat Treatment: Quenched in water

hitherto unpublished data on these materials are shown in Figs. 1, 2, and 3. Figs. 1 and 2 show that the permeability and point of magnetic transformation are increased with decreasing copper content and that this

1. General Electric Company, West Lynn, Mass.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

2. *Temperature Errors in Induction Watthour Meters*, A. I. E. E. TRANS., Vol. XLIV, 1925, p. 275. In this paper, the name "thermalloy" was applied to these alloys, but it was subsequently learned that this name had previously been applied to a heat resisting alloy. Hence, the name of this series of temperature sensitive magnetic alloys has been changed to "calmaloy," which is derived from caloric magnetic alloy.

change is accompanied by a decrease in the slopes of the temperature-flux curves. Fig. 3 shows that quenching gives a lower permeability than is obtained when the material is cooled slowly, but that the hysteresis is much less in the quenched material. Since low hysteresis is essential in these materials, the quenching treatment is used. The success which has attended their use in correcting other types of temperature errors

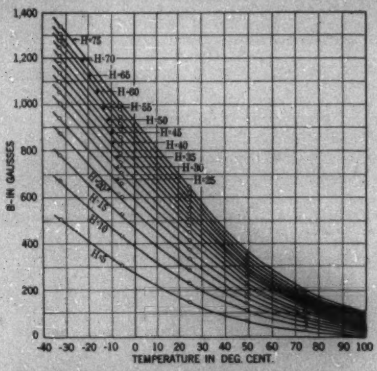



FIG. 2—FLUX TEMPERATURE TESTS ON CALMALOY

Composition: Cu. 30 per cent. Ni. 66.5 per cent, Fe. 2.2 per cent
Heat Treatment: Quenched in water

led to a consideration of the possibility of using them in correcting for cold junction error.

The first method attempted was the use of a calmaloy shunt in parallel with the air-gap of the instrument. By this method, it was possible to obtain correct com-

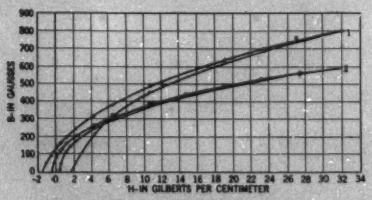



FIG. 3—HYSTERESIS TESTS ON CALMALOY

Composition Cu. 30 per cent, Ni. 66.5 per cent, Fe. 2.2% per cent
1. Cooled slowly in furnace
2. Quenched in water

pensation at only one point on the instrument scale since the correction supplied by the shunt was proportional to the scale reading, while the cold junction error was the same at all points in the scale. Fig. 4 illustrates the results which would be obtained if an instrument were correctly compensated for cold junction temperature variation at 70 per cent of full scale reading. It is evident that this method of compensation is suitable only for purposes requiring accuracy over a very narrow hot junction temperature range.

Since it is necessary to measure the temperature of the cylinder wall which should not exceed 310 deg. fahr. and the temperature of the cylinder head, which may be as high as 600 deg. fahr., and it is also desirable to use one instrument with two thermocouples and a selector switch for taking both measurements, it is evident that the type of compensation just described is not suitable for use in measuring engine temperatures. What is required is a compensation that will be effective over the entire range of the scale.

The required type of compensation was obtained by mounting a calmaloy vane on the instrument armature in such a relation to an auxiliary pole piece that the magnetic attraction between the vane and the pole piece produces a torque tending to move the instrument pointer toward the lower end of the scale. When the temperature of the instrument is lowered, the per-

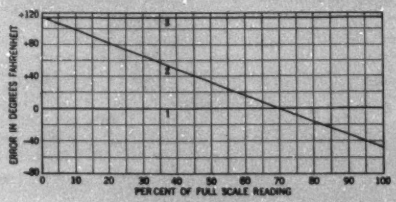



FIG. 4—COLD JUNCTION COMPENSATION OBTAINED BY USE OF A CALMALOY SHUNT

1. Calibration at 75 deg. fahr.
2. Calibration of compensated instrument at − 40 deg. fahr.
3. Calibration of uncompensated instrument at − 40 deg. fahr.

meability of the calmaloy vane is increased, thus causing it to exert a stronger torque; this balances the increase in torque due to the increase in millivolts due to the lowering of the cold junction temperature. Since both effects have a linear variation with temperature, a good compensation may be obtained over a wide range of cold junction temperatures.

It is the usual practise to connect a sufficient amount of manganin or other resistance wire having a low temperature coefficient in series with the armature of a millivoltmeter to minimize resistance changes due to changes in the temperature of the copper windings. It is evident that this is not a very desirable method to use in a case where only a very small amount of electrical energy is available for the operation of the instrument, since the sensitivity is reduced in the same proportion as is the temperature error.

The temperature error due to the change in resistance of the windings is proportional to the scale readings and hence could be perfectly compensated by a temperature sensitive magnetic shunt similar to that described in connection with the cold junction compensation. Principally on account of the manufacturing difficulties

which would be caused by using both methods of compensation in the same instrument, it was decided to use the calmaloy vane to compensate for both the cold junction error and the error due to the change in the resistance of the instrument. This problem may be understood more easily by referring to Fig. 5. It will be noted that the curve representing the total error is the sum of two errors, one increasing with increasing scale deflection, and the other remaining the same for

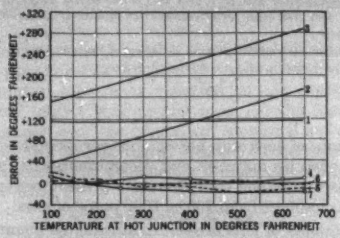



FIG. 5—RESULTS OBTAINED BY THE USE OF A CALMALOY VANE IN COMPENSATING FOR AMBIENT TEMPERATURE ERRORS IN THERMOCOUPLE TYPE TEMPERATURE INDICATORS

1. Error due to cold junction temperature at −40 deg. fahr.
2. Error due to change in instrument resistance at −40 deg. fahr.
3. Total error in uncompensated instruments at −40 deg. fahr.
4-7. Errors in compensated instruments at −40 deg. fahr. All instruments calibrated to read correctly at + 75 deg. fahr.

all points on the scale. It is necessary to provide a type of compensation which will increase with increasing deflection in the same manner as shown by the curve representing the total error. This is done by proportioning the magnetic circuit so that the rate of change of flux, and hence the torque, acting on the calmaloy vane is increased with increasing scale reading.

Fig. 6 illustrates the method of applying this compensation to a standard type d'Arsonval instrument. This instrument has a coil (*e*) of cylindrical section, iron pole pieces (*c c*[1]) having inside surfaces of spherical section and a spherical iron core which, together with the springs, is omitted from the drawing in order to avoid confusion. The compensating pole piece (*b*) which is made of iron is mounted on the pole piece (*c*). The calmaloy vane (*a*) is mounted parallel to the armature shaft. The pole piece (*c*[1]) is cut away as shown so that it will not exert an attraction which will oppose the attraction of the compensating pole piece for the calmaloy vane. The principal path of the flux which produces the compensating effect is indicated by the arrows. It will be noted that the flux, after crossing the air-gap between the compensating pole piece and the calmaloy vane, passes through the coil and across a second air-gap to the core. The length of this second air-gap is not changed when the armature is rotated, but may be varied by raising or lowering the armature by means of the jewel screws. This provides a convenient means for adjusting the compensation.

Fig. 5 shows the results obtained on four instruments compensated by this method. Although it is possible to secure a very accurate compensation, the cost is materially increased if it is attempted to hold an accuracy of better than 20 deg. fahr. for a change in ambient temperature from + 75 to − 40 deg. fahr. This means that the error will be less than one-fifth of

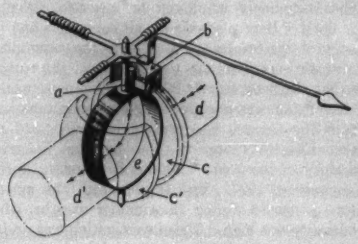



FIG. 6—D'ARSONVAL INSTRUMENT WITH CALMALOY COMPENSATION

the change in ambient temperature from the calibrating temperature of 75 deg. fahr.

On account of its simplicity, sturdiness, and small size, it is believed that the type of temperature indicator just described will be found useful for many purposes other than that for which it is particularly intended. It also appears that the possible uses of temperature sensitive magnetic alloys have not been exhausted.

# Phase Defect Angle of an Air Capacitor

BY W. B. KOUWENHOVEN* and C. L. LEMMON†
Member, A. I. E. E. Non-member

***Synopsis.***—*This investigation was undertaken in order to determine the conditions of atmosphere under which the air capacitor may be regarded as having zero loss.*

*A special guarded and shielded test capacitor was constructed having quartz insulation between the high-voltage and guard plates and low loss molded bakelite insulators between the measuring and guard plates. This capacitor was enclosed in a metal box and subjected to various conditions of temperature and humidity. Readings were made of continuous conduction current and a-c. phase defect angle. The measuring instruments used were the most sensitive available. A D'Arsonval galvanometer having a sensitivity of $1.5 \times 10^{-13}$ amperes was used in the continuous current work and a Wien bridge sensitive to three seconds in the a-c. measurements. A gradient of approximately 4000 volts per cm. was used in all tests.*

*Measurements were made of the effect of humidity at temperatures from 60 deg. fahr. to 100 deg. fahr. and in each run the humidity was varied from 40 to 95 per cent, approximately. Readings were made of continuous conduction current and the phase angle of the test capacitor was compared with that of a standard air capacitor in which the humidity was maintained at a low value. It was found that the conduction was zero and the phase defect angle of an air capacitor was less than three seconds for values of humidity below 90 per cent.*

*Observations were made also of the effect of the introduction of ions and dust particles into the condenser chamber.*

* * * * *

## Introduction

IMPROVEMENTS in impregnated paper cable manufacture have necessitated many experiments in the measurement of phase angle. The a-c. bridge and the dynamometer wattmeter are the two methods commonly employed to measure dielectric loss. Both of these methods use air capacitors and the accuracy of the results is based upon the assumption that the air capacitors are loss free, *i. e.*, the current leads the voltage by exactly 90 deg. The correctness of this assumption was questioned almost simultaneously by both the General Engineering Laboratory of the General Electric Company and by the Electrical Laboratory of the Johns Hopkins University,[1] during the summer of 1927. The trouble with the air capacitors developed during the summer months, when the humidity was high. This investigation was undertaken to determine whether or not the known sources of atmospheric ionization were sufficient to account for the phase defect angle found, and to study the effects of humidity and temperature upon the behavior of air capacitors. The phase defect angle of a capacitor is the angle by which its current fails to lead the alternating voltage by 90 deg.

## Sources of Atmospheric Conduction

It is a well recognized fact that atmospheric air contains charged particles called ions, which will move when exposed to an electric field, thereby causing conduction.[2] The sources[3a] of ionization are radium emanations, soil gases, ultra violet light, cosmic rays, photoelectric effects, the Lenard[4] effect, whirling dust clouds,[5] and the products of combustion.

The normal ionizing agents produce from ten[6] to thirty[7] ions of each sign per cu. cm. per second. These are removed by diffusion and recombination at such a rate that at any one time there are present per cu. cm. of the atmosphere from 700 to 1000 pairs[6] of ions.

The number of ions present in air may be counted by means of the "ion counter."[3b] The number not only varies at different localities, but also from hour to hour throughout the day. In cities the average number of small ions is 800 of both signs, per cu. cm., and of large ions 1800. The number of large ions present at any time depends mainly upon the amount of smoke in the air and may equal 60,000 or more per cu. cm. "Small ions[3c] consist of groups of some ten molecules, more or less grouped around a central charged molecule and forming a fairly stable complex or cluster." Large ions are small ions combined with dust or water particles, or both. The velocity of small ions is from one to two cm. per volt per cm. per second, and the velocity of large ions from 1/100 to 1/1000 that of the small ions. The charge on an ion is usually taken as $1.59 \times 10^{19}$ coulombs.

## Atmospheric Conduction—Phase Defect Angle

If a capacitor is placed in still air, ions will not flow from the outside air into the capacitor and the number of ions available,. to cause conduction, will be those generated per unit volume per second by the normal atmospheric ionizing agents. If these produce an average of 20 ions of each sign per cu. cm. per second, and if none of these recombines the current per unit volume of the capacitor will equal $3.2 \times 10^{-18}$ amperes.

Consider, for example, a high-voltage air capacitor having two measuring plates, electrically connected, one on either side of a high-voltage plate, each plate being 121.9 cm. (4 ft.) by 182.9 cm. (6 ft.). At a spacing of 5.08 cm. (2 in.) the volume of air enclosed by the condenser is 227,000 cu. cm., and assuming that the voltage gradient is sufficient to draw out all of the ions formed, the conduction current amounts to $0.72 \times 10^{-13}$ amperes. The electrostatic capacity of

*Assoc. Professor of Electrical Engg., The Johns Hopkins University, Baltimore, Md.

†Grad. Student in Electrical Engg., The Johns Hopkins University, Baltimore, Md.

1. For references see Bibliography.

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30-69

this capacitor equals 775 $\mu\mu$f. and at 60 cycles potential of 13,200 volts, the charging current is 4 milliamperes. The power factor of the capacitor under these conditions equals $1.8 \times 10^{-6}$ and this is negligible.

If the air in the vicinity of the condenser contains 60,000 ions of both signs per cu. cm., and if we assume that the air currents are sufficient to completely change the air in the capacitor once every second, then the conduction current would equal $2.2 \times 10^{-9}$ amperes, and the power factor, ($\cos \phi$), $0.55 \times 10^{-6}$. This corresponds to a phase defect angle of less than one second of arc and may be neglected.

It is evident, therefore, that the normal ionization of the atmosphere is not sufficient to account for the phase defect angles sometimes reported in air capacitors. Any phase defect that occurs must be the result of either leakage over the insulation, abnormal ionization caused by the flow of highly ionized air into the condenser space, or the presence of a dielectric other than air in the field.

## Experimental Work

As stated before, the object of this investigation was to determine the effect of humidity, temperature, and ionization upon the dielectric, atmospheric air. Measurements were made of the conduction current flowing through an air capacitor under high continuous potentials and also of the power factor at corresponding values of 60-cycle voltages. A special test capacitor described below was constructed for this purpose.

The continuous current conduction was measured by a high sensitivity D'Arsonval galvanometer and as a check a-c. measurements were made in a Wien bridge, comparing the test capacitor with a standard capacitor. The effect of temperature was first studied in order to be sure that no thermal e. m. fs. existed in the test capacitor circuit. After proving that thermal e. m. fs. were absent, humidity runs were made, each at a definite temperature ranging from 21 deg. cent. (70 deg. fahr.) to 38 deg. cent. (100 deg. fahr.). In each one of these runs the relative humidity was varied from a low value to the highest attainable. No appreciable continuous conduction current was found and the d-c. and a-c. methods checked within the limits of accuracy of the equipment.

During the work two sources of trouble developed, namely surface leakage over the insulation and conduction due to fibers. Both of these were carefully investigated. Later ionized gases and dust were introduced into the test capacitor and their effect upon the phase defect angle studied.

## The Test Capacitor

A flat plate capacitor (Fig. 1) was used as a test specimen, in which the atmospheric conditions could be varied. The high-voltage plate was 51 cm. (20 in.) $\times$ 38 cm. (15 in.), the guard ring 6.4 cm. (2.5 in.) wide, and the main or measuring plate 38 cm. (15 in.) $\times$ 25.4 cm. (10 in.). The width of the air-gap between guard and main plates was 0.159 cm. (1/16 in.) and all plates were of 0.318 cm. (1/8 in.) brass. The plates were polished and all sharp edges removed. The main plate was suspended from the guard plate by bakelite strips, running the full length of the condenser; brass studs, placed as near the center of these strips as was

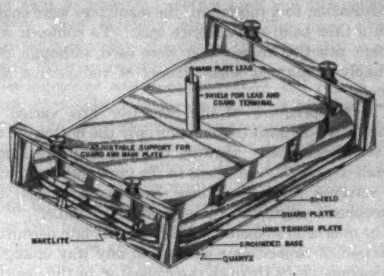


Fig. 1—Test Capacitor

consistent with rigidity, held the main plate. The main plate lead was a 0.635 cm. (1/4 in.) brass rod soldered by means of leads of equal length, to four symmetrically placed points on the main plate. The main plate was shielded by a brass case soldered and fastened mechanically to the guard ring. A brass tube concentric with the main plate lead was mounted on this shield and served both as the guard plate terminal and as a shield for the lead. The capacitance with 0.254 cm. (0.1 in.) spacing was 300 $\mu\mu$f. The capacitor was completely enclosed in a galvanized iron box. Outlets were provided for circulation of air and observation of conditions. An oil bath was used to control the temperature of the capacitor, which is shown in detail in Fig. 2.

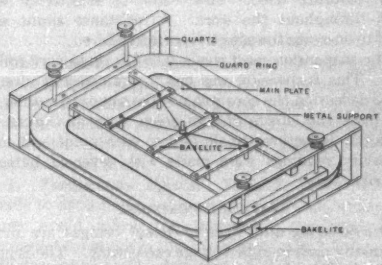


Fig. 2—Test Capacitor Details

All leakage paths were made as long as possible. The leakage path between main and guard plates was 4 in. long and the total cross-section of insulation was 1½ sq. in. Molded bakelite was used to insulate the main plate from the guard. The guard and high voltage

plates were both supported from a grounded base. All leakage over insulation from the high-voltage plate was led to ground and did not flow in the guard circuit. The guard ring was supported from the base by four quartz pillars. The best grades of low loss insulation available were used in the capacitor and care was taken to keep it out of the field. To reduce the chance of condensation to a minimum, the insulators were coated with a thin band of ozokerite wax. To conform with present practise brass plates were used, although they probably contained slight traces of radioactive substances.

The temperature of the capacitor was varied by means of an oil bath which heats only the bottom of the capacitor chamber. Heating of the bottom produced a small temperature gradient in the tank and circulating air currents resulted. These currents equalized the atmospheric conditions throughout the chamber.

The overhead suspension of the guard plate permitted variation of capacitance without in any way changing the leakage paths through the capacitor, or the position of the insulating supports with respect to the field. The guard and measuring plates were hung from two horizontal supports by four brass screws and the spacing was varied by adjusting the length of the four supports by thumb nuts. The construction is shown in Fig. 2.

### Continuous Current Measurements

A 1500-volt storage battery supplied current for the conductivity measurements. The high-voltage side of this battery was connected to the high-tension plate of the test capacitor. The guard plate of the test capacitor and the other side of the battery were grounded. A high-sensitivity galvanometer was connected between the main plate of the capacitor and ground. By varying the position of the pole pieces the galvanometer sensitivity was adjusted to a value of $1.5 \times 10^{-12}$ amperes per millimeter deflection at the scale distance used. This value of sensitivity was used throughout the work. A resistance shunt was used to decrease the sensitivity when desired.

The suspension used was a 0.007-in. gold wire rolled flat. This suspension was easily strained and after a large deflection the zero was not the same. In order to eliminate the effects of zero creep, care was taken to keep the deflections small, and at each point two conductivity readings were made with reversed battery polarity.

### A-C. Measurement

The Schering and Wien or Rosa[9] bridges are most frequently used in high-voltage cable work. The Schering bridge has three condensers in the network and the Wien only two; therefore, since we were studying the effect of air conditions upon capacitance, we chose the Wien bridge to check the continuous current results. The diagram of connections is given in Fig. 3. This bridge compares the capacitances and the difference in the phase angles of the two capacitors, $C$, and $C_t$, and does not therefore constitute a direct check upon the continuous current results. It was, however, the most sensitive method available, and by keeping the humidity and temperature in the standard capacitor, $C_s$, low and constant, while varying that in the test capacitor, $C_t$, we were able to detect any change in their relative phase defect angles.

In setting up the bridge care was taken to make a symmetrical disposition of the various elements of the network. The resistance in the two sides of the bridge were of the same size and type, symmetrically placed, shielded, and guarded. The leads between corresponding elements were the same length, shielded in an identical manner, and fixed in position. The series resistances $r_1'$ and $r_2'$ were completely shielded and were varied by means of a set of extension dials. The space relations of the parts on the two sides of the bridge were the same with respect to each other and to ground, and by this means the capacity unbalance to ground was brought to a minimum.

The standard capacitor was cylindrical in form and brass tubing was used for the plates. The main plate was entirely enclosed and was completely shielded and guarded. In order to maintain the relative humidity low and constant, a quantity of calcium chloride was placed in a container and mounted in the standard capacitor in a position outside the main field.

A Drysdale and Tinsley vibration galvanometer was used as a detector and as this did not give the desired sensitivity a three-stage impedance coupled amplifier was inserted between the bridge terminals and the galvanometer. The amplifier and bridge were isolated electrostatically by means of a shielded transformer. The power supply to the bridge was taken from a 5-kv-a., 60-cycle, sine wave, a-c. generator manufactured by the General Electric Company. The generator voltage was controlled by varying the field excitation, and the generator was driven by a motor supplied with current from the university storage battery. The speed was held constant.

At 60 cycles, and with the amplifier in circuit, the bridge could be balanced to better than 1/10 ohms in the ratio arms and to within plus or minus 100 ohms in the series resistance, $r_1'$, and $r_2'$, arms. The minimum phase defect angle that we could detect (plus or minus 100 ohms in the series resistance at a frequency of 60 cycles) was three seconds of arc. This was approximately 1/250 of the sensitivity of the continuous current measurements.

### Method of Varying the Humidity

Ions are not produced by slow evaporation from a water surface.[14] Therefore trays holding water were placed in the box containing the test condenser and to increase the water surface blotters were allowed to dip into the trays. There was a slight temperature gradient between the top and bottom of the box containing the capacitor and this aided in circulating the air.

A fan was used to stir up the air and this was operated so as to draw air out of the condenser space and discharge it outside of the box. When air carrying drops of moisture passes through a fan the suspended water particles are ionized in accordance with the Lenard effect.

The relative humidity was measured by means of wet and dry bulb thermometers placed at the same level as the capacitor and close to the plates. Runs using this method of humidity control were necessarily long and each test extended over a period of twenty-four hours or more. This was not a disadvantage, however, as it gave sufficient time to obtain all of the desired data.

It is easy to increase the rate of evaporation by heating the water slightly and thereby shortening the time of a run. After a number of attempts to use such schemes they were abandoned because of the danger of ionization and condensation.

## Operation

In this investigation two sets of data, continuous current conduction and a-c. phase angle, were taken concurrently on the same air capacitor. A complete switching arrangement was installed by means of which the capacitor could be transferred from one circuit to the other. Measurements were made at intervals consistent with the rate of change of the variable under observation.

In order to protect the high-sensitivity galvanometer from transients during the continuous current measurements a definite cycle of operation was adopted. With the galvanometer short circuited, the continuous voltage was applied to the capacitor circuit; after five minutes the galvanometer was placed in circuit, a reading taken, and again short circuited. The circuit was then opened and the capacitor short circuited for five minutes. Then with the galvanometer still short circuited, voltage was applied in the opposite direction, and after five minutes the second or reversed reading was taken. The reversed readings made the accurate determination of the galvanometer zero unnecessary, and also served to eliminate any contact potentials that might develop during a run. This method gave a very good check of conditions in the capacitor, and if the plates were free from dust or fibers and the insulation free from moisture, the difference between the two readings was not greater than half a centimeter.

Three main operations were necessary in balancing the a-c. bridge. The first was to obtain an approximate balance of the main bridge at reduced galvanometer sensitivity. The second was to connect a second galvanometer, not shown in Fig. 3, between the guard and main plates of the standard capacitor and balance by adjusting the resistance $r_6$. The third step was to connect the second galvanometer between the guard and main plates of the test capacitor and to balance by adjusting resistance $r_7$. These three steps were repeated until the bridge was in balance for full sensitivity of the galvanometer and full amplification of the amplifier.

Each of the humidity runs was made at a definite temperature and the relative humidity raised slowly from the lowest value obtainable to as near one hundred per cent as possible. Before each run the condenser plates were carefully cleaned. The final cleaning operation consisted of scraping the plates with a safety razor blade to remove the last traces of lint and dust. The capacitor was then assembled and placed in its tank with calcium chloride dryer. After twenty-four hours the dryer was removed and measurements were made with both alternating and continuous current. If the difference between the reversed continuous current galvanometer readings at 1500 volts was less than half a centimeter, it indicated that the condenser was free from lint and the test was continued. If the difference was greater than half a centimeter the condenser was cleaned again. After securing a satisfactory set of readings with dry air, water was placed in the chamber with the condenser, the humidity increased gradually, and observations were made of both phase angle and conduction current.

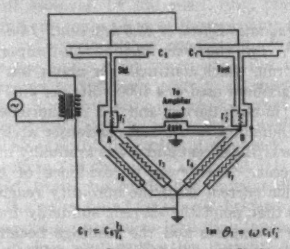


Fig. 3—Diagram Connections of A-C. Circuit

## Experimental Results

The results of the temperature test, the four humidity runs, and the effect produced by the introduction of ions into the test condenser, are given below. In addition there are included curves showing the variation of the conduction current with voltage for leakage over both insulation and fibers.

1. *Temperature Effects*: *Table I.* This run was made to determine whether or not a change in temperature would affect the measuring apparatus. The temperature range in this experiment was 7.2 deg. cent. (45 deg. fahr.) to 43.3 deg. cent. (110 deg. fahr.). Both continuous and a-c. measurements were made during the run. In Table I the results of the continuous current measurements are given and also of the capacitance of the test capacitor to the nearest micro-microfarad, as measured in the bridge. The capacitance increased during the run from 295 to 300 micro-microfarads, due to expansion. The power factor

balance of the bridge did not change during the test. The high sensitivity galvanometer remained at practically zero deflection throughout the entire run. The small deflections noted are inherent in a galvanometer with this type of suspension and sensitivity.

It is evident from the results that thermal electromotive forces were not present in the apparatus at any point in the range of temperature covered by the experimental work.

TABLE I
TEMPERATURE VARIATION
The voltage used in this test with both alternating and continuous current was 1500

| Time hr. min. | Temp. of test capacitor deg. fahr. | Per cent humidity | Capacitance of test capacitor m. m. f. | Cm. deflec. $1.5 \times 10^{-11}$ amp./cm. |
|---|---|---|---|---|
| 0:00 | 45 | 56 | 295 | 0.25 |
| 1:00 | 50 | 49 | 295 | 0.75 |
| 2:00 | 55 | 53 | 295 | 0.75 |
| 3:00 | 60 | 54 | 295 | 0.20 |
| 3:45 | 65 | 56 | 296 | 0.30 |
| 4:20 | 70 | 56 | 296 | 1.00 |
| 5:20 | 75 | 54 | 296 | 0.70 |
| 5:55 | 80 | 54 | 296 | 0.70 |
| 6:20 | 85 | 49 | 297 | 1.50 |
| 8:00 | 90 | 44 | 298 | 0.00 |
| 10:00 | 95 | 41 | 298 | 1.60 |
| 10:45 | 100 | 35 | 299 | 0.00 |
| 11:50 | 105 | 31 | 300 | 0.40 |
| 12:35 | 110 | 20 | 300 | 0.20 |

2. *Humidity Effects at 25.5 deg. cent.* (*78 deg. fahr.*)—*Table II.* Two runs were made at this temperature. In the first run, which continued for about ten hours, the voltage gradient used was 4000 volts per cm. (10.1 volts per mil), in both the a-c. and d-c. measurements. The relative humidity in the test condenser at the start of the run was 51 per cent and it was gradually increased to 93 per cent. There was no evidence of continuous conduction current until the humidity reached 93 per cent; at that point the current suddenly increased to $18 \times 10^{-11}$ amperes and the readings became erratic. The test was stopped at this point. The a-c. bridge results also showed that the difference in the phase defect angles of the two capacitors was practically constant up to 93 per cent humidity. Above this point the phase defect angle of the test capacitor was 3 minutes and 44 seconds, as compared to the standard. Readings were also taken at gradients of 2670 and 1350 volts per cm., which checked those at 4000 volts.

The second test at this temperature was made at a higher potential gradient of 5050 volts per cm., and continued for over 32 hr. The data given in Table II were taken during this run. The maximum temperature variation was 1 deg. fahr., and the capacitance remained constant to within one-half of one per cent. The relative humidity ranged from 68 to 91 per cent and the conduction current was zero up to 88 per cent humidity. Above this value it increased slightly, but did not become erratic.

In this test the a-c. measurements were made using a 1:1 ratio bridge and during the run the standard and test capacitors were interchanged a number of times. With the connections as shown in Fig. 3, the bridge measurements indicated that the phase defect angle of the test capacitor was three seconds, as compared to that of the standard. When the capacitors were interchanged the phase angle remained in the same side of the bridge; or in other words, the standard capacitor now had a power factor corresponding to three seconds of arc. Its source, therefore, lay in the bridge circuit, and we were not successful in eliminating it. In Table II the phase defect angle is reported as three seconds, the limit of the sensitivity of the a-c. bridge.

These two runs prove that at 25.5 deg. cent. the conduction current in an air capacitor is zero for values of the relative humidity below 90 per cent, and that if a capacitor has a phase defect angle it remains constant below 90 per cent humidity.

TABLE II
HUMIDITY EFFECT AT 25.5 DEG. CENT. (78 DEG. FAHR.)
Spacing of test condenser 0.18 cm. (70 mils)
Gradient 5050 volts per centimeter (14.3 volts per mil)
Voltage used in both alternating and continuous current tests, 1500

| Time hr. min. | Temperature of test cap. deg. fahr. | Per cent humidity | Test cap. capacitance m. m. f. | Phase defect angle | Cm. deflec. $1.5 \times 10^{-11}$ amp./cm. |
|---|---|---|---|---|---|
| 0:00 | 77.5 | 68.0 | 463.0 | 3 sec. | 0.50 |
| 1:15 | Placed water in trays in condenser chamber | | | | |
| 1:25 | 78.0 | 75.0 | 463.0 | 3 sec. | 0.50 |
| 2:15 | 78.0 | 77.0 | 463.0 | 3 sec. | 0.50 |
| 3:15 | 77.8 | 79.0 | 463.0 | 3 sec. | 0.50 |
| 4:15 | 77.8 | 79.0 | 462.5 | 3 sec. | 0.00 |
| 5:15 | 78.0 | 79.0 | 462.5 | 3 sec. | 0.25 |
| 6:15 | 78.0 | 81.5 | 462.0 | 3 sec. | 0.25 |
| 7:15 | 78.0 | 82.2 | 462.0 | 3 sec. | 0.50 |
| 8:15 | 77.8 | 81.4 | 462.0 | 3 sec. | 1.50 |
| 9:15 | 77.5 | 85.0 | 462.0 | 3 sec. | 0.25 |
| 10:15 | 77.5 | 85.0 | 461.5 | 3 sec. | 1.00 |
| 11:15 | 77.2 | 86.2 | 461.5 | 3 sec. | 0.50 |
| 12:15 | 77.0 | 87.0 | 461.5 | 3 sec. | 0.50 |
| 13:15 | 77.0 | 87.0 | 461.0 | 3 sec. | 1.50 |
| 20:15 | 77.0 | 88.5 | 461.0 | 3 sec. | 6.75 |
| 22:15 | 77.0 | 88.5 | 461.0 | 3 sec. | 3.00 |
| 32:15 | 77.0 | 91.0 | 461.0 | 3 sec. | 7.00 |

3. *Humidity Effect at 31.7 deg. cent.* (*89 deg. fahr.*)—*Table III.* This run extended over a period of thirty-two and one-half hours as the rate of change of water content was very slow. The results are given in Table III. As in the preceding runs readings were taken at several values of potential gradient, namely 4280, 2860, and 1725 volts per cm. The values obtained at the lower gradients check those given in Table III. The humidity increased slowly and in some instances several hours elapsed between successive readings. A careful check of conditions was made throughout the run to prove that singular points did not exist. At the start the humidity was 40 per cent and at the end of the run it had reached 98 per cent. The conduction current through the condenser was zero for the entire run. The maximum deflection obtained at any time was three cm. and in the majority of cases was less than 0.5 cm.

The results of the a-c. measurements in the Wien bridge showed that the phase defect angle of the test capacitor as compared to the standard did not vary by more than three seconds throughout the entire test.

TABLE III

HUMIDITY EFFECTS AT 31.7 DEG. CENT. (89 DEG. FAHR.)

Spacing of test condenser 0.35 cm. (138 mils)
Gradient 4280 volts per cm. (10.9 volts per mil)
Voltage used, 1500

| Time hr. min. | Temp. of test cap. deg. fahr. | Per cent humidity | Cm. deflection $1.5 \times 10^{-11}$ amp./cm. |
|---|---|---|---|
| 0:00 | 89.5 | 40 | 0.00 |
| 0:30 | Placed water in trays in condenser chamber | | |
| 1:00 | 89.5 | 46 | 0.00 |
| 1:30 | 88.2 | 46 | 0.00 |
| 2:30 | 88.8 | 48 | 0.00 |
| 3:30 | 91.8 | 51 | 0.00 |
| 4:30 | 90.2 | 53 | 0.70 |
| 5:30 | 89.5 | 56 | 0.00 |
| 6:30 | 89.0 | 61 | 0.20 |
| 7:30 | 89.0 | 62.5 | 1.00 |
| 8:30 | 88.0 | 62.5 | 0.75 |
| 9:30 | 87.0 | 71.0 | 0.50 |
| 10:30 | 86.8 | 73.0 | 0.50 |
| 11:30 | 86.5 | 79.0 | 0.50 |
| 12:30 | 87.2 | 80.0 | 0.25 |
| 13:30 | 87.4 | 82.5 | 0.00 |
| 14:30 | 86.8 | 84.0 | 2.00 |
| 15:30 | 87.8 | 86.0 | 2.50 |
| 17:30 | 88.2 | 86.0 | 1.00 |
| 19:30 | 89.2 | 88.0 | 1.00 |
| 22:30 | 88.5 | 87.0 | 3.00 |
| 25:30 | 89.8 | 90.0 | 0.25 |
| 26:30 | 88.0 | 90.5 | 0.00 |
| 32:30 | 88.0 | 98.0 | 1.50 |

This test indicated that at a temperature of approximately 31.6 deg. cent. (89 deg. fahr.) and over a humidity range of 40 to 98 per cent relative humidity there was no change in the apparent phase defect angle of the capacitor and its conduction current remained zero.

4. *Humidity Effects at 37.8 deg. cent. (100 deg. fahr.).* The run made at this temperature continued for twenty-four and a half hours, and a voltage gradient of 4000 volts per cm. was used. The relative humidity varied from 34 to 90 per cent during the run. The continuous conduction current through the capacitor was zero up to 90 per cent relative humidity, the galvanometer deflections being all one-half cm. or less. At 90 per cent there was a sudden increase of conduction current to $39 \times 10^{-11}$ amperes and the test was discontinued.

The Wien bridge measurements made at the same potential gradient indicated no change in the relative phase defect angles of the two capacitors up to 90 per cent humidity. At the 90 per cent point the test capacitor apparent phase defect angle was one minute as compared to the standard.

The test showed that below 90 per cent relative humidity the conduction current was zero and the apparent phase defect angle remained constant. Above 90 per cent the two changed in an irregular manner and definite values could not be obtained for them.

## Effect of the Introduction of Ions

Ions were introduced into the space between the plates of the capacitor by four methods, (a) Lenard effect, (b) spark discharge, (c) smoke, and (d) dust. Ionization produced by the Lenard effect is caused by the breaking up of drops of water when they strike an obstruction. The fan was set running at 200 rev. per min., driving air having a relative humidity of about 75 per cent, at a velocity of about 10 cm. per second, through the capacitor. Before the fan was started the conduction current was zero, but within less than ten minutes after starting the fan the current had reached a value of $15 \times 10^{-10}$ amperes. After running the fan for forty minutes it was stopped. About ten minutes later the galvanometer deflection came back on scale and the current gradually decreased. Ions produced by this method are very large and their mobility is low. The gradient in this test was 4000 volts per cm. and the current still persisted for several minutes after the fan had stopped. During the period that the fan was running, a measurement of the phase defect angle gave a value of 19 seconds.

Ions produced by spark discharge are very small and possess such a high mobility that we did not succeed in introducing them into the space between the capacitor plates. Smoke is a more satisfactory method of introducing ions into a capacitor. The size of these ions is intermediate between the electrons set free by the spark discharge and the large ions resulting from the Lenard effect. In Table IV are given data typical of a smoke ionization test. The relative humidity was low and the fan was used to drive tobacco smoke into the condenser. With the guard connected normally the ions were all removed by the guard ring, practically none reaching the main plate of the capacitor, and no appreciable change in either conduction current or phase angle was produced by the smoke. But with the guard connected to the main plate, *i. e.*, operating as an unshielded capacitor, the conduction current rose to $45 \times 10^{-11}$ amperes, and the phase defect angle to 32 seconds. The ratio of the width of the guard ring to spacing was 25 to 1 in this test. The phase defect angle as calculated from the conduction current does not check with the value found for the a-c. bridge measurement. It was not possible to take simultaneous measurements of loss and conduction current, and the volume of smoke varied.

TABLE IV

SMOKE

Spacing 0.37 cm. (146 mils)
Gradient 4050 volts per cm. (10.25 volts per mil)
Voltage used in alternating and continuous current tests, 1500

| Time hr. min. | Temp. of test cap. deg. fahr. | Per cent humidity | Capacitance of test cap. m. m. f. | Phase defect angle | Cm. deflec. $1.5 \times 10^{-11}$ amp./cm. |
|---|---|---|---|---|---|
| | Dry air without circulation | | | | |
| 0:00 | 85.8 | 47 | 224 | 3 sec. | 0.00 |
| | Dry air, smoke, filtered through glass wool | | | | |
| 0.30 | 85.8 | 47 | 224 | 3 sec. | 2.25 |
| | Dry air, smoke, blown directly into condenser | | | | |
| 1:00 | 85.8 | 47 | 224 | 3 sec. | 2.25 |
| | Dry air, without smoke, guard, and main plate connected together | | | | |
| 1:30 | 85.8 | 47 | 454 | 0 sec. | 1.00 |
| | Dry air, smoke, guard, and main plate connected together | | | | |
| 2:00 | 85.8 | 47 | 454 | 32 sec. | 30.00 |

Attempts were made, without success, to introduce sufficient dust particles into the test capacitor to cause conduction. Dust contains a large percentage of

carbonaceous matter and a sample was collected from the top of an instrument case about 8 ft. high, and placed on the lower plate of a small capacitor. At a voltage gradient of 4000 volts per cm. a slight haze was noticed and the particles could be seen vibrating between the plates. After a few minutes the action ceased and when the plates were examined both the upper and lower plates were found coated with a closely packed layer of dust. Dust is a possible source of conduction and loss in air capacitors.

It is evident from these results that the use of suitable guard rings will remove the small ions and electrons from air, but the large water vapor ions move so slowly that they can get by a guard ring even where the width is twenty-five times the spacing. It is clear also that if sufficient ions are introduced into the space between capacitor plates, they will cause conduction and produce a loss in an air capacitor.

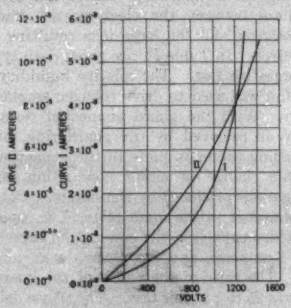


Fig. 4

Curve I Conduction Current
Curve II Surface Leakage

## Conduction Due to Fibers and Condensation on Insulation

Fibers were a constant source of trouble. At the voltage gradients used the fibers would line themselves up with the electrostatic field, and as the plates of our capacitor were close together they would bridge the gap and cause conduction. In Fig. 4 is shown a curve of the variation of the conduction current with applied voltage. In this test there was a large number of cotton fibers between the plates and the relative humidity was 42 per cent. At higher values of humidity the curves were much steeper.

In all our tests condensation on insulation was the limiting factor in the behavior of the air capacitor. The use of ozokerite helped to reduce this trouble, but did not eliminate it. Several tests were therefore made to determine the leakage current that would flow over the surface of a piece of insulation upon which moisture had condensed. In these tests the voltage was varied and a typical curve is reproduced in Fig. 4.

The interesting thing about this leakage current curve and also for the fiber conduction curve, although to a lesser extent, is their similarity to the curve of the ionization current through a gas as it approaches breakdown.

## Conclusions

The following conclusions may be drawn from this investigation:

1. The normal ionization of the atmosphere is not sufficient to produce a measureable phase defect angle in a-c. measurements at commercial frequencies, involving an air capacitor as a standard.

2. The a-c. bridge observations indicate that any apparent phase defect angle in an air capacitor remains constant at values of relative humidity below 90 per cent.

3. The continuous conduction current in a properly shielded and guarded air capacitor in quiet atmosphere is negligible at values of humidity below 90 per cent. Therefore such a capacitor may be considered as an ideal capacitance.

4. In an air capacitor there are present in addition to ionization two sources of conduction, fibers bridging the plates and condensation on insulation. The latter may be reduced by placing a band of ozokerite, or other similar material, around each possible leakage path, and by keeping the humidity low. The leakage path should be made as long as possible.

5. In an air capacitor it is advisable to insert a grounded metal plate in the solid insulation between the guard and high-tension plates. Such an arrangement eliminates practically all leakage current from the guard circuit.

6. In a properly designed air capacitor a guard plate should be provided, but this guard ring cannot be relied upon to remove all of the ions present in the atmosphere.

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# Transmission Research and Design with the Field as a Laboratory

BY F. E. ANDREWS*
Member, A. I. E. E.

and

C. L. STROUP†
Associate, A. I. E. E.

*Synopsis.—Overhead transmission lines are usually considered to be a class of equipment subject to certain types of troubles which cannot be avoided by means accepted as ordinary practise. It is the purpose of this paper: (1) to describe improvements in design of wood pole lines of the 33,000-volt class, which improvements have been developed and applied to the system with which the authors have been identified and which, it is believed, will greatly reduce the characteristic troubles, (2) to present an explanation of flashovers on wood structures, (3) to give the facts found in field investigations which form the basis for the improvements adopted, and (4) to describe the method used for field investigations and analysis of troubles.*

*The studies and investigations referred to deal primarily with the matter of insulation. Considerable information relative to the insulation values of wood in a structure as developed by laboratory tests has been published. Experience is cited in this paper to show the value of wood insulation in the structure developed from field experience on 33,000-volt lines, and there is presented a practical economical design of wood pole structures using wood braces, in place of the usual metal braces, which, it is believed, will be practically immune to lightning troubles. Data from laboratory tests are given to substantiate the conclusions developed in the field investigations. The performance of insulators with respect to mechanical and electrical breakage is shown and the use of insulators of more sturdy designs is discussed.*

*The most important conclusions are:*

*1. The lightning performance of wood pole transmission lines of moderate voltage can be greatly improved by the elimination of bonding, or partial bonding between insulator supports such as results from the use of steel crossarms or steel crossarm braces; and by the use of wood or other insulators in guys.*

*2. The record of wood pole overhead lines with ground wires and the information developed in the paper show that overhead ground wires as usually installed do not materially improve the operation of the lines.*

*3. Insulator breakage can be greatly reduced by the use of the more sturdy insulators which are available.*

*4. Field investigations, analysis of records of operation and troubles, and interpretation of results, systematically carried out, can result in great improvement in system reliability, and in better utilization of investment.*

* * * * *

## Introduction

OUR present electricity supply systems are characterized by the concentration of power generation in large stations and the supply of loads from transmission systems. The quality of the service is accordingly a function of the dependability of the transmission lines. It is therefore of basic importance that every means be utilized in both the design and the operation of our transmission lines to make them the utmost in reliability.

Within the past few years, remarkable engineering progress has been made with respect to the higher voltage lines; but until recently, lines operating at the lower voltage, *i. e.*, 66,000 volts and below, have received only passing attention, the supposition apparently being that these have been so well standardized in principles of design that they are about as satisfactory in operation as can be reasonably expected. The principal loads are directly dependent upon the lower voltage lines which, from this point of view, constitute the heart of any system. The material in this paper is based upon investigations and experiences with lines of this classification, with which the authors have been identified.

Their work in this connection has been principally with 33,000-volt wood pole lines. However, the principles and methods described are adaptable to lines of other voltages using wood pole construction, and in some respects, to all lines.

## Description of System

The system with which the authors have carried out their work covers an area of approximately 6000 square miles in the northeastern part of Illinois. The major portion of the energy is generated in two large stations at 12,000 volts, with a considerable part also furnished from stations of other companies associated with the interconnected system of the Chicago region. The interconnections between principal generating stations and with major distribution centers are at 132,000 volts. The intermediate voltage system, which is the direct transmission supply for most of the loads, operates at 33,000 volts, although a voltage of 12,000 direct from the station busses is used for loads close to the generating stations.

The mileage of each type of line is shown in Table I.

The 132,000-volt lines are of steel tower construction with overhead ground wires. The 33,000-volt and 12,000-volt lines are of wood-pole construction with steel structures used in special situations. The territory traversed by these lines is all of essentially the same character, most of it being flat or slightly rolling, and cultivated. Neutrals of all three systems are solidly grounded, although one portion of the 33-kv. system uses a neutral resistance distributed among several grounding points.

The wood-pole construction for both voltages, except that recently installed, is principally of the conventional type illustrated by Fig. 1. The insulators in general,

*Public Service Company of Northern Illinois, Chicago, Illinois.

†Jeffrey-DeWitt Insulator Co., Kenova, W. Va.: formerly with the Public Service Co. of Northern Illinois.

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30-75

except those recently installed, are of the pin type of so-called 45,000-volt rating, and are multi-part porcelain, two-piece and three-piece. Overhead ground wires, except on a few of the older lines, are not in use on the wood-pole construction.

### Investigations of Line Performance

Detailed investigations and analysis of all troubles and accurate systematic records and summaries of the operation of the 132,000-volt lines have given a basis for the design of these lines that is resulting in a highly satisfactory performance. The results of this work have brought out the necessity of devoting similar attention to the intermediate-voltage system.

Interruptions of 33,000-volt lines more frequently result in interruption to substations, and to customers directly served, than do interruptions of the high-voltage interconnections. Furthermore, the former

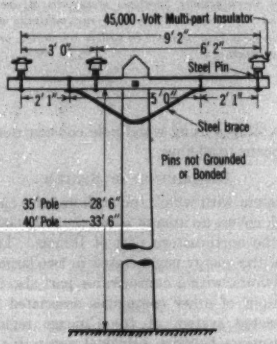


Fig. 1—Typical Wood Pole Construction 12- and 33-Kv. Lines

occur more often. From this point of view, the intermediate voltage lines and substations are considered the heart of the system and warrant the exercise of every reasonable means of improving their performance. Accordingly, investigations of the performance of these lines, carried on over a period of years, have finally culminated in the plan of investigation described and in the records illustrated. This has given the required information upon which to base improvements in design.

When the work of collecting data was started, an attempt was made to derive conclusions from repairmen's reports sent in from the field. The result was unsatisfactory, for while the extent of damage was quite completely described, the information needed for proper analysis of the trouble was not included.

Investigation by an engineer in several cases showed that much information not usually obtained was available with reference to cases of trouble, from which the cause and manner of failure could be determined. Engineers whose first duties were to make field investigation of trouble immediately following its occurrence were accordingly assigned to this work.

In cases in which it was necessary to obtain the facts, poles were climbed and a minute examination made. The following information was reported:

1. Number of insulators flashed (position on structures).
2. Path of arc (phase to phase) (phase to ground).
3. Guys, if any, and location.
4. Overhead ground wire, if any.
5. Earth connection and where connected (to hardware, or overhead ground wire, etc.).
6. A small sketch of the structure and associated equipment.
7. Exact location of all burns on insulators, tie wires, conductors, and hardware.
8. Location of all splinters and burns on crossarms or pole.

All cases of trouble are reported by the repair men who fill out a form provided, giving details of the trouble and repair work. The system operators' daily reports giving the detailed log of all switching operations, are received each morning and show what trouble has occurred during the preceding twenty-four hours. The engineers promptly make field inspections of all situations requiring their attention, to obtain data to supplement that given by the repair reports. In addition to this, a system operator's report is made out for each case of trouble, which shows the switches which opened, and all pertinent data relative to the system as affected by the trouble.

Reports of the bi-weekly line patrols of each line, showing location of broken insulators and other line defects, and the reports of regular line repairs also constitute an important source of information relative to line performance.

A card file by lines is kept, which is used as a working record and follow-up system for investigations in progress.

An insulator-record book is used in which is shown by lines, the insulator replacements reported and the engineer's inspection report on each insulator removed.

Each special investigation of trouble is covered by a report, these reports being filed by lines.

A chronological summary of the operating record for each line is kept, which shows for each interruption the time and duration, the interruption report number, and the cause. This summary, together with the other information described above, forms the basis for the final analysis as shown by Tables I, II, V, and VII.

Insulators are more susceptible to defect than any other single piece of equipment, and they are of paramount importance in maintaining service. Therefore, the practise of inspecting all insulators removed because of defects has been established. By this means, correct and complete information is obtained relative to the performance of various makes and designs of insulators, and a proper basis is set up for their selection and use.

The insulators when removed are marked by cloth tags to show reason for removal and location from which they are taken. An engineer makes an inspection at the earliest opportunity and records the location, type of insulator, cause of removal, and character and extent of damage. The information obtained from the insulator inspection is correlated in cases of electrical trouble with all other information on the case of trouble concerned.

Data collected in this way are of much use as a source for specific items of information needed from time to time with reference to the transmission system, but the most significant and valuable benefits cannot be derived from such information unless special effort is directed toward systematically analyzing and summarizing it. Use for much of the detailed information collected is not foreseen at the time it is recorded, but new questions and problems are continually arising for the answering of which the information is eventually utilized. It has been felt as the result of this experience, that no item of information in connection with the investigation of trouble or line performance is too insignificant to record.

The summary of line performance with respect to lightning and insulator damage is shown in Table I. This shows the comparison of operation of the lines of different voltages. The trip-outs indirectly due to lightning are those caused by lightning disturbances on lines or parts of the system other than the ones on which the trip-outs counted in this classification occurred. The larger proportion of flashovers which were found on plain structures, that is, those without guys or grounds, in comparison with those found at guyed or grounded locations is of significance. It is also of interest to point out that in practically all cases of the former two or three insulators were flashed over.

TABLE I
SYSTEM MILEAGE AND SUMMARY OF LIGHTNING, FLASHOVER, AND INSULATOR PERFORMANCE, 1929

| Mileage | 132 Kv. | 33 Kv. | 12 Kv. |
|---|---|---|---|
| Wood pole construction | 0 | 1045 | 130 |
| Steel tower construction | 297 | 25 | 10 |
| *Operating Record* | | | |
| Line trip-outs directly due to lightning per 100 miles | 1.00 | 45 | 15 |
| Line trip-outs indirectly due to lightning per 100 miles | | 26.5 | 12 |
| Total cases of insulator flashover located per 100 miles | 1.00 | 36 | 28 |
| Cases of insulator flashover located on lines with overhead ground wire per 100 miles of this type line | 1.00 | 20 | .. |
| Cases of insulator flashover located on grounded structures per 100 miles | .. | 11.5 | 6.9 |
| Cases of insulator flashover located on structures with guys but no grounds per 100 miles | .. | 9.5 | 7.1 |
| Cases of insulator flashover located on structures not guyed or grounded per 100 miles | .. | 15 | 14 |
| Cases of insulator flashover located on pole top switches per 100 switches | .. | 11 | 3.3 |
| Cases of insulator flashover located on steel towers per 100 towers | .. | 7 | 4.2 |
| Number of insulators changed due to electrical damage per 100 miles | 5.15 | 75.0 | 58.5 |
| Number of insulators changed due to external breakage per 100 miles | 8.1 | 139.0 | 204.0 |

The excess of the number of 33,000-volt direct lightning trip-outs over the number of flashover locations found is explained by the fact that flashovers frequently occur which do not leave sufficient evidence to be visible from the ground to the line patrolman.

Table II shows the classification of interruptions according to causes. It will be noted that the number of interruptions due to lightning was greatly in excess of those due to any of the other causes.

TABLE II
CLASSIFICATION OF INTERRUPTIONS RESULTING FROM AUTOMATIC OPENING OF OIL SWITCHES
12-Kv. and 33-Kv. Lines
Jan. 1—Dec. 31, 1929

| Cause | Per cent of total interruptions |
|---|---|
| Lightning, direct | 35.7 |
| Lightning, indirect | 22.7 |
| *Failure of insulators other than during lightning storms | 1.8 |
| Failure of system equipment external to the line | 5.1 |
| System disturbance exclusive of those due to lightning | 18.5 |
| Accidents | 4.0 |
| Trees | .8 |
| Wind, snow, ice, or other atmospheric conditions | 1.8 |
| Animals | .4 |
| Operating errors | .9 |
| From lines interconnecting with other companies | 2.0 |
| Unknown | 6.3 |

*Due principally to insulators with cracked porcelain parts which failed during wet weather.

## Lightning Flashovers

The best construction of the type generally used for wood-pole lines, and the use of better and higher voltage insulators has been ineffectual in improving the lightning performance. It was accordingly found necessary to consider other means to decrease the susceptibility of the lines to lightning.

Satisfactory explanation of the way in which the lightning flashovers occurred was not available, and a climbing inspection of a number of poles in widely scattered locations on which lightning flashovers had taken place was therefore undertaken for the purpose of finding out just what had happened. The types of structures inspected, the character of burns located, and the arc paths, are illustrated by Figs. 2 and 3. The results of the inspection are classified in Table III.

From this table, it can be seen that out of 47 structures on which flashovers were investigated, 19 structures without guys or grounds showed evidence of line-to-line arcs which did not go to ground. On the remaining 28 structures with guys or grounds, 20 flashovers went to ground, while 8 took place between conductors only. These latter were in locations where there was some separation on the pole between crossarm and guy. This information shows that a considerable number of all flashovers due to lightning occur on unguyed and ungrounded structures.

The following observations are derived from this information:

1. On poles not grounded or guyed, phase-to-phase flashovers occur without arcing to ground, the arc utilizing the steel brace with wood crossarm construction, or the steel crossarm, as part of the short-circuit path.

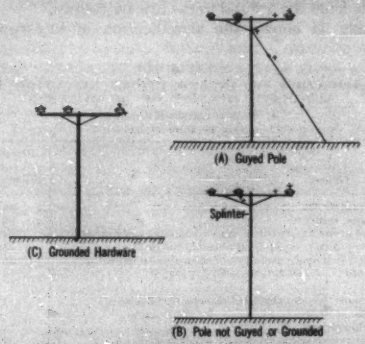


FIG. 2—CONVENTIONAL CONSTRUCTION. + INDICATES BURNS

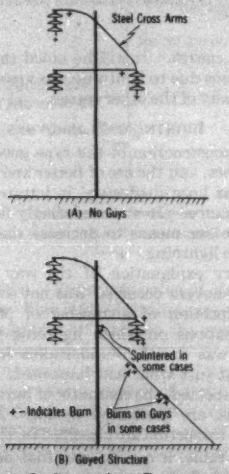


FIG. 3—STEEL ARM CONSTRUCTION

2. On grounded structures the flashovers are from line to ground, usually involving more than one phase. The flashovers to ground of the different phases on any one structure, may or may not occur simultaneously.

3. On guyed structures, with the guy separated on the pole from the steel arm or brace, line-to-line flashovers frequently occur without power arcs to ground.

4. Splinters found on poles between crossarms and guys with burns on insulators or conductors and on arms or braces, but with no burns on the guys, indicate that a power arc has taken place between conductors, but that the lightning has taken a path to ground over the guy without a follow-up power arc.

The operating record of the 132-kv. lines in the territory concerned shows that lightning voltages high enough to cause flashovers seldom occur. The lightning flashover value of the insulator strings based upon the wave used by the Pittsfield Laboratory of the General Electric Company and the calculated protective ratio of the overhead ground wire are such that flashover should not occur with induced voltages below 37 kv. per foot. Therefore, the induced lightning voltages on lines carried on wood-pole structures, such as those used for 33,000-volt lines, with the conductors about 33 ft. above the ground, should rarely exceed 1250 kv. The lightning voltage required to flash over the wood-pole structure to ground is estimated to be of the order of 3000 kv. minimum, which is considerably higher than the voltages actually occurring as given above.[1] This reasoning supports the observation made from the inspection of structures that flashovers occur on plain (non-grounded or non-guyed) structures without arcing to ground.

TABLE III

ANALYSIS OF PATH OF FLASHOVERS ON WOOD STRUCTURES

| Type of structure | Figure | Number of structures inspected | Number of structures on which no burns were found | Line-to-line burns only | Line-to-ground or guy burns on one or more conductors |
|---|---|---|---|---|---|
| Steel brace, wood x-arms, no guys, no grounds | 2-B | 14 | | 14 | |
| Steel X-arm no guys, no grounds | 3-A | 79 | 74 | 5 | |
| Totals without guys or grounds | | 93 | 74 | 19 | |
| Guyed or grounded structures | 2-A | | | | |
| Guyed structure steel x-arm no ground | 2-C | 17 | | 1 | 16 |
| Total, guyed or grounded | 3-B | 16 | 5 | 7* | 4 |
| Total, all structures | | 33 | 5 | 8 | 20 |
| | | 126 | 79 | 27 | 20 |

*Of these seven, four showed pole splinters between steel crossarm and guy.

Consideration of the large number of lightning flashovers which occur on plain structures, in relation to information which has been published on relative frequency of low and high values of lightning surge voltages, also appears to warrant the conclusion that many power arc flashovers must occur at voltages

1. For references see Bibliography.

much lower than those required for complete structure spark-over.[3]

The evidence and reasoning so far presented lead to the conclusion that flashovers on 33,000-volt wood pole construction occur at lightning surge voltages below those required to spark over the entire structure, and that these flashovers are line-to-line rather than from line to ground.[1,2,3] Inspection of the locations where flashovers have occurred and the information in Tables I and III show that flashovers are reasonably well divided between guyed or grounded structures, and plain structures without guys or grounds. Both classes of trouble have an important bearing on the line performance and must be materially reduced for satisfactory operation. Flashovers on guyed or grounded poles are readily explained by the fact that the lightning spark-over value of this type of structure is only that of the insulator alone or of the insulator plus the small distance over the wood arm from insulator pin to steel brace. This is obviously quite low on 33-kv. lines.

The following explanation of flashovers on plain structures is offered. The voltage distribution between line and ground over the insulators and structure is such that the voltage stress over the insulator, or between line and crossarm brace, is high enough to cause spark-over or incipient sparks between line and brace only, at voltages lower than those required for structure spark-over. The 60-cycle voltage on the line causes a power arc to follow over the simultaneous lightning sparks from more than one conductor to brace, and a short circuit is established from line to line through the brace. In some instances on guyed structures, as indicated by observations four and five referring to Table III, the evidence indicates a line-to-line short circuit without a power arc to ground, but with the lightning taking a path to ground through the guy.

## New 33,000-Volt Structure Design

It was apparent from the foregoing investigations that if material reduction were to be made in the number of lightning flashovers a radical change in design would be required. Experience with insulators of higher voltage rating in certain locations indicated that these alone would not give appreciably better results. More effective use of the inherent impulse insulation value of the wood in insulators was obviously necessary.[1,3,4] The next steps to be considered were the elimination of the conducting crossarm brace and an increase in the separation between conductors on the structures. It was believed that if these objectives could be accomplished, line-to-line short circuits could not occur except at a lightning surge voltage high enough to cause complete structure flashover. The design shown in Fig. 4 was accordingly worked out. It will be noted that this allows approximately 9 ft. of wood between insulator pins. The wood braces are so arranged that the distance on the crossarm from the point of attachment of the brace to the pole is equal to the distance between metal fittings on the brace. The dimensions selected were the result of using a standard crossarm to obtain the maximum practical separation between conductors. Separation less than 9 ft. might be reasonably satisfactory, but the resultant saving would be small and certainly not worth the chance that such lesser separation might not be satisfactory. It is believed that with this construction, incipient sparks forming over the insulators will not develop into short circuits, and that the only flashovers will be those caused by lightning voltages of such character and magnitude as to cause complete structure flashover to ground.

Evidence of the effectiveness of eliminating conducting parts between conductor supports on wood-pole construction in preventing line-to-line flashovers has been furnished by the performance of an H-frame line built with the same insulation as the standard 33-kv.

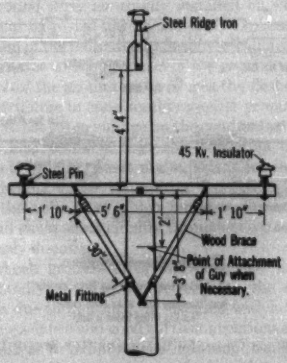


Fig. 4—New Design, 33,000-Volt Wood Pole Construction

wood-pole lines, but with a 5-ft. separation between insulator pins and with no metal braces short circuiting any portion of the wood crossarms. Investigation of all locations where flashovers had been found showed that the flashovers, with one exception, were all to ground on guyed structures. One case was found where a line-to-line flashover had occurred over the five feet of wood between insulator pins. This indicated that a separation of more than five feet on a wood-structure would generally be sufficient to prevent 33-kv. line-to-line short circuits, except for occasional unusually severe lightning voltages.

If flashovers of the plain structures are prevented by the new design, the guyed structures become the most susceptible to flashover. The obvious solution is to provide as much insulation as possible with respect to lightning between the line conductors and the grounded portions of the guys. This is accomplished by attaching the guys to the poles as far as possible below the

crossarms or insulator attachment to the pole, and by adapting the wood crossarm brace in tension as a guy strain insulator, with two of them used in series on each guy.

The vertical corner construction in use was modified to a design with a six-foot separation between conductors on the pole, wood-guy strain insulators, and the guys attached to the pole midway between line insulator attachments. The line insulation on corners was increased to three insulator units (6.5-inch spacing) in series. Maximum use is thus made of the inherent insulating value of the wood in the structure.

The design of the wood brace and guy insulator, illustrated in Fig. 5, is interesting. A wedge assembly is inserted into a saw-cut at the end of the wood member. The assembly is held together by means of steel plates on the outside of the wood, bolted as shown. The straps which take the load are slotted lengthwise.

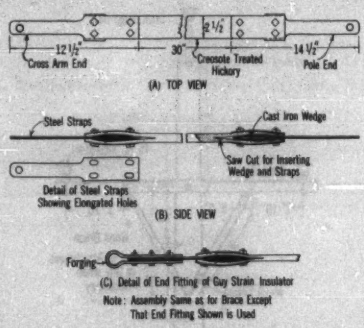


FIG. 5—WOOD CROSSARM BRACE AND GUY STRAIN INSULATOR

When tension or compression load is applied to the brace, the load is transferred from the end straps to the wood member by means of the wedge, which places the wood between the wedge and outside plates in compression with the bolts acting in tension. The slots in the end straps prevent shear on the bolts. The guy strain insulator under test develops a maximum strength in tension of 16,000 lb., the failure occurring in the end straps. The strength developed is not required of the brace, but this design was considered necessary for satisfactory assembly on the structure and for satisfactory operation during the life of the structure.

In order to obtain information as to the expected lightning performance of the new design, tests which gave the following approximate results were made with the cooperation of the General Electric Company at the Pittsfield high-voltage laboratory.

Tests on a guyed structure without guy insulators, using the old design, Fig. 1, and 45-kv. insulators, showed a lightning spark-over value of less than 400 kv., the insulator spark-over by itself occurring very close to the value required for complete structure flashover. On a plain wet structure without guys or grounds, using a 14-ft. effective length of pole and 70-kv. insulators, spark-over of the insulator itself occurred at about 900 kv., whereas the structure spark-over value was 2600 kv. The tests with a wet pole showed that with increasing height, the value at which the insulator spark-over occurred remained very nearly constant, while the structure spark-over value naturally increased with increasing length of pole. With a 45-kv. insulator the incipient spark-over on the insulator alone would have taken place at a value somewhat less than 900 kv. The value of lightning voltage at which this incipient spark takes place is considered to correspond to the value at which a 60-cycle arc would form as a short circuit between conductors with the steel-brace construction.

Tests with dry poles showed that spark-over of both the insulator and the complete structure took place almost simultaneously at nearly the same values of voltage.

The tests accordingly indicate that the line-to-line flashovers which take place on plain structures at low lightning-surge voltages may occur only when the structures are wet or possibly in connection with weathered or dirty structures whose behavior in the field is something like that of wet structures.

Tests of the new design, Fig. 4, showed the lightning spark-over value of the guyed structure without insulators in the guy to be approximately 1040 kv. The lightning generator arrangement used in these tests would not give sufficient voltage to cause structure spark-over with two insulators in the guy, but it is estimated, on the basis of correlated test data, that the two wood insulators to be used in the guy would raise the lightning spark-over value of the structure to approximately 1800 kv. It is believed that this is above the range of the usual maximum lightning-surge voltages which appear on the lines.

Pole-top switches appear to be especially susceptible to lightning flashover. These have heretofore been installed on wood poles by means of a grounded steel supporting frame. It was recognized that, if the trouble on the pole top switches were to be prevented, the same principles worked out for the new line construction would have to be applied to the pole-top switches. The matter has been taken up with the manufacturers, and several have worked out designs using wood-frame mountings with increased separation between phases, with wood-insulator interconnecting units in the operating mechanism and in the operating rod, and with only the operating handle grounded.

Another question which must be considered in connection with the new construction is the relation of line flashover value to that of station equipment flashover value. The change in design on the plain structures does not give a flashover value to ground materially different from that on old construction. However, the

use of insulation in the guys will greatly raise the flashover value of all guyed structures. Lines entering substations are usually built with guyed structures close to the line terminal.

These locations in the past have apparently been acting as "safety valves," as their flashover value has usually been below that of the station insulation. A failure in the insulation of station equipment, however, is generally so much more serious that it is important to have the flashover of these "safety valves" always coordinated with the station insulation. Out on the line away from station equipment, the insulation may be as high as the economics of the situation will permit, but adjacent to the station, the insulation should be reduced to a value below that of the station equipment. To prevent service interruptions due to flashover at these points of reduced insulation, lightning arresters may be used. If the lightning arresters function properly, the reduced insulation should not flash over; if the lightning arresters do not function properly, the reduced insulation acting as "safety valves" prevents breakdown of the station equipment. In case it is considered that lightning arresters are not economically feasible because of the small amount of power being transmitted or the relatively small amount of equipment at the station, the use of fused arcing devices or their equivalent may provide one solution to the problem.

The effect of the line insulator with respect to the lightning spark-over of a wood-pole structure not guyed or grounded is relatively small. The lightning spark-over value of a 45-kv. insulator alone is about 260 kv., while that of an average 30-foot pole with crossarm is about 6000 kv.[1] On a guyed structure of the new design with an estimated lightning spark-over value of 1800 kv., the line insulator will still contribute only a small part of the total insulation against lightning. The size of the insulator for lines of this class therefore appears to be relatively unimportant on a structure well-insulated from ground for lightning voltages, and will be determined by the requirements with respect to preventing leakage of power current of normal frequency.

## Overhead Ground Wires

The effectiveness of overhead ground wires on wood structures in reducing interruptions due to lightning has been an open question.[5] Overhead ground wires were removed from certain lines several years ago. Records before and after removal show no consistent difference in performance. Comparison of performance of the small mileage of lines still equipped with overhead ground wires with other lines in the same territory without ground wires shows the same result. This is illustrated by Table IV, which shows the two-year record of the performance of several lines with overhead ground wires. It is of interest to compare this record with that for the entire 33,000-volt system as given in Table I.

TABLE IV
LIGHTNING PERFORMANCE OF LINES WITH OVERHEAD GROUND WIRES

| Line | Length in miles | Number of trip-outs directly due to lightning, 1928, per 100 miles | Number of trip-outs directly due to lightning, 1929, per 100 miles |
|---|---|---|---|
| *A* | 31.13 | 29 | 51 |
| *B* | 26.44 | 33 | 57 |
| *C* | 30.82 | 20 | 10 |
| Total* | 88.39 | 27 | 36 |

*Totals figured by adding all T.O. and dividing by total miles.

The overhead ground wires are of either ⅜-in. galvanized steel or ¼-in. copper covered steel and are carried either on the pole top or at the end of a four-ft. crossarm, the other end of which carries one conductor. Earth connections are made at intervals of about every 600 to 800 ft. The down leads are fastened directly to the poles for the entire length and are terminated in ten-ft. galvanized ground pipes.

The difference between the effectiveness of the overhead ground wires as usually installed on wood structures, and on metal towers, is readily explained by consideration of the reduction in flashover value of the wood structure due to the presence of the ground wire. The presence of the ground wire reduces the flashover value of the structure in considerably greater proportion than it reduces the surge voltage on the conductors.

It is also probable that this reduction of induced voltage is in many cases not sufficient for the value of the lightning surge voltage on the conductors to be below the voltage at which incipient insulator spark-over will cause short circuits through the steel brace, as previously discussed.

Overhead ground wires on wood pole lines would undoubtedly be effective in reducing the number of outages due to lightning, if installed with low values of surge impedance and good earth connections and in such a manner as to maintain the lightning insulation value between conductors and ground wires above the values of lightning surge voltage for which a line is designed. The elimination of metal crossarm braces, the installation of the down-lead ground connections insulated by air or otherwise from the pole tops and conductors, and the use of insulated supports for the overhead ground wire, are methods which assist in increasing its effectiveness.

Except where lightning conditions are severe, it is probable that wood pole lines without metal crossarm span braces and with well insulated guys built without overhead ground wires will withstand most lightning surge voltages appearing on the conductors. In situations where splitting of structures from lightning is serious, the overhead ground wire, if installed so that the flashover value of the structure is not too greatly decreased, may be justified. The use of protective gaps to prevent structure damage should, of course, also be considered. The number of cases of lightning damage to wood structures on the system described has not been considered sufficient to warrant the general use of

protective measures with respect to pole or crossarm splitting.

### Insulator Performance

The study of damaged insulators removed from the line has yielded valuable information relative to the service obtained from insulators of various types. The total amount of insulator damage on the system from both electrical causes and from external breakage is

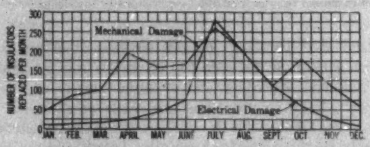


Fig. 6—Insulator Damage per Month for the Year 1928

shown by Figs. 6 and 7. Insulators replaced in connection with the annual line-insulator testing program are not included. The curves, together with the last two items in Table I, indicate that replacements are an item of considerable expense. The external breakage is shown to be more than twice the electrical damage. Fig. 8 shows a portion of a study of one line upon which an unusual number of damaged insulators has been replaced. This study was made with the object of visualizing the effect, if any, of the geographical and physical characteristics of the line upon the insulator

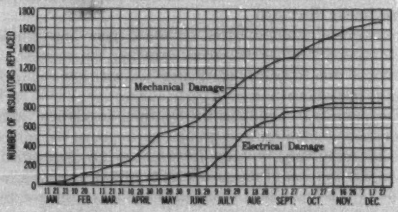


Fig. 7—Total Insulator Damage During the Year 1928

performance. The electrical and mechanical insulator damages are shown for each group of ten poles throughout the length of the line.

Table V gives an analysis of damage to insulators replaced on account of defects from electrical causes. This does not include all insulators flashed over during this period, as many arc-overs occur which do not damage the insulator sufficiently to be located. It will be noted that the greater percentage of insulators broken are of the two-piece type. This may be due to the difference in design of the two-piece and three-piece insulators, the latter being generally made up of shorter and thicker skirts of a smaller diameter than the former. A large percentage of the three-piece insulators are of designs now obsolete, which have developed many shell cracks.

It is also seen that a considerable number of both types of insulators is flashed but not broken, while about the same number has only one skirt broken and a much smaller number is shattered. These figures give an indication of the number of insulators which

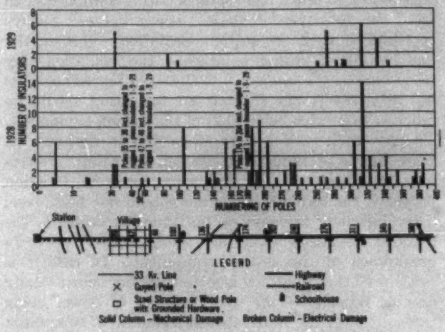


Fig. 8—Map of Line

remain on the line in a more or less hazardous condition after a flashover occurs, and until they are discovered by patrol and replaced.

A study of the records indicates that there is little difference in the susceptibility to lightning flashover between obsolete and new insulators. However, the data show quite conclusively that certain types of the

TABLE V
CLASSIFICATION OF INSULATOR DAMAGE FROM ELECTRICAL CAUSES
Jan. 1—Dec. 31, 1927

| Nature and extent of damage | Quantity of insulators damaged | | Damaged insulators per 1000 in service of each type | |
|---|---|---|---|---|
| | 2-piece | 3-piece | 2-piece | 3-piece |
| Small burn (not bad enough to replace) | 17 | 16 | 0.485 | 0.188 |
| Flashed but not broken | 84 | 104 | 2.4 | 1.22 |
| One skirt broken | 82 | 112 | 2.34 | 1.32 |
| More than one skirt broken | 15 | 22 | 0.429 | 0.259 |
| Shattered | 19 | 31 | 0.543 | 0.264 |
| Broken but unclassified | 17 | 35 | 0.485 | 0.412 |
| Total | 234 | 320 | 6.69 | 3.76 |

Total—2-piece insulators in service—35,000
Total—3-piece insulators in service—85,000

old insulators are much more susceptible to shattering than modern insulators, when flashover occurs. When shattering occurs, the line will often not go back into service, or the wire will drop onto the crossarm causing a structure fire. It appears that the cracks in the top

shells of the old insulators are an important factor in this kind of trouble.

The performance of the old insulators with shell cracks has been a matter of much concern. A line-insulator testing program which has been under way for several years has resulted in the removal of a large number of the cracked insulators from service. However, visual inspection of insulators in service and of those removed from service for various reasons other than the test program, indicates that because of the progressive cracking which occurs, the lapse in time between test periods, and the difficulty of picking out clean cracks, a considerable number of insulators with cracks is continually in operation. Records are available of two 33,000-volt lines, each with a different type of 45,000-volt insulator. In one case 89 per cent of the insulators had top-shell cracks, while in the other case 45 per cent were so affected. There were no cases of insulator failure (electrical breakdown through the porcelain) on these lines during 1929.

A good many cracks are also found in the center and bottom shells, and inspection of the insulators which have failed, frequently discloses old cracks in more than one shell. There is, accordingly, good ground for the belief that with 45,000-volt insulators on 33,000-volt lines, cracking of only the top shell does not seriously affect the operation of the line, and that the insulator failures which cause interruptions are practically all due to the failure of the porcelain in more than one shell. The study of cases of trouble in which conductors were burned down or in which structures were burned shows that the types of insulators in which cracks were prevalent, largely of the older types, were largely responsible for the conductor or structure failures aside from cases of lightning flashover. This is shown by Table VI.

TABLE VI
NUMBER OF CASES OF CONDUCTOR OR STRUCTURE FAILURES AS INFLUENCED BY INSULATOR CRACKING

| | With insulators free from cracking | With insulators subject to cracking |
|---|---|---|
| Conductor burned down due to lightning flashovers | 22 | 19 |
| Conductor burned down due to insulator failure (not lightning) | 0 | 19 |
| Total | 22 | 38 |
| Structure burned due to insulator failure (not lightning) | 0 | 103 |

The damage to insulators from external breakage is shown by Table VII. Damage of this class is due to such causes as blasting where the line is near quarrying operations, stone throwing, shooting, and so on. As was observed with respect to electrical breakage, two-piece insulator damage is relatively greater than the three-piece insulator damage.

It is frequently taken for granted that insulator breakage cannot be materially reduced. However, in an effort to accomplish something in this direction, installations of thick porcelain one-piece insulators were made in locations where an extraordinary amount of breakage was being experienced. The results are shown in Fig. 8. During 1928, with two-piece insulators, breakage was especially severe between poles 176 and 204, in the vicinity of a schoolhouse. One-piece insulators were installed on these poles early in 1929, and since that time no replacements have been required on account of breakage.

TABLE VII
CLASSIFICATION OF INSULATOR DAMAGE FROM EXTERNAL BREAKAGE
Jan. 1—Dec. 31, 1929

| Nature and extent of damage | Quantity of insulators damaged | | Damaged insulators per 1000 in service of each type | |
|---|---|---|---|---|
| | 2-piece | 3-piece | 2-piece | 3-piece |
| Small chip | 140 | 365 | 4.0 | 4.3 |
| One skirt broken | 285 | 370 | 8.14 | 4.45 |
| More than one skirt broken | 39 | 69 | 1.11 | 0.812 |
| Shattered | 1 | 8 | 0.0288 | 0.0941 |
| Broken but unclassified | 119 | 176 | 3.4 | 2.07 |
| Total | 584 | 997 | 16.7 | 11.7 |

Total 2-piece insulators in service—35,000
Total 3-piece insulators in service—85,000

A large number of the one-piece sturdy insulators placed in service during the past year have given an especially satisfactory record of operation. Of the total of 5000 installed during 1929, only five have required replacement because of breakage.

Two types of one-piece insulators are being used, both being selected primarily on account of their ruggedness. Other points, such as dependability of manufacturing processes and freedom from some of the causes which are believed to have contributed to troubles with multi-part insulators, were also considered. One type is similar in shape to the conventional two-piece unit. The other is more cylindrical in outline and has five thick narrow skirts of the same diameter.

The ability of various makes and types of insulators to withstand breakage was investigated in the laboratory. A one-inch steel ball was dropped on the skirt of an insulator by a special testing device from various heights starting at 18 in. and increasing by increments of 6 in. Three tests were made from each height, the tests being continued until the insulator was badly chipped or broken.

The comparison of the insulators tested is shown by Fig. 9. (*A*) is the thick-porcelain one-piece insulator of conventional shape, which is now being installed; *B*, *C*, *D*, *F*, *G*, and *H* are two-piece 45-kv. insulators of different manufactures, the shapes all being quite similar. As one outcome of these tests, suggestions made to one manufacturer resulted in design changes to one insulator which placed it in the class of the most sturdy insulators.

A considerable difference in decrease of flashover

value of different types of insulators, when broken, was also found as a result of these tests.

### Conductor Failures

A study of the cases of conductor failures due to the arc following lightning flashovers indicated that the susceptibility of wires to burn-down is a function of conductor size. The smaller sizes, No. 0 and

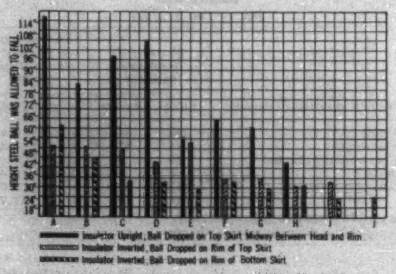


Fig. 9—Mechanical Shock Resistance Test of Insulators

The height of the lines, which show the shocks applied in different ways, indicates the points at which large chips or definite breaks occurred. Each group of lines represents one insulator.

smaller, show more cases of this kind of conductor failure than the larger sizes. Satisfactory data are not now available to evaluate the differences in this respect between the several wire sizes.

### Conclusion

The high degree of reliability being obtained from transmission lines of the higher order of voltages, 110,000 volts and above, which are insulated to withstand the lightning surge voltages to which they are subjected, indicates that it should be possible to build lower-voltage lines which will give a class of service not obtainable with designs ordinarily in use at present. Wood pole structures of the present ordinary design are subject to flashover from the action of lightning-surge voltages much lower than voltages required to cause structure flashover from line to ground. By revision of the present designs of wood pole structures to make full use of the inherent insulating value of the crossarms and poles against lightning surge voltages, and by elimination of metal braces or other parts tending to make conducting paths between phases, it should be possible to obtain highly satisfactory operation with respect to lightning troubles. Lines are now being constructed with wood crossarm braces and wood guy insulators which, it is believed, will be practically free from lightning troubles.

The performance of lines of the new design will be watched closely, and information relative to this will be available later.

The records of operation of wood-pole lines with overhead ground wires, when considered in connection with the information given relative to lightning flashovers, shows that the overhead ground wires as usually installed do not improve the performance of wood-pole lines. Overhead ground wires, to be effective, should be so installed that as much as possible of the inherent insulating value of the structure is retained.

Electrical breakage of old-style pin-type insulators is serious with respect to number of line failures due to flashover. Breakage of insulators from mechanical causes is greater quantitatively than from electrical causes. Mechanical breakage is greatly reduced by the use of more sturdy insulators which are now available.

Systematic thorough investigation of line troubles, with well-organized records and proper interpretation of the facts thus made available, are necessary if proper application of operating experience is to be made use of in the design of transmission systems. The importance of establishing a systematic plan of periodically summarizing and analyzing the facts available from the records is to be emphasized. The day-to-day records, by themselves, are usually of little value. It is only by regularly gleaning the facts from them by a well defined plan that they become valuable. These facts, properly used, will form a basis for great improvement in system reliability and more effective utilization of investment.

### Acknowledgments

The authors express their appreciation of the cooperation and assistance given them by Mr. F. W. Peek, Jr., of the General Electric Company, and his staff at the Pittsfield laboratory in obtaining the laboratory test data required, and for advice given on the problems discussed in this paper. They also gratefully acknowledge the help given by their associates and by the management of the Public Service Company of Northern Illinois in securing and making available the information contained in the paper.

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## Discussion

**J. T. Kelly:** I was particularly interested in one point which the authors brought out which seems rather peculiar at first glance and that is the flashover of an insulator without establishing an arc to ground. On any transmission structure involving wood members we have a series of insulators,—the insulator itself, a short section of crossarm between insulator and metal brace, a short section of pole perhaps, between the metal brace and grounded guy attachment, or other metal attachment. In many structures there is a great number of small insulating elements between conductor and ground. Now, that series of insulators is also something else. It is likewise a series of condensers, since a condenser is a dielectric interposed between two conducting plates, and if one thinks of a transmission structure, particularly a wood pole structure, in those terms, it is apparent that there may be a large series of condensers between line conductor and ground. In any series of condensers, when the weakest member of the series is over-stressed, that is the condenser of lowest capacitance, that condenser will discharge, and that is exactly the phenomenon which takes place and to which Mr. Andrews made reference.

This is a very useful point of view in visualizing some of these phenomena. It is also an extremely useful standpoint when analyzing radio trouble because if one thinks of the setup as a series of condensers, it will help many times in finding the particular condenser causing the radio trouble.

**C. L. Stroup:** I wish to thank Mr. Kelly for his words. In collecting data it became necessary to set up quite an organization to obtain the information and compile it in a systematic way. This organization is being maintained and will continue to function and it is hoped to obtain information which will be of operating value to the industry.

# Arcing Grounds and Effect of Neutral Grounding Impedance

BY J. E. CLEM*

Associate, A. I. E. E.

*Synopsis.—This paper was written to review and extend the theory of overvoltages due to arcing grounds because of the increasing tendency to use impedances between the neutral point and the ground, thereby losing the advantage of the solidly grounded neutral. The "third class conductor" theory of Steinmetz is touched upon very briefly and is considered as not applying to transmission line conditions. The theory when the phenomenon is controlled by normal frequency arc extinction, as presented by Peters and Slepian, is reviewed and the maximum voltage for this analysis is found to be* $3\frac{1}{2}E$, *where E is the normal line to neutral voltage. The theory when the phenomenon is controlled by oscillatory frequency arc extinction as originated by Dr. Petersen is given in detail but in a modified and extended form. The maximum voltage for a single-phase circuit when no damping is considered is found to be 6 E.*

*The analysis for the three-phase circuit is newly developed for the case in which there is an impedance between the neutral and ground and the maximum voltage is found to be* $7\frac{1}{2}E$ *when the effect of the damping factors and capacitance between lines is neglected. The method of determining the various reductions or damping factors is outlined.*

*The effect of a neutral grounding resistor is discussed and it is pointed out that a suprisingly high value of resistance can be used without incurring the possibility of dangerous overvoltages. It is shown that the use of reactance is more liable to result in overvoltages than resistance but that relatively large values of reactance can be used in conjunction with resistance.*

*The Petersen Coil is usually considered as causing the arc to go out by giving a balance of lagging and leading currents in the arc. It is brought out in this paper that there will be no voltages built up when the Petersen Coil is used whether or not the arc goes out.*

*The relation of the overvoltages on a non-grounded and an effectively grounded system is outlined, and a criterion for determining whether or not a system is effectively grounded is proposed.*

## Introduction

In the operation of power distribution systems overvoltages appear on the transmission lines, whether overhead or cable, from switching, arcing grounds, and lightning. These overvoltages are frequently of sufficient magnitude to cause interruption of service and sometimes to destroy apparatus. The hazard of arcing grounds is completely eliminated by connecting the neutral directly to ground, but the present day tendency is away from the direct ground connection on account of the necessity of keeping down the concentration of power in a short circuit, to reduce the damage to equipment at the location of the short circuit, to increase stability, and to a lesser extent to lower the duty on circuit breakers by inserting an impedance in the neutral. The purpose of this article is to review briefly the various analyses[1] proposed for the explanation of the overvoltages caused by arcing grounds, to extend the theory, and to apply it to grounded neutral circuits.

There are in general three methods of explaining the high voltages produced by arcing grounds. The first two are quite similar and are based on the familiar theory of the oscillatory charge of a capacitance through resistance and inductance. They differ only in the manner in which the arc is considered to go out. In one case the arc is considered to go out at the instant when the normal frequency current passes through zero. When the neutral is grounded through a moderate impedance the phenomenon will most likely be controlled by normal frequency arc extinction but it is useful to know what might happen if the phenomenon was controlled by oscillatory arc extinction. In both the arc is considered to strike again as soon as the faulty line rises to its maximum potential against ground.

The third method is due to Dr. Steinmetz and is based on what he termed a "third class conductor." In ordinary conductors an increase of current requires an increase of voltage and the resistance may be defined as

$$\frac{\Delta E}{\Delta I} = r$$

In an arc the characteristics are such that the ratio of voltage to current is not constant, the resistance tending to rise with decreasing current. An increment of current then requires a decrement of voltage and if the ratio be defined as $r'$

$$r' = -\frac{\Delta E}{\Delta I}$$

An oscillation dies away because the energy is consumed in resistance and the rate is given by the factor $\epsilon^{-rt}$ which occurs in the equations. If the quantity $r$ in the exponent should itself happen to be negative the factor would be $\epsilon^{rt}$ and the transient, instead of dying away, would increase beyond all bounds. However, from available data it appears that this characteristic probably does not apply to the arcing ground as it occurs on an overhead line.

## Summary

In this paper there is developed the following expression for estimating the maximum voltage that may be

*Central Station Engg. Dept., General Electric Company, Schenectady, N. Y.

1. For references see Bibliography.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

produced by an arcing ground on a grounded system, on the basis that the arcing ground voltage is controlled by oscillatory arc extinction.

$$\frac{V}{E} = \frac{3}{2}\,\frac{(2-d)(3-2b) - \left(1 + 2\frac{C}{C_m}\right)(1-d)}{3 - 2(1-a)(1-d)}$$

$V$ = maximum voltage to which sound lines oscillate
$E$ = normal voltage line to neutral-maximum
$1 - d$ = damping factor of oscillation
$1 - a$ = damping factor of redistribution of bound charge
$1 - b$ = damping factor due to presence of neutral ground impedance
$C$ = average capacitance of single conductor to ground
$C_m$ = average mutual capacitance between pairs of conductors

This equation, as has just been mentioned, is based on the assumption that the phenomenon is controlled by oscillatory frequency, arc extinction, whereas when there is an impedance in the neutral, the phenomenon is very probably controlled by normal frequency arc extinction. Also, the assumption is made that each successive striking of the arc from the faulty line to ground occurs at an increasing voltage. In addition, the ionization of the arc, which may cause it to be maintained, is neglected. These factors tend toward lower voltages.

In any oscillation the voltage will go as far on one side of the average or applied value as it does on the other, unless there is damping. When there is damping the voltage on the first oscillation fails to go to twice the applied and the factor $(1 - d)$ is a measure of this; for instance, if the applied voltage was 100 volts and on the first oscillation the voltage rose to 180 volts, the factor $(1 - d)$ would be 0.9.

In the analysis of the arcing ground condition the fundamental assumption is that a charge is trapped on the sound lines when the arc is extinguished. This bound charge, as it is called, is that required to establish the voltage present on the sound lines at the instant the arc goes out. This charge redistributes throughout the system between the extinguishing of the arc and the restriking of the arc on the next normal frequency cycle and establishes an average potential. However, during this interval a certain part of the charge leaks off to ground and the average potential is reduced proportionately and the factor $(1 - a)$ is the measure of this effect. As an example, if the bound charge was such that it would establish an average potential of 100 volts if no leakage occurred but actually does establish an average potential of 60 volts, the factor $(1 - a)$ is 0.6.

If, on an isolated system, one line becomes grounded the neutral rises to leg voltage above ground, but if the system is grounded through an impedance the shift of the neutral will be less depending upon the relative value of the neutral grounding impedance and the factor $(1 - b)$ makes allowance for this effect. For instance, if the leg voltage is 100 volts and on a fault the neutral rises to 30 volts the factor $(1 - b)$ would be 0.3.

On an ungrounded system the maximum voltage which may be developed by an arcing ground is $3\frac{1}{2}E$ if the phenomenon is controlled by normal frequency arc extinction and $7\frac{1}{2}E$ if controlled by oscillatory frequency arc extinction. The limiting value of $7\frac{1}{2}E$ is obtained when the effect of the mutual capacitance between conductors and all damping factors are neglected. On average lines the ratio of $C/C_m$ ranges from 0.18 to 0.28 so that the effect of mutual capacitance is to reduce the limiting overvoltage from $7\frac{1}{2}E$ to a value between $6.66E$ and $6.96E$. Fair values of the damping factors $(1 - d)$ and $(1 - a)$ are about 0.95, tending to be slightly higher for $(1 - d)$ and slightly lower for $(1 - a)$, and these reduce the probable maximum voltage for an arcing ground on an isolated system to a value between $5.3E$ and $5.7E$.

On a grounded system there can be no overvoltage from arcing grounds if the neutral is solidly grounded. In this case there is no neutral shift and the factor $(1 - b)$ becomes zero as also does the factor $(1 - a)$ with the result that no overvoltage appears from the calculations. However, if an impedance is inserted in the neutral the amount of overvoltage that may be calculated on the basis that the phenomenon is controlled by the oscillatory frequency arc extinctions depends upon the amount and kind of such impedance. If the impedance consists of resistance alone a surprisingly high value may be used without incurring any chance of dangerous arcing ground voltages being set up. As the resistance is increased the discharge of the bound charge to ground through the resistance changes from oscillatory to unidirectional and a value of resistance equal to twice the critical value can be used without exceeding a calculated voltage of $2\frac{1}{2}E$. If the impedance consists of reactance the calculated voltages will be higher but values of reactance high enough for practical purposes can be used without danger of serious arcing ground voltages. If the neutral grounding reactance is of such a value as to give a neutral shift of $66\frac{2}{3}$ per cent $E$ on short circuit the arcing ground voltage would calculate from $3.7E$ to $4E$, the variation

in calculating voltage being due to the variation in assumed mutual capacitance between lines—see Table III. When the values of neutral grounding impedance are such that these voltages are not exceeded the system will be effectively grounded.

The following tabulation gives the maximum voltages for the conditions already outlined.

TABLE I
TABULATION OF MAXIMUM VOLTAGES

| Isolated system | Single phase | Three phase |
|---|---|---|
| Initial arc | $3E$ | $2\frac{1}{2}E$ |
| Normal frequency arc extinction | $4E$ | $3\frac{1}{2}E$ |
| Oscillatory frequency arc extinction | | |
| Isolated System | | |
| a—No damping | $6E$ | $7\frac{1}{2}E$ |
| b—Capacitance only | | $6.7E$—$7E$ |
| c—Capacitance and damping | | $5.3E$—$5.7E$ |
| Effectively grounded system (see below) | | |
| a—Through resistance only | | $2\frac{1}{2}E$ |
| b—Through reactance only | | $3.7E$—$4E$ |

From this tabulation it is seen that the probable maximum voltage that may be produced on an isolated system by an arcing ground is approximately 5.5 times the normal line to neutral voltage. This is approximately the same as the overvoltages produced by switching surges. The insulation required for both types of overvoltages must be based on the 60-cycle flashover characteristics of the insulation.

It is customary at times to base the insulation of transformers and cables upon a decision as to whether the system can be classified as a grounded or non-grounded system. In the past it has usually been the practise to consider a system as non-grounded unless the neutrals were solidly grounded. For a non-grounded system the apparatus has, in general, insulation based on 3.46 times the rated line to neutral voltage and the maximum arcing ground voltages calculate in the neighborhood of 5.7 times. However, the apparatus gives satisfactory service and so must have some factor of safety. If insulation is used corresponding to a 2.73 test the arcing ground voltage should not calculate more than 4.5 times normal line to neutral voltage for the same factor of safety. This condition is satisfactorily met when the reactance between the neutral and ground is such that the neutral shift is less than two-thirds the normal line to neutral voltage; and is more than met when the resistance between the neutral and ground is such that the lagging component of the fault current is equal to or greater than the leading component. This condition gives a resistance less than the critical resistance previously mentioned. The foregoing statements are based on the assumption that the arcing ground phenomenon is controlled by the oscillatory arc extinction and if the phenomenon is controlled by the normal frequency arc extinction the arcing ground voltages will be less.

On this basis a system may be said to be effectively grounded when:

(a) *Grounded through resistance.* If a system is grounded through resistance only it may be classified as an effectively grounded system when the resistance is of such a value that the lagging component of the fault current is equal to or greater than the leading component of the fault current.

(b) *Grounded through reactance.* If a system is grounded through reactance only it may be classified as an effectively grounded system when the value of reactance is such that the neutral shift on a short circuit is not more than two-thirds the normal line to neutral voltage.

A system may be said to be grounded through resistance when resistance only is used between the neutral and ground. In this case some of the neutrals may be solidly grounded and the others grounded through resistance.

A system may be said to be grounded through reactance when a reactance coil is used between neutral and ground, when only part of the neutrals are grounded, or when grounding transformers are used.

The voltage figures previously given are the voltages that are produced on the sound lines under arcing ground conditions, and it was shown how the insulation might be affected. On an isolated system the voltage on the neutral would be two-thirds of the voltage on the sound lines, so that the maximum voltage which might appear on the neutral of an isolated transformer would be $3.53\,E$ to $3.8\,E$. On the assumption that the line end is insulated for a 3.46 test the neutral end should be insulated for a test of 2.04 to 2.31 times normal line to neutral voltage for the same factor of safety. If the system is effectively grounded as previously defined insulation corresponding to a test of two times leg voltage will be ample and a lower value may be used depending upon the calculated voltages and the neutral shift.

The Petersen Coil is a special case of reactance ground for which the reactance value is such that the lagging component of the short-circuit current is made equal to the leading component of the charging current in the fault. For this case the factor $(1 - a)$ becomes $-1$ so that the maximum voltage is limited to $1.34\,E$. The adjustment of the Petersen Coil is not critical so that considerable variation from the resonant value may be allowed without giving much increase in voltage. The Petersen Coil will keep the voltages down to harmless values regardless of whether or not it is set at the resonant value to extinguish the arc.

## Normal Frequency Arc Extinction

In Fig. 1 is shown a single-phase or two-wire circuit with Lines 1 and 2 and the winding of the power source of the circuit. In Fig. 2 are shown the voltages from Line 1 and Line 2 respectively to neutral or ground, and the voltage $E_{12}$, which is the voltage from Line 1 to Line 2 or the voltage between lines. The neutral or ground potential point is at the midpoint of the wind-

ing and the line voltages vary from $(+E)$ to $(-E)$ in respect to the neutral point.

In Fig. 3 are shown the voltages when an arc strikes from Line 2 to ground. The voltage of Line 2 to ground collapses and the potential of Line 2 becomes zero. This takes place almost instantly after the arc strikes. Line 1 is at an initial potential $E_1 = (+E)$ in respect to ground, but zero potential of Line 2 re-

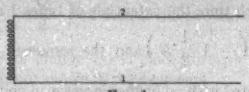


Fig. 1

quires a potential of $(+2E)$ on Line 1. Consequently the potential of Line 1 goes from potential $(+E)$ to potential $(+2E)$ through an oscillation, the impressed voltage being $2E$. The applied voltage producing the oscillation is $(2E - E)$ or $E$, and therefore the ampli-

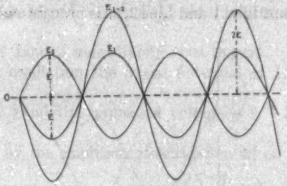

Fig. 2

tude is $E$, and this, neglecting damping, added to the impressed voltage $2E$ gives the maximum value of $3E$. After steady conditions are reached, Line 2 is at ground or zero potential and the line potential $E_1$, to ground,

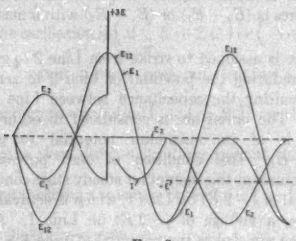

Fig. 3

and voltage $E_{12}$, between lines, coincide, the arc current $I$ being represented 90 deg. ahead of $E_1$.

When the current $I$ passes zero, the arc is assumed to go out. At this instant Line 1 is at a potential $(-2E)$ and has a charge sufficient to establish this potential. This charge diffuses throughout the entire system so that the average potential becomes $(-E)$, the line potentials varying harmonically above and below this potential level as shown in the right hand part of Fig. 3, on the assumption that the defective Line 2 does not arc to ground again.

However, the arc is assumed to strike again as in Fig. 4. This time the initial voltage of Line 1 is 0, the impressed voltage is $2E$, and the amplitude of the oscillation is $2E$ so that the maximum potential that Line 1 reaches is $4E$. As before, the arc goes out when the arc current passes through zero and Line 1 is at a potential of $(-2E)$ and conditions again are exactly as they were before the arc struck. This process may be

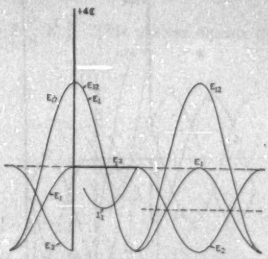

Fig. 4

repeated with no further increase in voltage until the circuit conditions change in some way.

The analysis for a three-phase circuit is similar to that just given for the single-phase circuit. In Fig. 5 is shown the circuit and in Fig. 6 are shown the voltages. Line 2 is the faulty line and it arcs to ground at the instant of maximum potential and immediately goes to ground or zero potential. Zero potential on Line 2 requires a potential of $1.5E$ on both Line 1 and Line 3 but these two lines are at an initial potential $\left(+\frac{1}{2}E\right)$ and

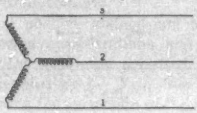


Fig. 5

pass from the initial condition of $\left(+\frac{1}{2}E\right)$ potential to the ultimate condition of $\left(+1\frac{1}{2}E\right)$ through an oscillation. The impressed voltage producing the oscillation is $\left(+1\frac{1}{2}E\right)$ and the applied voltage

$\left(1\frac{1}{2}E - \frac{1}{2}E\right) = E$, therefore the amplitude is $E$, giving $2\frac{1}{2}E$ as the maximum voltage of the first oscillation.

After the oscillation has died out conditions are also shown in Fig. 6. Line 2 is at zero potential and Lines

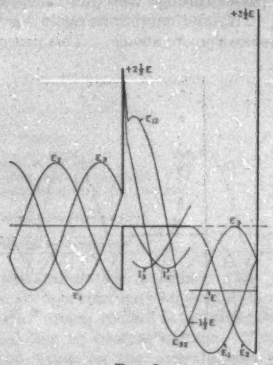

FIG. 6

1 and 3 have the potential $E_{12}$ and $E_{32}$ as shown. The arc current is made up of $I_3$ and $I_1$ which are shown 90 deg. ahead of their respective voltages. The arc will go out at the instant the arc current $(I_3 + I_1)$ is zero. At this instant Lines 1 and 3 are both at a potential of $1\frac{1}{2}E$ and the charge on the conductors necessary to produce this potential diffuses throughout the system

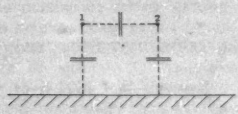

FIG. 7

and establishes an average system potential of $(-E)$, about which the potentials of the three lines vary.

When the faulty Line 2 reaches its maximum potential of $(-2E)$ the arc again strikes and at this instant Lines 1 and 3 are at an initial potential $\left(-\frac{1}{2}E\right)$. Line 2 then goes to zero potential which condition requires a potential of $\left(+1\frac{1}{2}E\right)$ on both Lines 1 and 3. However, Lines 1 and 3 are at a potential $\left(-\frac{1}{2}E\right)$ and an oscillation results, the applied voltege is $2E$, therefore the amplitude is $2E$ which gives a maximum voltage on Lines 1 and 3 of $3\frac{1}{2}E$. As before the arc will go out when the arc current passes through zero at which time the potentials of Lines 1 and 3 will again be at $\left(-1\frac{1}{2}E\right)$ and the sequence of events will be repeated with no further increase in voltage.

## OSCILLATORY FREQUENCY ARC EXTINCTION

*Single-Phase Circuit.* The analysis for the single-phase circuit will be given complete and in detail to illustrate the method of analysis. In Fig. 7 are represented the two wires of a single-phase circuit, together with the respective capacitances. The effective value of these capacitances at any instant depends upon the potentials of Line 1 and Line 2, as is brought out in the

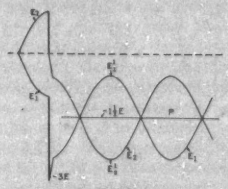

FIG. 8

Appendix. In Fig. 2 is shown the voltage wave of the two wires in respect to ground. The maximum voltage to ground of either line wire is $E$ and the voltage between wires is $(E_2 - E_1)$ or $(E_1 - E_2)$ with a maximum of $2E$.

The arc is assumed to strike from Line 2 to ground, thereby reducing the potential of Line 2 to zero and short circuiting the capacitance between Line 2 and ground. The initial arc is considered to occur when Line 2 is at its maximum potential to ground $(E_2 = +E)$. This condition of zero potential of Line 2 requires at this instant for steady state conditions a potential of $(-2E)$ on Line 1, which is equivalent to impressing a voltage of $(-2E)$ on Line 1. At the instant the arc strikes the potential of Line 1 is $(-E)$ and the transition from $(-E)$ to $(-2E)$ takes place as an oscillation (see Fig. 14A). It is assumed that the arc goes out the first time the oscillatory arc current passes through zero which is practically simultaneous with the instant of maximum potential of Line 1.

In Fig. 8 are shown the conditions immediately after the arc has struck and the conditions at the instant the arc has gone out. At the instant the arc goes out the

voltage to ground on Line 1 is $(-3E)$, which necessitates a corresponding charge $(-Q)$ on the sound line. After the arc goes out this charge distributes itself over the system passing through the apparatus at the end of the line and establishes the average potential to ground of the system as $\left(-1\frac{1}{2}E\right)$, corresponding to a charge of $\left(-\frac{Q}{2}\right)$ on each of the two lines. This redistribution of charge takes place through an oscillation which is not shown in the diagrams.

After steady conditions are attained, conditions are as indicated on the right of Fig. 8. However, this steady state cannot be maintained as the faulty Line 2 will again arc to ground and it is assumed that this will occur when its potential to ground becomes a maximum. This is shown in Fig. 9 in which the second arc is shown as striking when the voltage of the faulty Line 2 has reached a value of $\left(-2\frac{1}{2}E\right)$. At this instant the potential of Line 2 immediately goes to zero. For the resulting oscillation the initial potential of Line 1 is $\left(-\frac{1}{2}E\right)$ and the impressed voltage is $(+2E)$, as required by the condition of zero potential on Line 2. The transition from a potential of $\left(-\frac{1}{2}E\right)$ to $(+2E)$ takes place through an oscillation which has an applied voltage of $\left\{+2E-\left(-\frac{1}{2}E\right)\right\}$ or $\left(+2\frac{1}{2}E\right)$. The maximum potential to which Line 1 oscillates during the oscillation is $\left(2\frac{1}{2}E+2E\right)$ or $\left(+4\frac{1}{2}E\right)$, at which instant the arc goes out, leaving a charge corresponding to a potential $\left(+4\frac{1}{2}E\right)$ on Line 1. This charge then diffuses itself throughout the entire system establishing an average potential of $\left(+2\frac{1}{4}E\right)$ through the entire system.

As before, the potentials of Line 1 and Line 2 vary about this average potential and when the potential of Line 2 reaches its maximum value of $\left(+3\frac{1}{4}E\right)$ the arc strikes again. At this instant the potential of Line 1 is $\left(+1\frac{1}{4}E\right)$ so that the resulting oscillation has an impressed voltage of $(-2E)$ and an applied voltage and amplitude of $\left(-2E-1\frac{1}{4}E\right)=\left(-3\frac{1}{4}E\right)$. The potential of Line 1 goes to a maximum of $\left(-5\frac{1}{4}E\right)$ at which instant the arc goes out. A charge corresponding to a potential of $\left(-5\frac{1}{4}E\right)$ is left on Line 1 and this charge diffuses as before throughout the entire system, establishing an average potential over the two lines of $\left(-2\frac{5}{8}E\right)$. This process repeats itself until

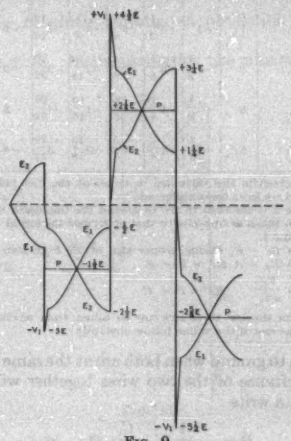


FIG. 9

the maximum voltage is attained or something happens to remove the system voltage.

The maximum possible voltage can be determined from the following considerations and reference to Table II. Let the maximum potential of a negative oscillation be denoted by $(-V_1)$, (see Fig. 9). Immediately following the extinction of the arc the charge associated with the voltage $(-V_1)$ will distribute itself throughout the system and establish a potential $P$. To determine $P$ it is necessary to know the relationship existing between the various capacitances involved; these are developed in the Appendix. When Line 2 arcs to ground it goes to zero potential and the potential $(-V_1)$ to which Line 1 oscillates is established over the capacitance $C_g$, requiring a charge

$$Q_1 = -V_1 C_g \tag{11}$$

The capacitance $C_g$ is defined as the capacitance of one line wire to ground when the other line wire is grounded, *i. e.*, at zero potential.

The arc goes out when the oscillatory arc current passes through zero and this charge $Q_1$ now diffuses throughout the system and establishes the average potential $P$ over the capacitance of the two line wires in parallel. If $C_a$ be defined as the capacitance of one of two wires to ground when both are at the same potential, the capacitance of the two wires together will be $2\,C_a$ and we can write

$$P = -\frac{1}{2}\,V_1\,\frac{C_g}{C_a}\,(1-a) \qquad (12)$$

The factor $(1-a)$ is added to make allowance for any charge that may leak off and for the charge that may be taken up by the terminal apparatus. It should be noted that the resistance in the circuit does not have any effect upon the final average voltage $P$ except to influence the time required to reach the steady state conditions.

After a half cycle the voltages are

$$E_1 = -\frac{1}{2}\,V_1\,\frac{C_g}{C_a}\,(1-a) + E \qquad (13)$$

$$E_2 = -\frac{1}{2}\,V_1\,\frac{C_g}{C_a}\,(1-a) - E \qquad (14)$$

and when the faulty Line 2 reaches this potential the arc will strike again. These expressions for $E_1$ and $E_2$ have been obtained directly from (12) by adding or subtracting $E$. These expressions can be obtained by considering that the charges on the two lines must total to the value given in (11) and using the expressions for $Q_1$ and $Q_2$ given in the appendix.

When the arc strikes, the potential of Line 2 drops to zero losing its charge, and the charge $Q_1'$ which is associated with the voltage $E_1$, must now establish another voltage $E_1'$ over the capacitances $C_g$, of Line 1 to ground, when Line 2 is at ground potential. This involves a change in the electrostatic field only and takes place very rapidly.

The charge associated with the potential $E_1$ according to the equations in the Appendix is

$$Q_1' = C\,\frac{E_1 - E_2\,\dfrac{C}{C_m}}{1 - \dfrac{C^2}{C_m^2}} \qquad (15)$$

and upon substituting the values of $E_1$ and $E_2$ from (13) and (14) there results

$$Q_1' = C_g\left\{E\left(1 + \frac{C}{C_m}\right) - \frac{1}{2}\,V_1\,(1-a)\right\} \qquad (16)$$

and the potential established by this charge is

$$E_1' = E\left(1 + \frac{C}{C_m}\right) - \frac{1}{2}\,V_1\,(1-a) \qquad (17)$$

The fact that Line 2 is at zero or ground potential requires that Line 1 be at a potential $(+\,2\,E)$ but instead it has the potential $E_1'$ and this difference between impressed and initial potential produces an oscillation having an amplitude of

$$A = \{\,2\,E - E_1'\,\}\,(1-d) \qquad (18)$$

and giving a maximum voltage of

$$V_1' = 2\,E + A \qquad (19)$$

The limiting value will occur when the maximum potential of any oscillation is the same as that of the immediately preceding oscillation, that is when $V_1' = V_1$ and then

$$V_1 = 2\,E\,\frac{2 + \left(1 - \dfrac{C}{C_m}\right)(1-d)}{2 - (1-a)\,(1-d)} \qquad (20)$$

This expression gives the maximum voltage that can be set up by an arcing ground on a single-phase circuit with the analysis based on the extinction of the arc when the oscillatory current first passes through zero.

The maximum possible value is six times normal line to neutral voltage as compared with four times as obtained from the preceding analysis. Table II further illustrates the building up of the voltage on the sound line and also fixes six times as the limit. By inspection of Table II and Fig. 9 it can be seen that the values of $V_1$ and $V_1'$ have the following relation between any two consecutive values,

$$V_1' = V_1 + \frac{1}{2}\,(6 - V_1)$$

TABLE II
DERIVATION OF MAXIMUM VOLTAGE

| Arc No. | | 1 | 2 | 3 | 4 | 5 | $N$ | $N+1$ | $N+2$ |
|---|---|---|---|---|---|---|---|---|---|
| Line 2 | $E_2$ | +1 | $-2\frac{1}{2}$ | $+3\frac{1}{4}$ | $-3\frac{5}{8}$ | $+3\frac{13}{16}$ | | −4 | +4 |
| Line 1 | $E_1$ | −1 | $-\frac{1}{2}$ | $+1\frac{1}{4}$ | $-1\frac{5}{8}$ | $+1\frac{13}{16}$ | | −2 | +2 |
| Line $V_1$ | $E_1$ | −1 | $-\frac{1}{2}$ | $+1\frac{1}{4}$ | $-1\frac{5}{8}$ | $+1\frac{13}{16}$ | | −2 | +2 |
| Impressed $V$ | $E_0$ | −2 | +2 | −2 | +2 | −2 | | +2 | −2 |
| Amplitude | $A$ | −1 | $+2\frac{1}{2}$ | $-3\frac{1}{4}$ | $+3\frac{5}{8}$ | $-3\frac{13}{16}$ | | +4 | −4 |
| Max. $V$ | $V_1'$ | −3 | $+4\frac{1}{2}$ | $-5\frac{1}{4}$ | $+5\frac{5}{8}$ | $-5\frac{13}{16}$ | −6 | +6 | −6 |
| Average $V$ | $P$ | $-1\frac{1}{2}$ | $+2\frac{1}{4}$ | $+2\frac{5}{8}$ | $+2\frac{13}{16}$ | $-2\frac{29}{32}$ | −3 | +3 | −3 |
| Line 1 | $E_1'$ | $-\frac{1}{2}$ | $+1\frac{1}{4}$ | $-1\frac{5}{8}$ | $+1\frac{13}{16}$ | $-1\frac{29}{32}$ | −2 | +2 | −2 |
| Line 2 | $E_2'$ | $-2\frac{1}{2}$ | $+3\frac{1}{4}$ | $-3\frac{5}{8}$ | $+3\frac{13}{16}$ | $-3\frac{29}{32}$ | −4 | +4 | −4 |

Voltages given in the table are in terms of the line voltage $E$. All reducing factors have been neglected.

Since Line 2 is assumed to arc to ground the impressed voltage is $2\,E$ with the sign taken as opposite to that of $E_2$ and the initial voltage is the voltage of Line 1.

$A = E_0 - E_1$ taking proper sign of $E_0$ from sign of $E_1$

$V_1' = E_a + A$ $E_1' = P - E$

$P = \dfrac{V_1'}{2}$ $E_2' = P + E$

The values for the first three arcs can be taken from or checked against Fig. 9 and the rest of the values follow obviously

which indicates that $V_1$ can never be greater than 6. Writing in the values 6 for $V_1$ in the column for the $N$th arc it is seen that the $(N+1)$th and $(N+2)$th arcs give no higher values, thereby establishing the limit as 6 times line to neutral voltage, for the voltage produced by an arcing ground in a single-phase system.

### Three-Phase Circuit—Impedance in the Neutral

Since the present day tendency is toward limiting fault currents by placing an impedance in the neutral ground connection, the analysis for the three-phase

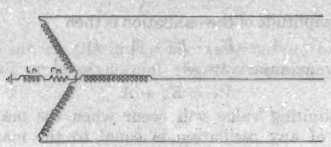


Fig. 10

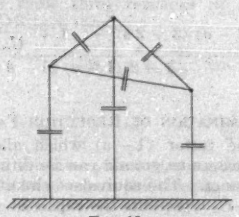

Fig. 10A

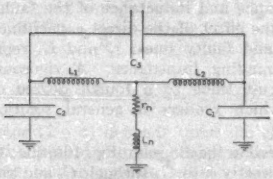


Fig. 10B

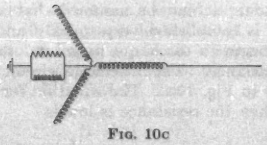

Fig. 10C

circuit will be made for that condition. As mentioned before it is likely that the phenomenon will be controlled by normal frequency arc extinction when the neutral is grounded but it is useful to determine limiting values of neutral grounding resistance or reactance on the basis that the voltages are controlled by oscillatory frequency arc extinction. This method will give conservative values. Let the circuit be as shown in Fig. 10 with $r_n$ and $L_n$ as the neutral grounding impedance. The capacitances involved are indicated in Fig. 10A and the voltages are as shown on the left in Fig. 11.

When the faulty Line 2 first arcs to ground its potential drops at once to zero and cuts out the capacitance between Line 2 and ground. Lines 1 and 3 are at a potential $\left(+\frac{E}{2}\right)$ while the condition of zero potential on Line 2 requires a potential of $\left(+1\frac{1}{2}E\right)$ on Lines 1 and 3, thus impressing this voltage on the two sound lines. The sound lines have an initial voltage of $\left(+\frac{1}{2}E\right)$ so that the voltage applied is $\left(1\frac{1}{2}E - \frac{1}{2}E\right) = E$ which initiates an oscillation with an amplitude of $E$. In the oscillation the maximum volt-

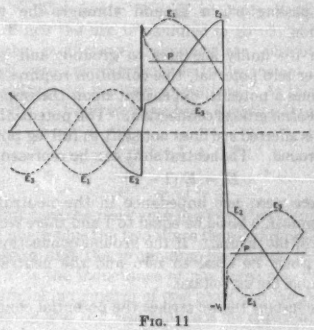


Fig. 11

age attained by the sound lines is $\left(+2\frac{1}{2}E\right)$ (neglecting all damping or reducing factors) at which instant the arc is assumed to go out. The charge required to produce a potential of $V_1 = \left(+2\frac{1}{2}E\right)$ on the two sound lines now diffuses throughout the system and establishes an average potential over the three lines of $P = \frac{2}{3}V_1$. As soon as the faulty Line 2 reaches its new maximum $E_2 = P + E$, it again arcs to ground and the sound lines oscillate to a new maximum and then the arc goes out. The bound charge on the two lines establishes a new average potential, the faulty line arcs to ground at the next instant of its maximum potential, and the process is repeated.

The limiting voltage is found as follows. Let $(-V_1)$,

Fig. 11, be the maximum potential which the sound lines reach on any oscillation. This potential on the two sound lines requires a charge dependent upon the capacitance to ground of the two sound lines when the third line is grounded, it is

$$Q_1 = -2\,C_g\,V_1 \tag{21}$$

This charge establishes an average potential $P$ over the capacitances of the three wires in parallel, or $3\,C_o$. If there was no connection to ground from the neutral no charge would be lost and the potential would be in proportion to the capacitances involved. When there is a connection between the neutral and ground part of the charge passes to ground and the potential $P$ is reduced proportionately. When $V_1$ is the potential of the sound lines at the instant the arc goes out we can write for $P$

$$P = -\frac{2\,C_g}{3\,C_o}\,V_1\,(1-a) \tag{22}$$

The factor $(1-a)$ is introduced as before to take into account the reduction in potential due to part of the charge passing off to ground through the ground connection.

When the faulty line arcs to ground, and goes to ground or zero potential, this condition requires on the sound lines a potential dependent upon the impedance in the neutral ground connection. The potential of the neutral is affected and does not shift to full leg potential above ground. The neutral shift can be represented by

$$E_n = E\,(1-b) \tag{23}$$

If there were zero impedance in the neutral, *i. e.*, a solid ground, $b$ would be equal to 1 and there would be no shift of the neutral. If the ground connection were open $b$ would be equal to zero and the neutral shift would equal the leg voltage.

At the instant the arc strikes the potential conditions are

$$E_1 = -\frac{2\,C_g}{3\,C_o}\,V_1\,(1-a) + \frac{1}{2}\,E \tag{24}$$

$$E_2 = -\frac{2\,C_g}{3\,C_o}\,V_1\,(1-a) - E \tag{25}$$

$$E_3 = -\frac{2\,C_g}{3\,C_o}\,V_1\,(1-a) + \frac{1}{2}\,E \tag{26}$$

The arc now strikes and Line 2 drops to zero or ground potential which condition requires a potential of approximately $\left(E\,(1-b) + \frac{1}{2}\,E\right)$ on the sound lines so that the impressed voltage $E_o$ is

$$E_o = E\,(1-b) + \frac{1}{2}\,E \tag{27}$$

At the instant just before the arc struck the sound Lines 1 and 3 had charges dependent upon the voltages $E_1$, $E_2$, and $E_3$ at that instant. Substituting Equations (24), (25), and (26) in the equations developed in the Appendix the charge $Q_1'$ on the sound line is found to be

$$Q_1' = C_o\left\{\frac{1}{2}\,E\left(1+\frac{2\,C}{C_m}\right) - \frac{2}{3}\,V_1\,(1-a)\right\} \tag{28}$$

This charge together with an equal one on Line 3 establishes a potential $E_1'$ over the capacitance $2\,C_g$ of the two sound wires to ground

$$E_1' = \frac{1}{2}\,E\left(1+\frac{2\,C}{C_m}\right) - \frac{2}{3}\,V_1\,(1-a) \tag{29}$$

The amplitude of the oscillation is then

$$A = (E_o - E_1')\,(1-d) \tag{30}$$

and the maximum voltage

$$V_1 = E_o + A \tag{31}$$

The limiting value will occur when the maximum voltage of any oscillation is equal to the maximum voltage of the immediately preceding oscillation. It is

$$V_1 = \frac{3}{2}\,E\,\frac{(2-d)\,(3-2\,b) - \left\{1+\frac{2\,C}{C_m}\right\}\,(1-d)}{3-2\,(1-a)\,(1-d)} \tag{32}$$

## Determination of Reduction Factors

$(1-a)$ The factor $(1-a)$ which allows for the charge that passes to ground can be estimated in the following manner. The equivalent circuit is as shown in Fig. 10B. $C_2$ represents the capacitance of the two sound lines and $L_2$ the inductance; $C_1$ and $L_1$ represent the capacitance and inductance of the faulty line; $C_3$ represents the effect of the direct capacitance between the sound and faulty lines; $r_n$ and $L_n$ represent the neutral grounding impedance. A rigorous analysis of this circuit leads to a fourth degree differential equation which renders a general solution out of question.

It is noticed in the diagram, Fig. 10B, that the $C_2$ can discharge directly into $C_1$ through $C_3$ and that there is no appreciable inductance nor resistance in this circuit. On this account it can be assumed that an average potential $P$ is established very quickly and then the three lines begin to discharge to ground through the neutral impedance. The discharge circuit will then be as shown in Fig. 10B. The equation for condenser discharge when the resistance is low is

$$e_c = e\,\epsilon^{-\alpha t}\left\{\operatorname{Cos}\omega t + \frac{r}{q}\operatorname{Sin}\omega t\right\} \tag{4}$$

$r_2$ = phase resistance of circuit plus three times resistance of grounding impedance, *i. e.*, $r_2 = r_1 + 3\,r_n$

$x_2$ = phase reactance of circuit plus three times the reactance of the grounding impedance, *i. e.*, $x_2 = x_1 + 3\,x_n$

$L$ = phase inductance of circuit plus three times inductance of grounding impedance

$C$ = capacitance of one line wire to ground when all three have same potential.

If $x_3$ is the inductive reactance of one phase plus three times the reactance of the grounding impedance, then

$$L = \frac{x_3}{\omega_o} \tag{33}$$

If $x_a$ is the capacitive reactance of one line when all three are at the same potential then

$$C = C_a = \frac{1}{\omega_o x_a} \tag{34}$$

The arc on the faulty line restrikes at the end of one-half cycle of normal system frequency and the time $t$ is

$$t = \frac{\pi}{\omega_o} \tag{35}$$

Substitute these three relations in Equation (4) just given and there results

$$\frac{e_c}{e} = \epsilon^{-\pi n_3}\left\{ \operatorname{Cos} \pi\,\theta + \frac{n_3}{\theta} \operatorname{Sin} \pi\,\theta \right\} \tag{36}$$

$$\theta = \sqrt{\frac{x_3}{x_3} - n_3^2} \qquad n_3 = \frac{r_3}{2\,x_3} \tag{37}$$

On making the same substitution in the equation for condenser discharge when the resistance is high there results

$$\frac{e_c}{e} = \epsilon^{-(n_3-\phi)\pi}\,\frac{1+\dfrac{n_3}{\phi}}{2} + \epsilon^{-(n_3+\phi)\pi}\,\frac{1-\dfrac{n_3}{\phi}}{2} \tag{38}$$

$$\phi = \sqrt{n_3^2 - \frac{x_a}{x_3}} \qquad n_3 = \frac{r_3}{2\,x_3} \tag{39}$$

The factor $(1-a)$ depends upon the charge which leaks off the ground and the charge which remains is proportional to the voltage left on the capacitance which is given as $e_c$ in the preceding equation. If no charge leaked off $(1-a)$ would equal 1 and also $e_c/e = 1$; if all the charge leaked off $(1-a)$ would be equal to zero and also $e_c/e = 0$. Since by definition the factor $(1-a)$ is a measure of the charge that leaks off to ground, it is obvious that

$$(1-a) = \frac{e_c}{e} \tag{40}$$

The expression for $(1-a)$ in the oscillatory case appears to indicate that with a solidly grounded neutral, $r = 0$, no damping would result, the average potential $P$ being then the same as if the neutral were isolated. This would be true if there were no resistance at all in the circuit, the only difference then would be that the solidly grounded case would be oscillatory and the isolated case non-oscillatory. However, there is a certain amount of resistance in the rest of the circuit which will cause damping. Also, this equation apparently indicates that infinite ohms in the neutral give 100 per cent damping, but it should be remembered that increasing resistance gradually changes the discharge over into a non-oscillatory condition and it can then be shown that infinite ohms give zero damping. Such very high values of ohms would not be considered for grounding purposes so this condition is only of passing interest.

$(1-b)$ The factor $(1-b)$ which allows for the reduced neutral shift may be estimated as follows. When the faulty line arcs to ground a short circuit is established and the current flowing through the neutral grounding impedance produced a voltage drop. The neutral shift is equal to the voltage drop across the neutral grounding impedance, and if this is designated by $E_n$ and normal line to neutral voltage as $E$ there results

$$(1-b) = \frac{E_n}{E} \tag{41}$$

$(1-d)$ The factor $(1-d)$ is simple of determination. Since the arc is assumed to go out at the first time the oscillatory frequency arc current passes through zero this corresponds to the instant of maximum voltage on the two sound lines. At this instant $\operatorname{Cos} \omega\,t = -1$ and we have from Equation (1) appendix

$$\frac{e_c}{e} = 1 + \epsilon^{-at} \tag{42}$$

$$\epsilon^{-at} = (1-d) \tag{43}$$

In this case the resistance involved $r''$ is the resistance of one phase plus the two times the parallel resistance of one phase and the grounding impedance, the inductance $x''$ is the inductance of one phase plus two times the parallel inductance of one phase and the grounding impedance and the capacitance is the capacitance $C_g$ of one of the two sound lines to ground when the third line is at ground potential. Making the proper substitutions we get

$$(1-d) = \epsilon^{-b} \tag{44}$$

$$b = \frac{\pi\,n_2}{\theta_g} \qquad x_g = \frac{1}{2\,\pi\,f\,C_g}\,\theta_g$$

$$\theta_g = \sqrt{\frac{x_g}{x''} - n_2^2} \qquad n_2 = \frac{r''}{2\,x''} \tag{45}$$

The factor $(1-d)$ can be taken as unity without serious error.

## Effect of Grounding Impedance

*Resistance Ground.* When it becomes desirable to put an impedance in the neutral ground connection the value chosen should be such that the possibility of arcing ground conditions is remote when the analysis is based on the assumption that the phenomenon is controlled by oscillatory frequency arc extinction. This method of analysis gives higher voltages than the

analysis based on normal frequency arc extinction, and accordingly if limits are set by the pessimistic analysis the values chosen will surely be conservative and safe. When resistance alone is used it is surprising how high a value may be used. The limiting value can be determined by calculations on the circuit involved. There

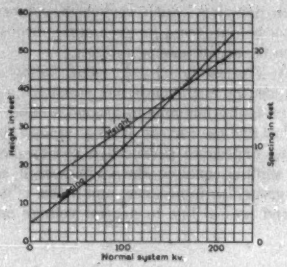


FIG. 12

are some general considerations that apply and these will be discussed briefly.

When the arc goes out the bound charge redistributes itself over the system and drains off to ground through an oscillation when the resistance in the neutral is lower than the critical value. As long as the resistance is below the critical value the bound charge will be entirely drained off at the end of half a 60-cycle period and no arcing ground voltages can be built up. For this condition $\theta$ of Equation (37) must be real and therefore

$$\frac{r_3}{2\,x_3} = n_3 < \sqrt{\frac{x_a}{x_3}} \tag{46}$$

In this expression $r_3 = 3\,r_n$; $x_3 = x_1$, ($x_1$ is the circuit reactance) and $x_a = \dfrac{1}{\omega\,C_a}$ so that

$$r_n < \frac{2}{3}\sqrt{x_a\,x_1} \tag{47}$$

As long as the grounding resistance $r_n$ is less than the critical resistance $\frac{2}{3}\sqrt{x_a\,x_1}$ no arcing ground voltage will be built up.

To calculate the limiting resistance as based upon this criterion it is first necessary to find out what the value of $x_a$ might be. In Fig. 12 are two curves drawn to show the average spacing and height of conductors as dependent upon the nominal system voltage. These curves represent average conditions and are of course approximate. They are based upon data published by the *Electrical World* some years ago. In Table III are the results of capacitance calculations made for circuits of these proportions and various voltage ratings. An examination of this tabulation shows that the value

TABLE III
CAPACITANCE CALCULATIONS—AVERAGE CIRCUIT PROPORTIONS

| Kv | 33 | 44 | 66 | 110 | 132 | 154 | 220 |
|---|---|---|---|---|---|---|---|
| Cond. spacing | 4 | 5 | 7 | 11 | 13 | 15 | 22 |
| Ave. spacing | 5.0 | 6.3 | 8.8 | 13.9 | 16.4 | 18.9 | 27.7 |
| | | | Horizontal spacing | | | | |
| Height—$h$ | 18 | 20 | 24 | 32 | 35 | 39 | 50 |
| Ave. image $R$ | 36.4 | 40.6 | 49.0 | 65.9 | 72.4 | 81.0 | 104.8 |
| $C$—0.250 | 0.010960 | 0.010810 | 0.010580 | 0.010225 | 0.010101 | 0.009970 | 0.009705 |
| $C$—0.375 | 0.011503 | 0.011365 | 0.011104 | 0.010695 | 0.010595 | 0.010453 | 0.010150 |
| $C$—0.500 | 0.011990 | 0.011710 | 0.011502 | 0.011070 | 0.010960 | 0.010815 | 0.010495 |
| $C_m$—(mutual) | 0.04498 | 0.04800 | 0.05220 | 0.05720 | 0.06000 | 0.06140 | 0.06550 |
| $C_a$—0.375 | 0.00761 | 0.00771 | 0.00779 | 0.00778 | 0.00782 | 0.00780 | 0.00775 |
| $C/C_m$ 0.375 | 0.256 | 0.237 | 0.213 | 0.187 | 0.177 | 0.170 | 0.155 |
| $I$ | 16.44 | 22.1 | 33.7 | 56.0 | 67.5 | 78.3 | 111.4 |
| | | | Vertical spacing | | | | |
| Height—$h$ | 22 | 25 | 31 | 43 | 48 | 54 | 72 |
| Ave. image $R$ | 44.0 | 50.0 | 61.7 | 85.5 | 95.4 | 107.3 | 143.3 |
| $C$—0.250 | 0.010708 | 0.010548 | 0.010298 | 0.009900 | 0.009788 | 0.009678 | 0.009383 |
| $C$—0.375 | 0.011255 | 0.010780 | 0.010797 | 0.010391 | 0.010265 | 0.010121 | 0.009789 |
| $C$—0.500 | 0.011680 | 0.011487 | 0.011185 | 0.010745 | 0.010613 | 0.010464 | 0.010119 |
| $C_m$—(mutual) | 0.0412 | 0.0432 | 0.0458 | 0.0493 | 0.0508 | 0.0515 | 0.0542 |
| $C_a$—0.375 | 0.00728 | 0.00733 | 0.00733 | 0.00731 | 0.00731 | 0.00726 | 0.00719 |
| $C/C_m$—0.375 | 0.273 | 0.256 | 0.236 | 0.211 | 0.202 | 0.197 | 0.181 |
| $I$ ave | 15.7 | 21.1 | 31.7 | 52.6 | 63.1 | 72.9 | 103.4 |

Conductor Radius in Inches
$I = 3\,E\,(377)\,C_a$ for 100 miles.

of $C$ varies only slightly over the entire voltage range, and that $C_m$ is practically constant for either vertical or horizontal spacings. The difference in value of $C_m$ for horizontal and vertical spacing is small so that it appears reasonable to use the average value throughout the entire voltage range for both spacings.

Information has been published[3] that the charging current flowing in the ground, $I_f$ of Fig. 13C and D averages 1.5 $I_n$, where $I_n$ is the normal three-phase changing current, and that $I_f$ averages 2 $I_n$. These

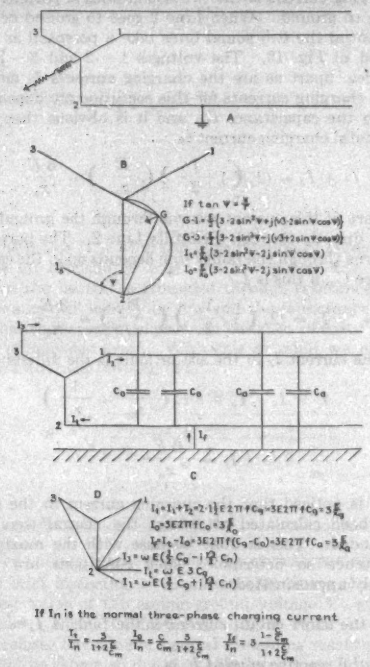


FIG. 13

figures were based on tests on low-voltage transmission systems, and would be exact if the ratio $\frac{C}{C_m}$ were 0.25.

The average of this ratio for 33 kv., 44 kv., and 66 kv. is 0.245 with a variation less than that which might be encountered in such tests so that it was quite reasonable to form such a conclusion from the tests.

Using the average figure of 0.00752 $\mu$ f. for $C_a$, $x_a$ in ohms can be written, if $L$ is length of line in miles.

$$x_a = \frac{.3525\ 10^6}{L} \tag{48}$$

If $x_1$ is expressed in per cent then $x_1$ ohm is given by

$$x_1 \text{ ohms} = \frac{x_1 \sqrt{\text{kv.}^2}\, 10}{\text{kv-a.}} \tag{49}$$

Inserting these values in Equation (47) we find

$$r_n < 1.25 \sqrt{\frac{x_1\, 10^6}{L.\ \text{kv-a.}}} \tag{50}$$

The critical resistance obtained from (50) for various overhead circuits has been tabulated in Table IV. If

TABLE IV
CRITICAL RESISTANCE FOR OVERHEAD SYSTEM

$$z = 1.25 \text{ kv.} \sqrt{\frac{X_1 \cdot 10_9}{L \cdot \text{kv-a.}}} \quad X_1 \text{ assumed 25 per cent}$$

$$z = \frac{2}{3} \sqrt{x_a x_1}$$

| Kv. | Kv-a. / L | 5,000 | 10,000 | 25,000 | 50,000 | 100,000 | 200,000 |
|---|---|---|---|---|---|---|---|
| 33 | 25 | 584 | 413 | 261 | .... | .... | .... |
| | 50 | 413 | 292 | 185 | .... | .... | .... |
| | 100 | 292 | 207 | 131 | .... | .... | .... |
| 44 | 25 | 777 | 550 | 347 | .... | .... | .... |
| | 50 | 550 | 388 | 246 | .... | .... | .... |
| | 100 | 388 | 275 | 174 | .... | .... | .... |
| 66 | 25 | 1166 | 825 | 521 | 370 | .... | .... |
| | 50 | 825 | 583 | 370 | 261 | .... | .... |
| | 100 | 583 | 413 | 261 | 185 | .... | .... |
| 110 | 50 | .... | 980 | 616 | 435 | 308 | .... |
| | 100 | .... | 687 | 435 | 308 | 218 | .... |
| | 200 | .... | 486 | 308 | 218 | 154 | .... |
| 132 | 50 | .... | 1166 | 739 | 522 | 370 | .... |
| | 100 | .... | 825 | 522 | 370 | 261 | .... |
| | 200 | .... | 582 | 370 | 261 | 185 | .... |
| 154 | 50 | .... | .... | 862 | 610 | 431 | 308 |
| | 100 | .... | .... | 610 | 431 | 308 | 215 |
| | 200 | .... | .... | 431 | 308 | 215 | 154 |
| 220 | 50 | .... | .... | 1231 | 871 | 616 | 435 |
| | 100 | .... | .... | 871 | 616 | 435 | 308 |
| | 200 | .... | .... | 616 | 435 | 308 | 218 |

the resistance in the neutral is less than the values in this table no arcing ground troubles should be experienced.

For cable circuits the quantity $x_a$ is quite variable and so the critical resistance must be calculated from the expression

$$z = \frac{2}{3} \sqrt{x_1 x_c} \tag{47a}$$

For a cable circuit using three-phase cables the critical resistance is shown in Table V.

It is possible to use values much higher than those determined by the preceding analysis and still have the arcing ground voltages within safe limits. When the resistance is in excess of the critical resistance fixed by (47) the discharge to ground is no longer oscillatory and the factor $(1 - a)$ must be determined from Equation (38). If we let $z$ be the critical or limiting value

TABLE V
CRITICAL RESISTANCE FOR CABLE SYSTEMS
(Three-Phase Cables)

| Rated voltage | $X_1$ 100,000-kv-a. | $X_a$ 100 miles | | $Z$ | |
|---|---|---|---|---|---|
| | 10% | Isolated | Grounded | Isolated | Grounded |
| 7.5 | 0.05625 | 104.3 | 88.2 | 1.616 | 1.485 |
| 12.5 | 0.15625 | 119.3 | 103.8 | 2.876 | 2.683 |
| 15 | 0.225 | 126.5 | 111.2 | 3.556 | 3.333 |
| 20 | 0.4 | 140.0 | 126.0 | 4.99 | 4.742 |
| 25 | 0.625 | 155.0 | 142.2 | 6.566 | 6.288 |
| 33 | 1.089 | 171.0 | 158.0 | 9.10 | 8.75 |

$$Z = \frac{2}{3}\sqrt{x_1 x_a}$$

$Z$ will vary inversely as $\sqrt{\text{Kv-a.}}$
$Z$ will vary inversely as $\sqrt{\text{Length of line}}$
$Z$ will vary directly as $\sqrt{\text{Per cent reactance}}$
Thus at 7.5 kv. for 25,000 kv-a., 25 miles, and 15 per cent reactance $Z = 7.92$ ohms

as determined from (47) and $r_n = k\,z$ the value used we can write

$$r = \frac{2}{3} k \sqrt{x_a x_1} \tag{51}$$

$$\phi = \sqrt{\frac{x_a}{x_1}}\,(k^2 - 1)^{1/2}\, n_3 = k\sqrt{\frac{x_a}{x_1}} \tag{52}$$

$$1 - a = \frac{k + \sqrt{k^2 - 1}}{2\sqrt{k^2 - 1}} \quad \frac{\epsilon^{\pi}\sqrt{\frac{x_a}{x_1}}\,\sqrt{k^2 - 1}}{\epsilon^{\pi}\sqrt{\frac{x_a}{x_1}}\,k} \tag{38a}$$

If a resistance 50 per cent greater than the value determined from (47) were used, then $k$ in these last two expressions would be 1.5.

The quantity $x_a$ is the capacitive reactance of one line when all three are at the same potential and this is very approximately twice the customary line to neutral capacitive reactance. If we consider that the normal charging current will never be more than 100 per cent, then $x_a$ will never be less than 200 per cent and for a fair average value of $x_1$ 25 per cent the factor $\sqrt{\frac{x_a}{x_1}}$ will not be less than 2.83.

Using this relation in (38a) and then in (32) the following is obtained for increasing values of $r_n$. In the calculation $(1 - d)$ and $(1 - b)$ are taken as unity and $\frac{C}{C_m}$ as 0.15.

TABLE VI

| $k$ | $(1-a)$ | $V$ |
|---|---|---|
| 1.1 | 0.0056 | 2.35 $E$ |
| 1.2 | 0.0119 | 2.37 $E$ |
| 1.5 | 0.0357 | 2.41 $E$ |
| 2.0 | 0.0962 | 2.51 $E$ |
| 3.0 | 0.227 | 2.77 $E$ |

It is quite obvious from this tabulation that the resistance in the neutral can easily be three times the critical resistances obtained from Equation (47) without running into any danger of trouble from arcing grounds.

It is also possible to fix a limit[2] for $r_n$ such that the lagging component of the current in the arc is equal to or greater than the leading component. The leading component of the arc current is that part of the charging current of the two sound lines in parallel that goes to ground. When Line 2 goes to ground or zero potential the two sound lines take a potential as indicated in Fig. 13. The voltages $1 - 2$ and $3 - 2$ are 60 deg. apart as are the charging currents $I_1$ and $I_3$. The charging currents for this condition are dependent upon the capacitance $C_g$, and it is obvious then that the total charging current is

$$I_t = I_1 + I_3 = (2)\left(1\,\frac{1}{2}\right)\left(\frac{E}{x_g}\right) = \frac{3\,E}{x_g} \tag{53}$$

Part of this current returns through the ground and part directly through the faulty Line 2. The part that returns through the faulty line depends upon the capacitance $C_o$, if this is $I_o$

$$I_o = (2)\left(1\,\frac{1}{2}\right)\left(\frac{E}{x_o}\right) = \frac{3\,E}{x_o} \tag{54}$$

The current $I_f$ in the arc or fault is the difference

$$I_f = I_t - I_o = 3\,E\left(\frac{1}{x_g} - \frac{1}{x_o}\right) \tag{55}$$

$$I_f = \frac{3\,E}{x_a} \tag{55A}$$

It is noticed that the charging current in the fault has been calculated as though the neutral were not grounded. This is done because with the maximum resistance so determined such conditions are very closely approximated.

If the short circuit current in the fault is $I_s = \frac{E}{X_s}$

then the reactive current $I_x$ is

$$I_x = I_s \frac{x_s}{\sqrt{r_n^2 + x_s^2}} = \frac{E_x}{r_n^2 + x_s^2} \tag{56}$$

and since $I_x$ is set equal to $I_f = \frac{3\,E}{x_a}$

$$r_o < \frac{1}{\sqrt{3}}\sqrt{x_a x_s}\sqrt{1 - \frac{3\,x_s}{x_a}} \tag{57}$$

The limiting value as determined from (57) is less than that as determined from (47).

*Reactance Ground.* When reactance is used for grounding the neutral the following equation, which is obtained from Equation (32) by letting the factor

$(1 - d)$ be unity, may be used to estimate the arcing ground voltage.

$$V_1 = \frac{3}{2} E \frac{5 - 4b - 2\frac{C}{C_m}}{3 - 2(1 - a)} \tag{58}$$

The neutral grounding reactor affects the factor $(b)$ and also the factor $(1 - a)$. If $I_s$ is the short-circuit current flowing in the fault and $x_s$ the system reactance such that

$$I_s = \frac{E}{x_s} \tag{59}$$

then

$$1 - b = \frac{x_n}{x_s} \tag{60}$$

and

$$b = 1 - \frac{x_n}{x_s} \tag{61}$$

The factor $(1 - a)$ in the form previously given contains an exponential part and a trigonometric part. When the neutral is grounded through reactance, the resistance will usually be low and the inductance high so that the exponential part can be taken as unity without appreciable error. With this in mind we obtain from Equations (**40**) and (**37**)

$$(1 - a) = \operatorname{Cos} n\,\theta \tag{62}$$

$$\theta = \sqrt{\frac{x_a}{x_2}} = \sqrt{\frac{x_a}{x_1}\,\frac{1}{1 + 3\frac{x_a}{x_1}}} \tag{63}$$

$$x_c = \frac{x_a - x_1}{3} \text{ for } \theta = 1 \tag{63a}$$

The value $x_c$ might be called the critical reactance.

A brief inspection of Equation (**50**) shows that the lowest value of the arcing ground voltage $V_1$ will be obtained when the factor $(1 - a)$ is equal to $-1$. Therefore, the value of neutral grounding reactance $x_n$ should be chosen so that $\theta$ as calculated from Equation (**63**) is an odd integer. Because of necessary assumptions made in the derivation of the formula and uncertainty in the exact determination of the line constants, the use of these expressions should be limited to values of $\theta$ less than 4.

For the condition that $\theta = 1$ as in Equation (**63a**) this gives a value of neutral grounding reactance about the same as the Petersen Coil but it should be noted that the method here given is different from the ordinary method of calculating Petersen Coils. The value of $\theta$ is not critical in the neighborhood of $\theta = 1$. This is brought out in Table VII, in which are shown calculated voltages for various values of neutral grounding reactance above and below the critical value. It is quite apparent from this table that considerable variation from the critical value can be permitted without any high voltages resulting.

TABLE VII

Tabulation shows variation of calculated arcing ground voltages for variation of neutral grounding reactance above and below the critical value

| $\frac{x_n}{x_c}$ | $\theta$ | $\frac{V_1}{E}$ | $\frac{x_n}{x_c}$ | $\theta$ | $\frac{V_1}{E}$ |
|---|---|---|---|---|---|
| 1.0 | 1.0 | 1.36 | 1.0 | 1.0 | 1.36 |
| 1.1 | 0.913 | 1.38 | 0.9 | 1.105 | 1.39 |
| 1.2 | 0.84 | 1.43 | 0.8 | 1.234 | 1.52 |
| 1.3 | 0.778 | 1.92 | 0.7 | 1.4 | 2.60 |

*Petersen Coil.* The Petersen Coil is a special type of neutral grounding reactor in which the lagging current which the coil permits to flow when one line becomes grounded is equal to the charging current of the two sound lines. For this condition the lagging component of the fault current is practically equal to the total short circuit current so that

$$I_s = \frac{E}{x_s} = I_f = \frac{3E}{x_a} \tag{64}$$

But $x_s = x_n + x$ in which $x_n$ is the reactance of the Petersen Coil and $x$ is one-third the sum of the zero, positive, and negative sequence reactances of the circuit. And then

$$x_n = \frac{x_a}{3} - x \tag{65}$$

$$x_n = \frac{x_a - (x_o + x_1 + x_2)}{3} \tag{65a}$$

The value of $\theta$ corresponding to the value of $x_n$ given for the Petersen Coil by Equation (**65**) is

$$\theta = \sqrt{\frac{x_a}{x_a - x_o - x_2}} \tag{66}$$

The reactance of the Petersen Coil as given by (**65a**) will be less than the critical value given by (**63a**) by an amount depending upon the relative values of the zero and negative phase sequence reactances. The value of $\theta$ as given by (**66**) for the Petersen Coil is very nearly unity.

The principle of operation of the Petersen Coil is that of balance between the short-circuit current and charging current in the fault. When this balance exists the arc is supposed to go out from lack of current to maintain it. When the Petersen Coil is out of tune there is no longer a balance of lagging and leading currents and the arc persists. However, this is not serious because no harmful overvoltages will result unless the unbalance is considerable, as reference to Table VII will show.

*Series Resistance and Reactance.* For a neutral grounding impedance consisting of resistance and reactance the damping factor $(1 - a)$ should be deter-

mined from (**40**) in combination with (**38**) or (**36**) depending upon the values of the circuit constants.

*Parallel Resistance and Inductance.* It has been found cheaper to obtain a given required value of ohms by the use of an inductance than by use of resistance. However, an inductance in the neutral ground connection causes the arcing ground voltages to calculate higher than resistance. This can be overcome by the use of a high resistance in parallel with the inductance, and this resistance need not be expensive because it need not have a high current carrying capacity.

An exact analysis of this circuit leads to a third degree differential equation which does not readily permit a general solution. With the circuit as shown in Fig. 10c the equation for the current is

$$i = \frac{E_o}{L} \frac{\left(\frac{r_n}{L_n} p + p^2\right)}{F(p)}$$

$$F(p) = p^3 + \left(\frac{r_n}{L_n} + \frac{r}{L} + \frac{r_n}{L}\right) p^2 + \left(\frac{1}{L\,C} + \frac{r\,r_n}{L\,L_n}\right) p + \frac{r_n}{L\,L_n\,C} = (p+c)\,(p+b)\,(p+a)$$

In this equation ($i$) is the discharge current to ground from the charges trapped on the two sound lines. What we are interested in is the voltage left on the lines at the end of one-half of a normal frequency cycle or the voltage on the condenser part of the equivalent circuit, which is

$$E_c = E_o - \frac{i}{p\,C}$$

$$E_c = E_o - \frac{E_o}{L\,C} \left\{ \frac{\left(\frac{r_n}{L_n} - c\right)}{(c-a)\,(c-b)\,(p+c)} + \frac{\left(\frac{r_n}{L_n} - b\right)}{(b-a)\,(b-c)\,(p+b)} + \frac{\left(\frac{r_n}{L_n} - a\right)}{(a-b)\,(a-c)\,(p+a)} \right\}$$

$$= E_o - \frac{E_o}{L\,C} \left\{ \frac{\left(\frac{r_n}{L_n} - c\right)(1-\epsilon^{-ct})}{c\,(c-a)\,(c-b)} - \frac{\left(\frac{r_n}{L_n} - b\right)(1-\epsilon^{-bt})}{b\,(b-a)\,(c-b)} + \frac{\left(\frac{r_n}{L_n} - a\right)(1-\epsilon^{-at})}{a\,(b-a)\,(c-a)} \right\}$$

In the solution the numerical values of the roots are substituted at this point.

Let $\quad b = n - j\,m \qquad K = c - n$

$\quad a = n + j\,m \qquad K' = \frac{r_n}{L_n} - n$

$$\phi = \frac{n\,(K\,K' + m^2) - m^2\,(K - K')}{n^2 + m^2}$$

$$\theta = \frac{(K\,K' + m^2) + n\,(K - K')}{n^2 + m^2}$$

$$E_c = E_o - E_o \left\{ \frac{\frac{r_n}{L_n} - c}{L\,C\,(K^2 + m^2)\,c} (1 - \epsilon^{-ct}) + \frac{\theta}{L\,C\,(K^2 + m^2)} - \frac{\theta}{L\,C\,(K^2 + m^2)}\,\epsilon^{-nt}\,\text{Cos}\,mt + \frac{\phi}{L\,C\,(K^2 + m^2)\,m}\,\epsilon^{-nt}\,\text{Sin}\,mt \right\}$$

As an example, consider a 66-kv. line, 50 miles long, carrying 25,000-kv-a. and assume 25 per cent system reactance at point of fault, and also assume that the neutral is grounded through 50 per cent reactance in parallel with 1000 ohms resistance. Then

| | Actual | Effective |
|---|---|---|
| $r_n$ | 1000 ohms | 1000 ohms |
| $L_n$ | 0.2306 $H$ | 0.2306 $H$ |
| $L$ | 0.1153 $H$ | 0.0384 $H$ |
| $r$ | 12 ohms | 4 ohms |
| $C_g$ | 0.375 $\mu$ f. | 1.125 $\mu$ f. |

The solution of the differential operator gives

$$c = 29760$$
$$b = 305 - j\,1859 = n - j\,m$$
$$a = 305 + j\,1859 = n + j\,m$$

From which

$$K = 29.41\,10^3 \qquad K' = 4.035\,10^3$$
$$\phi = -\,14.52\,10^3$$
$$\theta = 36.6$$
$$\frac{1}{L\,C} = 24.2\,10^6$$
$$K^2 + m^2 = 869\,10^6$$
$$\frac{1}{L\,C\,(K^2 + m^2)} = 0.02785$$

$$E_c = E_o - E_o \{\, 0.0245\,(1 - \epsilon^{-29760t}) + 1.018 - 1.018\,\epsilon^{-305t}\,\text{Cos}\,1859\,t - .2175\,\epsilon^{-305t}\,\text{Sin}\,1859\,t \}$$

When $t = 0$ this equation gives the condenser voltage as the initial voltage and when $t$ is very large the condenser voltage is practically 0. The fact that it is not 0 is probably due to some slight inaccuracy in the solution for the roots. The factor $(1 - a)$ is equal to $\epsilon^{-305t}$ and at the end of one-half a normal frequency cycle is approximately 0.08, so that there is no chance for arcing ground voltages.

As a second example assume that the grounding device consisted of a 500 per cent reactance in parallel with 1210-ohm resistance and then $r_n = 1210$ ohms

and $L_n = 2.306\,H$. The roots of the differential operator are ($c = 31370$), ($b = 380 - j\,1037$), ($a = 380 + j\,1037$) so that the damping factor is $(1 - a) = \epsilon^{-380t}$ and at the end of half a normal frequency cycle $(1 - a)$ is about 0.043.

It can be said in general that it is possible to ground the neutral through a very high relative value of reactance shunted by a resistance and still be entirely free from danger of arcing ground voltages.

## Appendix

### Basis of Analysis

The analysis of arcing ground phenomena is based on the familiar theory of condenser and discharge

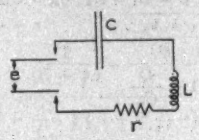


Fig. 14

charge through a resistance and inductance with the constants considered concentrated as shown in Fig. 14. When a constant voltage $e$ is suddenly applied the condenser voltage $e_c$ is given by

$$\frac{e_c}{e} = 1 - \epsilon^{-at}\left\{\operatorname{Cos} w\,t + \frac{r}{q}\operatorname{Sin} w\,t\right\} \tag{1}$$

$$\frac{e_c}{e} = 1 - \epsilon^{-at}\left\{1 + \alpha\,t\right\} \tag{2}$$

$$\frac{e_c}{e} = 1 - \epsilon^{-at}\left\{\operatorname{Cosh} \mathcal{B}\,t + \frac{r}{s}\operatorname{Sinh} \mathcal{B}\,t\right\} \tag{3}$$

$$= 1 - \frac{1}{2}\,\epsilon^{-at}\left\{(r+s)\,\epsilon^{-\frac{s}{2L}t}\,\frac{s}{2L}\,t - (r-s)\,\epsilon^{-\frac{s}{2L}t}\right\} \tag{4}$$

$$a = \frac{r}{2L}\quad \omega = \sqrt{\frac{1}{LC} - \frac{r^2}{4L^2}} \qquad q = \sqrt{4\frac{L}{C} - r^2} \tag{5}$$

$$\mathcal{B} = \sqrt{\frac{r^2}{4L} - \frac{1}{LC}} \qquad s = \sqrt{r^2 - 4\frac{L}{C}} \tag{6}$$

$e_c$ = voltage across capacitor at time $t$
$e$ = applied voltage for charge-initial voltage for discharge
$r$ = resistance in ohms
$L$ = inductance in henrys
$C$ = capacitance in farads

Equations (1), (2), and (3) are for the oscillatory, critical, and non-oscillatory cases respectively. For discharge the expressions are the same except that the figure 1 is left out, leaving on the right side only the term affected by $\epsilon^{-at}$.

It is easy to see from Equation (1) that the maximum value of condenser voltage occurs when $\omega\,t = \pi$ and is

$$e_c = e\,(1 + \epsilon^{-at}) \tag{7}$$

The limiting maximum occurs when $r = o$ and is $2\,e$. The amplitude $A$ of the oscillation is equal to the applied voltage. Suppose the condenser already had a voltage $e_1$ at the time a voltage $e_o$ was impressed, then the voltage applied to the condenser would be the difference between the impressed and the initial voltage. The following relations would hold

Initial voltage $= e_1$
Impressed voltage $= e_o$

$$\text{Applied voltage} \quad e = e_o - e_1 \tag{8}$$

$$\text{Amplitude} \quad A = e_o - e_1 \tag{9}$$

$$\text{Maximum voltage} \quad V = e_o + A \tag{10}$$

These relationships are illustrated in Fig. 14A.

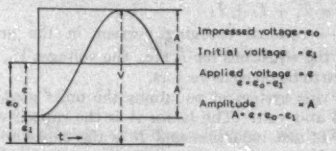


Fig. 14A

### Capacitance Relations—Overhead Lines

The capacitance relations in a three-phase or single-phase circuit can be obtained easily from the standard potential equations. These equations give the potential of a conductor due to its own charge and to all the charges on nearby conductors. These equations are

$$V_1 = Q_1 A_1 + Q_2 B_{12} + Q_3 B_{13}$$
$$V_2 = Q_1 B_{21} + Q_2 A_2 + Q_3 B_{23}$$
$$V_3 = Q_1 B_{31} + Q_2 B_{32} + Q_3 A_3$$

In this equation the voltages are above zero potential. For overhead lines the surface of the earth is usually taken as the neutral plane and the voltage $V_1$, etc., are then voltage to ground.

Capacitance is defined as ratio of charge to potential and therefore

$$C_{11} = \frac{Q_1}{V_1} \qquad C_{22} = \frac{Q_2}{V_2} \qquad C_{33} = \frac{Q_3}{V_3}$$

$C_{11}$ = Effective capacitance of conductor to ground

$$Q_1 = \frac{D_3'}{D_3} \qquad Q_2 = \frac{D_3''}{D_3} \qquad Q_3 = \frac{D''\,'}{D_3}$$

$$D_3 = \begin{vmatrix} A_1 & B_{12} & B_{13} \\ B_{21} & A_2 & B_{23} \\ B_{31} & B_{32} & A_3 \end{vmatrix} \qquad D_3'' = \begin{vmatrix} A_1 & V_1 & B_{13} \\ B_{21} & V_2 & B_{23} \\ B_{31} & V_3 & A_3 \end{vmatrix}$$

$$D_3' = \begin{vmatrix} V_1 & B_{12} & B_{13} \\ V_2 & A_2 & B_{23} \\ V_3 & B_{32} & A_3 \end{vmatrix} \qquad D_3''' = \begin{vmatrix} A_1 & B_{12} & V_1 \\ B_{21} & A_2 & V_2 \\ B_{31} & B_{32} & V_3 \end{vmatrix}$$

If we write

$$K_1 = A_2 A_3 - B_{23}^2 \qquad K_{12} = A_3 B_{12} - B_{23} B_{31}$$
$$K_2 = A_3 A_1 - B_{31}^2 \qquad K_{23} = A_1 B_{23} - B_{31} B_{12}$$
$$K_3 = A_1 A_2 - B_{12}^2 \qquad K_{31} = A_2 B_{31} - B_{12} B_{23}$$
$$K = A_1 K_1 - B_{12} K_{12} - B_{31} K_{31}$$

then

$$Q_1 = V_1 \frac{K_1}{K} - V_2 \frac{K_{12}}{K} - V_3 \frac{K_{31}}{K}$$

$$Q_2 = - V_1 \frac{K_{12}}{K} + V_2 \frac{K_2}{K} - V_3 \frac{K_{23}}{K}$$

$$Q_3 = - V_1 \frac{K_{31}}{K} - V_2 \frac{K_{23}}{K} + V_3 \frac{K_3}{K}$$

$$I_1 = 2 \pi t \left( V_1 \frac{K_1}{K} - V_2 \frac{K_{12}}{K} - V_3 \frac{K_{31}}{K} \right)$$

$I_1$ = charging current line 1, others in same manner.

$I_e = I_1 + I_2 + I_3$

$I_e$ = residual charging current in the ground.

In the equations for $I$, etc., the voltages $V_1$, $V_2$, and $V_3$ are to be taken as vectors.

In this system of equations the units used are the farad and volt. The factor $A$ is the capacitive coefficient of self induction and $B$ is the capacitive coefficient of neutral induction.

$$A = \frac{1}{C} \qquad C = \frac{0.03883}{\text{Log} \dfrac{2h}{r}} \text{ in mcf./mi.}$$

$$B = \frac{1}{C_m} \qquad C_m = \frac{0.03883}{\text{Log} \dfrac{R}{S}} \text{ in mcf/mi.}$$

Log's to be taken to base 10.

$C$ = self capacitance of a conductor to ground.
$C_m$ = neutral capacitance between pairs of conductors.
$h$ = height of conductor above ground.
$r$ = radius of conductor.
$R$ = distance from a conductor to image of the other.
$S$ = spacing between conductors.

*Single-phase Circuit*, Fig. 15.

For two-wire circuit the foregoing method gives

$$C_{11} = C_1 \frac{1 - \dfrac{V_2}{V_1} \dfrac{C_2}{C_{12}}}{1 - \dfrac{C_1 C_2}{C_{12}^2}} \qquad C_{22} = C_2 \frac{1 - \dfrac{V_1}{V_2} \dfrac{C_1}{C_{12}}}{1 - \dfrac{C_1 C_2}{C_{12}^2}}$$

$C_{11}$ = effective capacitance to ground of first wire
$C_{22}$ = effective capacitance to ground of second wire.

For a single-phase circuit there results

$$C_a = C_1 \frac{1 - \dfrac{C_2}{C_{12}}}{1 - \dfrac{C_1 C_2}{C_{12}}} \qquad C_e = C_1 \frac{\dfrac{C_2}{C_{12}}}{1 - \dfrac{C_1 C_2}{C_{12}^2}}$$

$$C_g = C_1 \frac{1}{1 - \dfrac{C_1 C_2}{C_{12}^2}} \qquad C_n = C_1 \frac{2}{1 + \dfrac{C_1}{C_2} - 2 \dfrac{C_1}{C_{12}}}$$

$C_a$ = capacitance to ground of one of two wires, when connected in multiple
$C_g$ = capacitance to ground and second wire, when second wire is grounded
$C_e$ = capacitance to second wire only, when second wire is grounded
$C_n$ = capacitance of one wire to neutral when part of single-phase circuit.

If the conductors are transposed to obtain balanced condition to ground there results

$$C = C_1 = C_2 \quad C_m = C_{12}$$

$$h = \sqrt{h_1 h_2} \qquad r = \sqrt{r_1 r_2}$$

$$C_a = \frac{C}{1 + \dfrac{C}{C_m}} = \frac{1}{(A + B)}$$

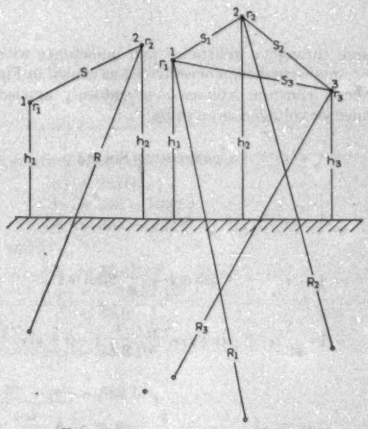


FIG. 15 FIG. 16

$$C_g = \frac{C}{1 - \dfrac{C^2}{C_m^2}} = \frac{A}{(A - B)(A + B)}$$

$$C_e = C \frac{\dfrac{C}{C_m}}{1 - \dfrac{C^2}{C_m^2}} = \frac{B}{(A - B)(A + B)}$$

$$C_h = \frac{C}{1 - \dfrac{C}{C_m}} = \frac{1}{(A - B)}$$

$$C_g = C_a + C_e$$

*Three-Phase Circuit,* Fig. 16.

For the three-phase circuit only the transposed condition will be considered, and then:

$$C = C_1 = C_2 = C_3 \qquad C_m = C_{12} = C_{23} = C_{31}$$

$$H = \sqrt[3]{h_1 h_2 h_3} \qquad r = \sqrt[3]{r_1 r_2 r_3}$$

$$R = \sqrt[3]{R_1 R_2 R_3} \qquad S = \sqrt[3]{S_1 S_2 S_3}$$

$$C_a = \frac{C}{1 + 2\dfrac{C}{C_m}} = \frac{1}{A + 2B}$$

$$C_g = \frac{C}{\left(1 - \dfrac{C}{C_m}\right)\left(1 + 2\dfrac{C}{C_m}\right)}$$

$$= \frac{A}{(A - B)(A + 2B)}$$

$$C_o = \frac{C}{C_m}\,\frac{C}{\left(1 - \dfrac{C}{C_m}\right)\left(1 + 2\dfrac{C}{C_m}\right)}$$

$$= \frac{B}{(A - B)(A + 2B)}$$

$$C_n = \frac{C}{1 - \dfrac{C}{C_m}} = \frac{1}{(A - B)}$$

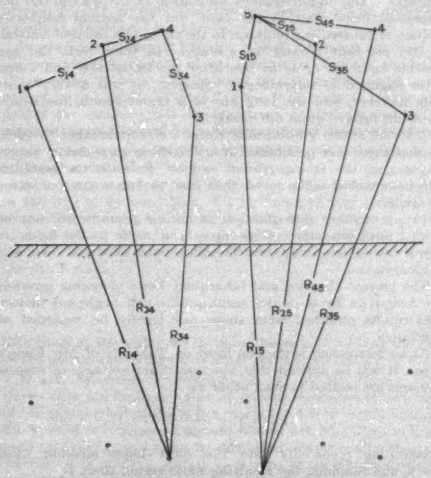


Fig. 17




Fig. 18

$C_a$ = capacitance to ground of each of three conductors when all three are in multiple

$C_g$ = capacitance to ground and third conductor, when third conductor is grounded, of each of two conductors in multiple

$C_o$ = capacitance to grounded wire of each conductor for conditions as for $C_g$

$C_n$ = capacitance to neutral of each conductor of a three-phase circuit.

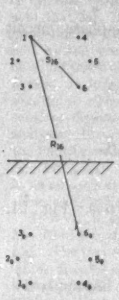


Fig. 19

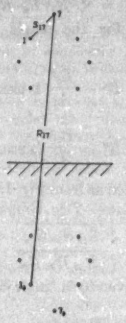


Fig. 20

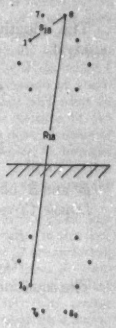


Fig. 21

*Three-Phase Circuit—One Ground Wire.* Fig. 17.

$h, r, R, S,$ same as Fig. 16.

$$S_4 = \sqrt[3]{S_{14} S_{24} S_{34}}$$

$$R_4 = \sqrt[3]{R_{14} R_{24} R_{34}}$$

The formulas given for the three-phase circuit apply if

$$A - \frac{B_4^2}{A_4} \text{ is used in place of } A$$

$$B - \frac{B_4^2}{A_4} \text{ is used in place of } B$$

*Three-Phase Circuit—2 Ground Wires.* Fig. 18.

$h, r, R, S, R_4, S_4,$ same as Fig. 16 and Fig. 17.

$$S_5 = \sqrt[4]{S_{15} S_{25} S_{35}}$$

$$R_5 = \sqrt[4]{R_{15} R_{25} R_{35}}$$

The formulas given for the three-phase circuit apply if

$$A - \left(\frac{A_5 B_4 - B_5 B_{45}}{A_4 A_5 - B_{45}^2}\right) B_4 - \left(\frac{A_4 B_5 - B_4 B_{45}}{A_4 A_5 - B_{45}^2}\right) B_5$$

is used for $A$

$$B - \left(\frac{A_5 B_4 - B_5 B_{45}}{A_4 A_5 - B_{45}^2}\right) B_4 - \left(\frac{A_4 B_5 - B_4 B_{45}}{A_4 A_5 - B_{45}^2}\right) B_5$$

is used for $B$

*Three-Phase Double Circuit Line.* Fig. 19.

$$S' = \sqrt[3]{S_{14} S_{25} S_{36}}$$

$$R' = \sqrt[3]{R_{14} R_{25} R_{36}}$$

$$S'' = \sqrt[3]{S_{24} S_{36} S_{16}}$$

$$R'' = \sqrt[3]{R_{24} R_{36} R_{16}}$$

The formulas given for the single three-phase circuit apply if

$$A + B' \text{ is used for } A.$$
$$B + B'' \text{ is used for B.}$$

*Double Circuit Line with One Ground Wire.* Fig. 20.

$$S_7 = \sqrt[3]{S_{17}\,S_{27}\,S_{37}}$$
$$R_7 = \sqrt[3]{R_{17}\,R_{27}\,R_{37}}$$

The equations for the single three-phase circuit apply if

$$A + B' - \frac{B_7^2}{A_7} \text{ is used for A}$$

$$B + B'' - \frac{B_7^2}{A_7} \text{ is used for B}$$

$B'$ and $B''$ obtained as from Fig. 19.

*Double Circuit Line—Two Ground Wires.* Fig. 21.

$$S_8 = \sqrt[4]{S_{18}\,S_{28}\,S_{38}} = S_7$$
$$R_8 = \sqrt[4]{R_{18}\,R_{28}\,R_{38}} = R_7$$

The equations given for a single circuit line apply if

$$A + B' - \frac{2\,B_7^2}{A_7 + B_{78}} \text{ is used for } A.$$

$$B + B'' - \frac{2\,B_7^2}{A_7 + B_{78}} \text{ is used for B.}$$

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*Frequency Conversion by Third Class Conductor and Mechanism of the Arcing Ground and Other Cumulative Surges*, by C. P. Steinmetz, A. I. E. E. Trans., Vol. 42, 1923.

"The Intermittent Grounding Effect," by W. Petersen, *Elektrotech. Zeitsch.*, Nov. 22 and 29, 1917.

2. "Grounding the Neutral through Resistance or Reactance," by W. W. Lewis, *General Electric Rev.*, June 1929.

3. "Inductive Interference Report," Railroad Commission of California, April 1, 1919. See also Reference No. 2


## Discussion

**L. V. Bewley:** There are two generally accepted theories of arcing grounds, which have been called the normal frequency arc control, and the oscillatory frequency arc control, corresponding respectively to the way in which the arc is assumed to go out. Hitherto these theories have been developed from the following assumptions and premises:

(1) A system of lumped constants.
(2) Line-to-line capacitance neglected.
(3) Line-to-ground capacitances equal for each line.
(4) Line reactance neglected.
(5) Transformer reactance neglected.
(6) Transformer saturation neglected.
(7) Load connections neglected.
(8) Load at instant of fault neglected.
(9) Line losses neglected.
(10) Neutral impedances neglected.
(11) Gap ionization and characteristics neglected.
(12) Traveling waves non-existent.
(13) Location of fault on the line not taken into account.
(14) High-frequency oscillation assumed to overshoot 10 per cent.
(15) Arc waits each time for a successively increasing normal system frequency crest before striking.
(16) The possibility of a superimposed subsequent switching surge not taken into account.
(17) Neutral voltage not considered.

In his paper Mr. Clem has contributed the following three refinements to the oscillatory frequency arc extinction theory:

(a) Effect of line-to-line capacitance.
(b) Effect of impedances in the neutral.
(c) Approximate expressions for damping.

He has not made a definite decision, however, as to which theory is nearer the truth, but has favored the one which gives the most pessimistic results.

It seems to me that the principal defects of the theory as it now stands, lie in assumptions (12), (15), and (16). Certainly the presence of traveling waves is going to change the character of the phenomena, and how these traveling waves behave will depend decidedly upon items (4), (5), (6), (7), (8), (9), (10), (11), (13), and (16). Some of these effects are optimistic and some pessimistic, but in what direction their resultant points, I do not know. It does not appear reasonable to suppose that a gap which breaks down initially at the crest of the normal voltage wave, will require 2½ times as much potential to break it down the second time, 3¼ times as much the third time, and so on. In fact, just the reverse would be expected, due to gap ionization, and partial disintegration of the insulation.

In a series of laboratory arcing ground tests on a circuit of lumped constants representing a three-phase transmission line, taken at Pittsfield, the high-frequency oscillations were confined entirely to the neutral voltage, and occurred there only for very high neutral impedances. There was no evidence of a high-frequency oscillation in either the free or faulty line-to-ground voltages. The high-frequency oscillation in the neutral did not overshoot more than 75 per cent, yet the normal frequency voltage of the free line built up, in the case of an isolated neutral, to 314 per cent normal leg voltage. In these tests the gap became ionized a cycle or two after the initial arc, and thereafter reignited at insignificant voltages. It was a very short gap, however, and the long arc of a transmission line would no doubt behave quite differently.

A severe arcing ground may cause a circuit breaker to open, so that there is a possibility of a switching surge being superimposed on the arcing ground surges. Perhaps the resulting rise in potential will exceed that due to either type of surge by itself.

In my opinion, this question of arcing grounds will not be settled until exhaustive tests have been made in the fields on actual transmission systems, including both overhead lines and cable systems.

The present theories and laboratory tests of arcing grounds are hedged in by so many assumptions and neglected factors that results obtained with them can hardly be regarded as conclusive.

As an interesting little side light on Table II of Mr. Clem's paper, it will be noticed that the maximum voltages of successive arcs are related to each other as

$$V_k = 3 + \frac{V_{k-1}}{2}$$

Substituting repeatedly into the right hand member until $k = 2$, and summing the resulting finite series, there is

$$V_k = 3 + \frac{V_{k-1}}{2} = 3 + \frac{1}{2}\left(3 + \frac{V_{k-2}}{2}\right)$$
$$= \ldots\ldots = 6 - \frac{3}{2^{k-1}}$$

Thus the ultimate maximum voltage approaches $V = 6$ as a limit.

**H. M. Trueblood:** Where operating conditions in power systems are such as to permit it, the use of neutral impedance as a means of limiting short-circuit currents is a valuable and important inductive coordination measure. The figures Mr. Clem has arrived at for overhead systems, as shown in his Table IV, are therefore very encouraging. They indicate that from the standpoint of arcing grounds, at least, neutral resistances in overhead systems may have values sufficiently large to afford very definite relief in the average case of inductive exposure. On the other hand, the figures in Mr. Clem's Table V are not so encouraging, that is to say, the magnitudes of neutral impedance shown in the right-hand column of the table would in most cases be too small to be of much value as a measure of inductive coordination where the problem involves voltages induced in communication circuits at times of faults to ground on power systems.

This leads to the thought that a more careful examination should be made of the effects of various factors which Mr. Clem has found it necessary to ignore or merely to approximate in his analysis of this very complicated question. For example, the assumption is made that extinction of the arc occurs on the oscillatory frequency basis, although it is stated that the phenomenon is probably controlled by normal frequency arc extinction. Other assumptions are also made in the direction of conservatism in estimating the upper limiting values of neutral impedance which may safely be used. In the absence of information, it is natural and indeed advisable to do this, as the two examples cited by Mr. Clem in his presentation indicate. Incidentally, it is interesting that in both examples, neutral reactance and not resistance was involved. I think it is important to evaluate these unknown factors more closely, and while I have no specific suggestions to offer at this time as to how we might go about doing this, I sympathize strongly with the view expressed by Mr. Bewley that the real way to get an answer to questions of this kind is by tests.

In reading the paper I found myself somewhat confused by the considerable variety of capacitance coefficients employed. There seems to be a distinct need of standardization of terminology in this field. It seems to me that it would help a good deal if the various kinds of capacitance coefficients could all be made to depend upon the fundamental idea of direct capacitance.

Mr. Clem's conclusion from Table II, that the maximum voltage is six times normal line-to-neutral voltage, can be obtained rather simply as follows: Considering absolute values in the line of figures "Max. V" in Table II, any term can, of course, be obtained by adding the difference between it and the next preceding term to that preceding term. Examination of the sequence with this in mind shows that the absolute value of the $n$th term is

$$3\left(1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \ldots + \frac{1}{2^{n-1}}\right)$$

The limit of the sequence in parentheses is 2, so that the ratio of the maximum voltage to normal voltage is 3 times 2, or 6.

**H. H. Spencer:** Expression No. 47 of Mr. Clem's paper shows that the limiting value of ground resistance is two-thirds of the geometrical mean of the reactance due to capacitance and the system reactance. I should like to ask Mr. Clem to designate that for us, so we can be sure what system reactance to use: whether it is positive, negative, or zero phase sequence or some weighted average value. I should think the arithmetical mean of the three would be the best value since the ground short circuit current with a single-phase fault is equal to three over the sum of the per unit reactances.

**J. E. Clem:** Mr. Bewley called attention to the fact that several assumptions were made in working out the theory of my paper. This is perfectly true and it is in line with the general practise used in solving problems which involve many variables. This is done because it is expected that the assumptions will be made in such a way as will not seriously impair the usefulness of the final result. In connection with this it is interesting to note that Mr. Bewley presented an equation for ground wire protection in his discussion of Mr. Dwight's paper which he said he had worked up by considering practically everything he could think of. That equation is identical with one which I worked up independently on the simple assumption of static conditions. The decision as to what to neglect and what to consider depends to a great extent upon the purpose of the analysis. If, as in this case, the purpose is the determination of the limiting values then only the major items need be brought in. Frequently the attempt to include a lot of minor factors in an analysis merely increases the work without improving the engineering value of the result.

However, it appears that I have included more factors than Mr. Bewley realizes in the analysis with impedance in the neutral. For that case his items 4, 5, 7, 9, 13, and 17 are included, either directly or indirectly, in addition to the items he mentioned. That leaves 6, 8, 11, 12, 15, and 17. The important items are 11, 13, and 16. If the gap is relatively short, ionization will probably tend to cause the arc to maintain itself and to prevent the building up of the arcing ground phenomenon. For item 15 it is hard to visualize just how the arc would wait for successively increasing voltages before restriking but the fact that overvoltages have been built up due to an arcing ground indicates that something akin to this does take place. In regard to item 16 if a switching surge were to be superposed upon the arcing ground phenomenon then voltages higher than 5½ to 6 times normal line to neutral voltage should be observed. However, during the surge voltage investigation of the past few years no voltages higher than these have been observed as a result of the switching surge on the system of the Consumers Power Company. This system operates with an isolated neutral and therefore should be subject to the higher arcing ground voltages.

I am heartily in agreement with Mr. Bewley's ideas in regard to tests on the transmission line. Tests in the field under operating conditions are the ultimate proof of any analysis and I should like to venture the prophecy that the tests will not show as high voltages as are indicated in the analysis. However, the design of insulation must be based on extreme conditions and an analysis which gives limiting values which are not entirely impossible of attainment has a value.

Dr. Trueblood calls attention to the fact that the limiting values of resistance in Table V are relatively less than those in Table IV. Table V refers to cable systems and the relatively larger capacitance of cable systems reduces the critical resistance. This need not cause undue apprehension because cable circuits do not cause as much telephone interference as overhead lines.

There is no need for anyone to be confused by the capacitance coefficients since they all depend upon two fundamental values of direct capacitance. These are the capacitance of a conductor to ground and the mutual capacitance between pairs of conductors. All capacitance values of involved configuration of conductors can be expressed by means of these two fundamental values.

The reactance $x_1$ used in Equation (47) should be taken as the positive sequence reactance.

# Fused Grading Shields

BY H. A. FREY[1] and E. M. SKIPPER[1]
Associate, A. I. E. E. Non-member

*Synopsis:—The fused grading shield was developed primarily to reduce the number of outages due to insulator flashovers on transmission lines. Recent practise of reducing the insulation adjacent to terminals has increased the number of flashovers in these sections. The fused grading shield while not always economically feasible for entire lines provides a means of obtaining the reduced insulation without increased outages.*

*Laboratory and field data are presented showing the characteristics of the device as well as the results of several years of operating experience.*

THE use of fuses in conjunction with grading shields and arcing horns was first tried on two circuits of the Columbia-Terminal Station line of the Union Gas and Electric Company in the spring of 1927. The device as first installed has been very completely described by Mr. Philip Stewart of the Union Gas and Electric Company in previous papers.[2] It consisted of the usual grading shield and arcing horn combination except that the grading shield was insulated from the line by two standard suspension units. These two units were then short circuited by means of a high-voltage fuse of the carbon tetrachloride type. In the event of a flashover of the insulator string the arc formed between the grading shield and the top arcing horns, forcing the ground current to flow through the fuse. The operation of the fuse extinguished the arc by disconnecting the grading shield from the line. This operation was so rapid that no line outage occurred.

This device operated so successfully during the 1927 lightning season that in 1928 the company decided to equip the remaining two circuits between Columbia and Terminal Station with similar equipments. The original fused grading shields, requiring as they did two additional insulator units per string, were not particularly economical. The redesigned assemblies eliminated this feature. The grading shield was placed in its usual position at the bottom of the string with fuses in place of arcing horns at the ground end. Expulsion type fuses replaced the carbon tetrachloride fuses and with this set-up it was found possible to use two fuses per assembly in place of one. Tests showed that except in rare cases no arc would strike to both fuses at once. This, of course, meant that after one operation there would still be one fuse available in the event of further trouble at the same point.

The 1928 operating experience on this line was again very favorable and has been completely reported by Mr. Stewart.[3]

The adoption of the double ended expulsion type of fuse which is now standard on fused grading shield assemblies was the outcome of a large number of short circuit tests using various shield and fuse combinations. For various line voltages the proper voltage rating of the fuse is as follows:

| Line voltage | Fuse |
|---|---|
| 22,000 | 15 kv. |
| 33,000 | 25 " |
| 66,000 | 37 " |
| 110,000 | 73 " |
| 132,000 | 73 " |

Coincident with these tests a number of impulse tests was also run to determine the correct setting of the grading shield and the fuses in order to assure the formation of the arc between the shield and the tips of the fuses. The tests which were made for this purpose were conducted using an impulse of very steep wave-front and with a tail falling to one-half crest value in about five microseconds. This type of wave, having a very steep front, is more severe from the standpoint of cascading than the usual wave encountered in practise. Obviously if the arc cascaded the insulator string and failed to strike to the fuse, the entire object of the device would be defeated.

It was found that if the arcing distance between fuse and shields did not exceed 80 per cent of the striking distance across the unshielded string, satisfactory arc clearing characteristics could be expected.

The foregoing tests, of course, all fall under the general heading of Development Tests but a number of tests has also been made to determine the operating characteristics of the device. These tests have been conducted both in the high-current testing laboratory of the General Electric Company and in the field. On all of the short circuit tests the arc was originated by means of a piece of fine fuse wire strung between the fuse tips and the shield. Table I gives a summary of these tests.

It will be noted that out of 21 tests there were 2 arcs which failed to clear or, ignoring the laboratory tests, 2 out of 15. On both of these tests the available current was very small. The time required for any fuse to operate and clear the circuit becomes greater as the short circuit current decreases. With currents of the order of 100 amperes the time required for the fuse to clear is so great that even moderate winds are likely to blow the arc away from the fuse tips and onto the tower hardware in which position, of course, it is beyond

1. Locke Insulator Corp., Baltimore, Md.
2. Report to Overhead Systems Committee of N. E. L. A. presented in Chicago in October 1927.
3. *Fused Arcing Horns and Grading Rings*, by P. Stewart, A. I. E. E. TRANS., Vol. 48, July, 1929, p. 891.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*



30-65

TABLE I—LABORATORY AND FIELD TESTS

| Test No. | Date | Nature of test | Line voltage Kv. | Kv. to ground | Frequency cycles per sec. | Interrupted current | Time to clear sec. |
|---|---|---|---|---|---|---|---|
| 1 | Apr. 1928 | Laboratory | | 37 | 25 | 572 | 0.06 |
| 2 | " " | " | | 37 | 25 | 630 | 0.06 |
| 3 | " " | " | | 37 | 25 | 770 | 0.025 |
| 4 | " " | " | | 37 | 25 | 1482 | 0.04 |
| 5 | " " | " | | 37 | 25 | 1720 | 0.04 |
| 6 | " " | " | | 37 | 25 | 2340 | 0.02 |
| 7 | May 1928 | Field | 66 | 38 | 60 | 100 | 0.60 Failed to clear |
| 8 | " " | " | 66 | 38 | 60 | 115 | 1.0 Failed to clear |
| 9 | " " | " | 66 | 38 | 60 | 250 | 0.075 |
| 10 | " " | " | 66 | 38 | 60 | 250 | 0.067 |
| 11 | " " | " | 66 | 38 | 60 | 400 | 0.042 |
| 12 | " " | " | 66 | 38 | 60 | 2500 | 0.0125 |
| 13 | June 1929 | " | 110 | 63.5 | 60 | 314 | 0.0675 |
| 14 | " " | " | 110 | 63.5 | 60 | 388 | 0.05 |
| 15 | " " | " | 110 | 63.5 | 60 | 639 | 0.146 |
| 16 | " " | " | 110 | 63.5 | 60 | 1112 | 0.0416 |
| 17 | " " | " | 110 | 63.5 | 60 | 1955 | 0.046 |
| 18 | " " | " | 110 | 63.5 | 60 | 2878 | 0.025 |
| 19 | " " | " | 110 | 63.5 | 60 | 3454 | 0.021 |
| 20 | " " | " | 110 | 63.5 | 60 | 4002 | 0.021 |
| 21 | " " | " | 110 | 63.5 | 60 | 5120 | 0.021 |

the control of the fuse. This is what happened in the two cases in question. Two hundred amperes appear to be the minimum current limit for satisfactory operation of the fused grading shield. The upper limit of short circuit current has not as yet been determined but tests have been made on short circuit currents as high as 5120 amperes with perfect success.

Figs. 1, 2, and 3, are respectively the oscillograms taken during tests 17, 19, and 21. It should be noted that the maximum recovery voltage shown on these oscillograms is 1.225 times normal.

In addition to the tests listed in this tabulation, a series of tests was conducted by the Carolina Power and Light Company at the Swannanoa Substation near Asheville, North Carolina. Unfortunately no oscillograph was available to record accurately the current and duration of the arc. It is estimated, however, that the short circuit current of the system at this point is around 250 amperes. The system voltage is 66 kv.

The four fuse grading assembly of the type shown in Fig. 4 was used for this test. Seven arcs were started, all of which cleared successfully without operation of the line relays. During one short circuit two fuses were blown. In this case the wind carried the arc from the tip of the fuse from which it had started to the tip of an adjacent fuse. Attempt was made to repeat this on succeeding tests by starting the arc on the windward side. Despite this no further example of more than a single fuse operating occurred.

Fig. 5 shows the fused grading shield during another field test clearing a ground current of 2878 amperes. The flame is quite clearly being ejected from both ends of the tube. It will also be noted that the original arc between the tips of the fuse and grading shield is remaining well clear of the insulator string.

Fig. 6 shows a grading shield from which six arcs had been initiated prior to the taking of the photograph. While the shield was slightly burned, it is still perfectly serviceable. Indications are that with the rapid clearing of the arc the life of the grading shield will be practically indefinite.

Fused grading shields were first designed for use on all the insulator strings of a complete transmission line but it is unlikely that this type of installation is to be recommended except under special conditions where line outages assume extremely serious proportions. Where the expenditure can be justified by conditions there is little doubt that almost perfect protection will result.

The fused grading shield, however, has another very definite use which is certainly economical and practical. This use is as relief gaps on those insulator strings immediately adjacent to terminals.

The modern tendency in transmission line design is largely toward the overinsulation of the line with a view to reducing the number of outages caused by insulator flashover. This practise has resulted in improved line service but where the path of the storm is close to a line terminal it has in many cases merely shifted the burden to the substation apparatus. It is relatively easy to add a few units to an insulator string and for the higher voltages at least relatively inexpensive. On the other hand it is very difficult and expensive to attempt to raise the insulation of the substation apparatus to the level of the increased line insulation. It has therefore become customary to reduce the line insulation immediately adjacent to the terminal to a value which will balance with the terminal equipment insulation.

Due to the rapidity with which lightning surges on transmission lines are attenuated most disturbances originating several miles out on the line will probably be reduced below dangerous proportions before they reach the reduced insulation. Nevertheless, there will naturally be an increased number of flashovers adjacent to the terminals resulting in a corresponding increase in number of line outages. There is also the

added danger of damaging the insulator units at this point, thus causing a prolonged outage while repairs are being made. The use of a standard grading shield on the shortened strings will prevent the insulator damage but cannot prevent the line trip-out when flashover occurs.

Fig. 1

Fig. 2

Fig. 3

Figs. 1, 2, and 3—Oscillograms Obtained during Field Tests

Showing short-circuit current and time to clear

If the fused grading shield is applied to the reduced insulation at the terminals and the gap between the fuse tip and shield adjusted to give the desired flashover voltage, then the excess voltage on the line will be relieved without an outage since the power current to ground is interrupted by the fuse without operation of the line relays. Unlike the lightning arrester the fused

Fig. 4—Four-Fuse Type Assembly

Fig. 5—Fused Grading Shield in Operation during One of Field Tests

Fig. 6—Grading Shield after Six Tests at High Current

grading shield can be expected to care for only those surges whose magnitude is sufficient to arc the gap.

The lightning arrester would protect the station equipment from the hammer blows of smaller transients.

For this class of service a fused grading shield equipped with four fuses, so that each assembly is capable of clearing four arcs without fuse renewal, has been developed. Two and three fuse assemblies have also been applied to this service to fit special conditions and each type of installation has been attended with marked success.

These reduced gaps should be installed on each line for a distance of approximately one-fourth mile out from the terminal. A number of installations has been made equipped with only a single assembly on each line wire. So far, no difficulties have arisen as a result of the use of this single gap but as an additional safety factor it is certainly advantageous to have more than one gap on each conductor.

It is important to remember that the last gap adjacent to the terminal should be placed as close as possible to the apparatus to be protected, otherwise it is quite possible that reflections will so build up within the substation as to result in breakdown or arc-over of the apparatus without affecting the fuse grading shield.

In Table II is listed the proper gap setting of a fused grading shield to balance with modern substation equipment. Here again it must be remembered that much of the older equipment was designed with lower insulation than that which is now being used. Hence in some cases it may be necessary to use a still smaller gap in order to balance with this old substation insulation. In many cases the switch insulators or bus supports in the substation constitute the weak link. When such is the case it may be necessary to set the reduced gap below the tabulated values in order to prevent flashover on disconnect switches and bus supports.

TABLE II—GAP SETTINGS TO BALANCE WITH STANDARD STATION EQUIPMENT

| Line voltage in kv. | Fused grading shield gap in in. | Approximate impulse FO of gap | Approximate 60-cycle flashover of gap |
|---|---|---|---|
| 33 | 10 in. | 310 | 103 |
| 66 | 21 in. | 605 | 206 |
| 88 | 31 in. | 900 | 290 |
| 110 | 37 in. | 1060 | 345 |
| 132 | 41 in. | 1170 | 380 |

Figs. 4, 7, and 8, show the 4, 3, and 2, fuse assemblies respectively. The 3 and 4 fuse types are most commonly used for substation protection where it is probable that more than one arc may occur on an assembly during the course of a storm. The two fuse assembly has been applied to substations but is primarily applicable to line service.

The double ended expulsion fuse which was chosen for use with fused grading shields presents several unique features.

The fusible link of this fuse is placed at the upper end of a weatherproof fiber tube. To the lower end of the link is fastened a long copper pigtail which runs the entire length of the tube. The pigtail is held taut by a compression spring at its lower end. The tube is capped at either end. The cap on the lower end is held in place by friction but the cap at the upper end is sweated in. When the fusible link is melted the compressed spring is released. The combination of forces of the released spring and of the gases generated in the tube blow out the cap and vent the tube, extinguishing the arc.

Fig. 7

With the expulsion type of fuse it is desirable to build up the internal gas pressure promptly in order to obtain quick clearing. With the double end fuse only the lower cap opens on low-current operation so that there is no loss of pressure from the upper end of the fuse. The spring also aids in obtaining quick clearing under low currents since it hurls the copper pigtail free of the fuse tube as soon as the fuse element melts. The maximum current rupturing capacity of an expulsion

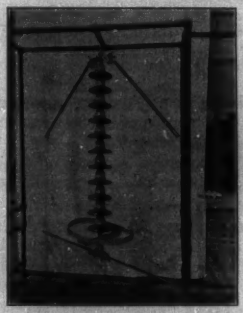

Fig. 8

Figs. 7 and 8—Three- and Two-Fuse Type Assemblies

fuse may be the point at which the fuse tube bursts due to excessive pressure. When the internal pressure becomes excessive in a double ended fuse the upper cap is blown out and the tube is vented from both ends. The double ended action is particularly desirable for fuses used on Fused Grading Shields since it reduces the unbalanced reaction. In rupturing high currents this unbalanced reaction might otherwise become sufficiently severe to give a violent kick to the supporting insulators.

Some fears have been expressed that the spring and copper pigtail which are expelled from the fuse might be sufficiently hot to start fires in grass or other inflammable material on which they might fall. During the tests it was found that in most cases the spring and pigtail were cool enough to be picked up by hand immediately after striking the ground. After a few of the very high current tests, notably No. 20 and No. 21, the elements were quite hot. In no case, however, was there any evidence of actual burning of the metal. It is this continued combustion of metal after falling from the line which has been responsible for grass fires in the past.

During the high-current tests the expelled elements were thrown about 30 ft. from the insulator string.

Further tests were made to determine the point at which corona formation would start about the copper pigtail in the fuse tube. It was found that with a standard 110-kv. fused grading shield of the two fuse type mounted on an eleven-unit string, the corona point was 82 kv. when the fuses were parallel to the conductor. With the fuse at right angles to the conductor, the corona point was 89 kv. The normal corona point on the standard grading shield assembly would be in the vicinity of 90 to 95 kv.

## Operating Experience

Since the installation of the first fused grading shield in actual service an attempt has been made to keep an accurate record of its performance.

Table III represents a summary of the operating characteristics of those fused grading shields which have been installed during the past three years. This table shows the approximate short circuit currents to ground, the number of failures to clear, and the number of cases of damage of substation apparatus protected by the fused grading shield and damage to the insulators on which the fused grading shield is mounted. Four trip-outs which may have been caused by arcs on the fused grading shield are also listed. Only the operations on the Union Gas and Electric Company's system which have not been previously reported by Mr. Stewart are included in this table. Lightning arresters were not used on any of the installations listed in Table III.

Table IV gives a list of those fused grading shield installations on which there have been no operations reported to date. All of the installations represented in this table are made as substation relief gaps except those on the Union Gas and Electric Company's system.

The only case of flashover or damage to the substation equipment to be protected is that reported by the Pennsylvania Water and Power Company, where there have been four bushing flashovers since the fused grading shields were installed. Two of the bushing flashovers occurred simultaneously, one at each end of the line, apparently as a result of the same surge. In an effort to prevent a repetition of this the gap was reduced somewhat. After the reduction there were two more bushing flashovers. These occurred during an exceptionally bad lightning season during which a large number of fuses was blown on this same system. There is little doubt that had no fused grading shields been installed the number of substation flashovers would have been considerably greater.

On this system each end of the line wire is provided with 15 reduced gaps. This probably accounts for the large number of fuse operations shown on the operating records. The bulk of these fuse operations occurred during the second season.

The installation of fused grading shields on the Memphis Power and Light Company's North Memphis,

TABLE III—OPERATING DATA

| Operating company | Line or substation | System voltage | Ground current amperes | Connected capacity kv-a. | No. of gaps on each line wire | Distance nearest gap to apparatus to be protected | Date put in operation | No. of operations | No. of failures to clear | No of cases of insulator damage | No. of case of F. O. of substation apparatus | No. of trip-outs of line relay |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Memphis Pr. & Lt. | N. Memphis Ripley & Covington Stations | 66 kv. | 500 to 800 | | 1 | 100-400 ft. | June or July 1929 | 2 | None | None | None | 2 |
| Minn. Pr & Lt. | Hibbing Substa. | 110 kv. | 415 to 920 | 72,000 kv-a. | 3 | 100 ft. | May 27 1929 | 1 | " | " | " | 0 |
| Minn. Pr. & Lt | Naahwauk Substa. | 110 kv. | 422–1033 | 72,000 kv-a. | 3 | 200 ft. | May 27, 1929 | 1 | " | " | " | 1 |
| Union Gas & Elec. Co. | Hartwell Substa. | 66 | 1500–2000 | 285,000 kv-a. | On all towers | 200 ft. | May 1928 | 4 | " | " | " | 0 |
| Penna. Water & Pr. Co. | | 70 kv | 300–600 | 16,000 | 15 | 40–75 ft. | Spring 1928 | 95 | 1 | 1 | 4 | 1 |
| Carolina Pr. & Lt. Co. | Swannanoa Substa. | 66 kv. | 250–300 | 90,000 | 1 | 70 | April 1929 | 8 | None | None | None | 0 |
| Carolina Pr. & Lt. Co. | Brisco Substa. | 110 | About 500 | 108,000 | 1 | 2500–3000 ft. | Sept. 1929 | 2 | " | " | " | 0 |

TABLE IV—FUSED GRADING SHIELD INSTALLATIONS FROM WHICH NO OPERATIONS HAVE BEEN REPORTED

| Operating company | Station or line | System voltage | Approx. ground current | Connected capacity kv-a. | No. of gaps on each line wire | Distance of nearest gap to apparatus | Date put in operation | Remarks |
|---|---|---|---|---|---|---|---|---|
| Alabama Pr. Co. | Leeds Substa. | 110 kv. | 4460 | 300,000 | 3 | 900 ft. | About Aug. 1929 | |
| Alabama Pr. Co. | Anniston Substa. | 110 kv. | 2700 | 300,000 | 3 | 1000 ft. | About Aug. 1929 | |
| Carolina Pr. & Lt. Company | Spruce Pines Substa. | 66 kv. | 350 | 90,000 | 1 | 30 ft. | Oct. 1929 | |
| Carolina Pr. & Lt. Company | Cape Fear Substa. | 110 kv. | 1500 | 108,000 | 1 | about 1 mile | Sept. 1929 | |
| Louisiana Pr. & Lt. Company | Sterlington Sta. | 110 kv. | 1500–2000 | 100,000–175,000 | 1 | 500–1000 ft. | July 1929 | |
| Union Gas & Elec. Co. | Armco Line | 66 kv. | 1000–1500 amperes | 24,000 | Used on every tower | | June 1928 | No outages on line |

Ripley and Covington Substations are of the four fuse type. The distance from North Memphis to Covington is 29 mi. and from Covington to Ripley 14 mi. There have been two cases of fuse operation, each accompanied by a line trip-out. The first operation resulted in the blowing of all fuses on all line wires at North Memphis, a total of 12 fuses. The second operation resulted in the blowing of one fuse on one line wire at Covington and one fuse on each of two line wires at Ripley. Apparently these operations were due to the same surge.

Both of these surges must have been very severe in order to have arced so many gaps. The line trip-outs were undoubtedly caused by the flashover of other insulator strings out on the line which were not protected by fused grading shields.

On the installation at the Minnesota Power and Light Company's Nashwauk Substation there has been one fuse operation and a simultaneous line trip-out. This line trip-out is believed to have been due to the arc at the fused grading shield but it is possible that it may have been due to another flashover out on the line on an unprotected insulator string.

It is interesting to note that none of the operating companies has reported any trouble arising from the recovery voltage after a fuse operation. In addition to the operations listed in Table III Mr. Stewart has already reported 7 interruptions and 12 interruptions prevented by the fused grading shields on the Union Gas and Electric System. Some of the fuses on this system are of the carbon tetrachloride type and some of the single ended expulsion type. None of the double ended fuses are in use on the Union Gas and Electric system.

So far no installations have been made using relief gaps on the station side of the choke coils. There is some doubt as to whether such an installation would be successful since it is possible that disturbances set up by the operation of the fuse would cause oscillation between the choke coils and the transformer. A relatively small recovery voltage might be magnified by such reflections to dangerous proportions.

The successful operation of the fused grading shield on any system is dependent not only upon the characteristics of the device itself but also upon the operating characteristics of the system. Before being installed on any system a careful check should be made on the relay settings to see that they are not too fast for the operation of the fuses. Obviously if the relays operate before the fuse clears the line will be tripped out even though the fuse might be quite successful in clearing the arc.

The use of fused grading shields on delta connected systems should be given very careful preliminary consideration since on such systems the only current available for operating the fuse is the very small charging current of one line to ground, and any unbalanced currents which may be present on the system. There is some reason to believe that when used on delta systems flashover on one conductor would result in a corresponding flashover on another conductor. If this is the case there are really two fuses and two arcs in series with the line voltage.

Where difficulty is encountered in installing the fused grading shield relief gaps close to the substations, several rather interesting types of construction have been developed. In one case, the Biscoe substation of the Carolina Power and Light Company, it was impossible to get the relief gap on a suspension string close to the station due to the presence of dead end towers at this point. There was not sufficient mechanical clearance in the jumper loop to place the fused grading shield on insulator strings supporting the jumper. The problem was solved by placing a vertical insulator string between the jumper and the tower crossarm and then suspending the insulators which support the fused grading shield on the bottom of this string with the fuse at the live side and the grading shield connected electrically to ground by means of vertical tie down. This installation at the Biscoe station has had two satisfactory operations so far.

## Summary

1. The minimum short circuit current which the fused grading shield, using a double ended expulsion fuse, can be expected to clear satisfactorily is about 200 amperes.

2. The maximum short circuit which can be cleared has not been determined but it is in excess of 5100 amperes.

3. Out of a total of 28 tests made in the laboratory and in the field there have been only two cases of failure to clear. Both of these were with currents under 200 amperes.

4. Operating records show that out of a total of 113 operations on modern assemblies in service there has been only one failure to clear with consequent damage to line insulators and four cases of flashover within the substation. There have been four cases in which the line has tripped out simultaneously with a fused grading shield operation. Of the four, two on the Memphis Power and Light Company system were probably due to other flashovers on unprotected strings. This leaves two cases of line trip-out for which the fused grading shield is probably responsible.

## Discussion

**F. E. Andrews:** In regard to Mr. Frey's paper, it is interesting to point out that in connection with the new construction described in *Transmission Research and Design with the Field as a Laboratory* (Andrews and Stroup, see p. 959), there is quite a considerable problem, particularly on the pole top switches. We have old style pole top switches with steel crossarms and grounded structures. If we wish to improve the performance of a line we change it to the improved construction, with a new pole-top switch of corresponding design. It is a pretty expensive thing. So it seems to me that the fused grading shield using two fuses for each assembly may be the answer and we are making a number of such installations with the expectation that these installations will take care of the flashovers which occur very frequently on these pole top switches without causing us any line outage.

There are two or three questions I should like to ask Mr. Frey. What methods are recommended in regard to the inspection and replacement of fuses on these grading shields? Can the work be done without taking the lines out of service or should they be inspected after every lightning storm? Also, what size fuse is used and what would be the ampere rating of the fuses of this type, and how does the fuse rating compare with the current required for rupturing.

**J. E. Clem:** Messrs. Frey & Skipper in their paper state that the arcing distance between the fuse tip and grading ring must not exceed 80 per cent of the unshielded length of the insulator string to insure that the arc will always strike to the fuse. This requirement is correct and means either that the flashover voltage of the insulator string must be reduced by the application of the fused grading shield assembly, or that the insulator string must be increased in length if it is desired to maintain the lightning flashover voltage. Part of the increased length required is due to the ring itself, but by far the greater part is due to the space required by the fuses. The rating of the fuses for various line voltages as given in the paper was selected on the basis of using a fuse having a voltage rating approximately equivalent to the normal line to neutral voltage of the system. This gives fuses that sometimes are quite long relative to the length of the insulator string.

The use of lightning arresters is considered to be the most satisfactory method of protection, but in order that the best results be secured, it is desirable that the insulation level adjacent to the station be kept at the proper value for the rated circuit voltage, either by reducing the number of line insulators near the station, or by the installation of a limiting gap. When the fused grading shield assembly is used to establish the required reference insulation level, it should be borne in mind that it is necessary that the reference insulation level be definitely and positively established. This requires an assurance that there are more fuses available than will be used up before the fuses can be replaced. This requirement probably holds when the fuse grading shield assembly is applied on the line for a short distance outside the station. However, when only one installation is made it is advisable to install at this point a plain gap having the proper setting and then to supplement this gap with the fused grading shield assembly set at a lower value. It seems that the use of the limiting gaps at one point is preferable to the use of several on the line outside the station because the lightning arrester has a much better chance of protecting the one gap closely adjacent to it than it has of protecting several gaps at varying distances up to a quarter or half a mile out from the station.

**O. R. Schurig:** In referring to the application of expulsion fuses to fused grading shield assemblies, the authors have pointed out that at certain low currents, say 100 amperes, an occasional failure of the fuses has been observed, that is, the arc whipped to ground before the fuse cleared the circuit. It must be pointed out, however, that similar fuses in the same series of tests interrupted satisfactorily at all higher currents up to 2500 amperes. In subsequent tests short-circuit currents up to 5000 amperes were cleared with the fuses in fused grading shield assemblies.

With the above points in mind attention is now called to the authors' data in Table III showing that the range of currents over which grading shield fuses have to operate is relatively small, something like 2 or 3 to one. On the basis of Table III, therefore, a grading ring fuse required to interrupt several thousand amperes would not be called upon to interrupt currents of 100 or 200 amperes and vice versa.

On systems requiring grading shield fuse operation at low interrupting currents of the order of 100 or 200 amperes, fuses suitable for the lower current range should be used.

I should like to ask the authors if it is necessary to have fuses to clear at currents below 200 amperes.

The second point to which I wish to call attention is the application of expulsion fuses to the protection of transformers in substations and branch circuits. In this application, the fuses are mounted with both ends connected to metal conductors on insulators. In other words, we do not begin by drawing an arc in the open air as in the gradual shield fuse. Hence the tendency to arc to ground is eliminated at all currents both low and high within the interrupting rating and fuses will interrupt satisfactorily over a wide range of currents.

**W. H. Colburn:** This paper presents another method of protection against those surges which may result in flashover of insulators or damage to equipment and is itself a testimony to the unsatisfactory conditions which exist in regard to such protection. Among operating engineers there is no unanimity of opinion as to the best method of affording such protection.

What is most needed now is full and accurate data on operating experience and maintenance costs on the various methods, lightning arresters, ground wires, plain and fused grading shields, etc., over a long period, as well as capital outlay therefor, to enable us to arrive at conclusions regarding the best method of surge protection to adopt.

**H. A. Frey:** Replying to Mr. Andrews' questions concerning the determination of whether or not a fuse is blown and what steps would need to be taken to keep the fuses in proper order on a transmission line,—these fuses have all been equipped with white caps in the lower end which are expelled when the fuse blows. The open end of the fuse can then be seen from the ground. Blown fuses can be replaced while the line is alive. Originally 10 ampere fuses were used but more recently 5 ampere fuses have been used with success. The 5 ampere fuse is the present standard.

Mr. Clem has pointed out that in many cases it may be desirable to use a single fused grading shield gap set for somewhat lower value than would be otherwise necessary and used in conjunction with a plain grading shield gap set for the value just necessary to balance the station insulation. That certainly is a very good idea where there will be less than the usual number of fuses used on each line wire. Ordinarily enough fuses are placed on each line wire so that there is very little possibility of all fuses blowing during one storm before they can be replaced.

Mr. Schurig asks if there is any necessity for a fuse which would operate below 200 amperes. Present experience leads us to believe there is no necessity for such a fuse. As a matter of fact, the fuses which are being used at present seem to fulfill all the requirements very well. Such need may arise when fuses are to be applied to delta connected systems.

In closing I should like to point out again that the tests which are included in the paper were made in three different locations. The first set was made in the high-current laboratory of the General Electric Company at Schenectady, the second set was made at the Hartwell Substation of the Union Gas and Electric Company, and the last set in the Spring of 1929 at the Bessemer Field Laboratory of the Alabama Power & Light Company.

# Reduction of Eddy Current Losses
## by the Inverted Turn Transposition and the Twisted Lead Transposition

BY JOHN M. LYONS*
Associate, A. I. E. E.

***Synopsis.***—*The first section of the paper contains a brief review of the general theory underlying the determination of extra copper losses in armature windings carrying alternating currents. Simplified methods of calculation are then described.*

*The second part extends the study of the inverted turn transposition to the special case of three-phase windings having two phases connected in series to form a single-phase winding and the third phase left idle. Formulas and tables are presented to show what reductions in copper losses may be expected for this connection, and to aid in deciding what type of transposition is best for a given winding.*

*The final section of the paper deals with the twisted lead transposition, and presents formulas and tables showing reductions in extra losses to be gained from this method of inversion and connection. Details of the derivations of the formulas and examples of the use of the twisted lead transposition are contained in appendices at the end of the paper.*

* * * * *

### I. Introduction

THE problem of determining the extra copper losses in rectangular conductors composing the armature windings of large alternators has been covered in detail in the well-known papers listed in the references. From these and many other investigations several methods have been adopted commercially for reducing the parasitic eddy current losses and the extra heating which they produce. The methods now in use group themselves into two general classes. One class includes transpositions of the conductor laminations in the slot, and the second includes inversions or twists of whole conductors or leads in the end portions. This paper will be concerned only with the second class.

The "inverted turn transposition" has been used to great advantage on large multi-turn coils. In a previous Institute paper by Mr. I. H. Summers[1] the four arrangements of inverted turns as shown in Figs. 2-7 inclusive were described, and the corresponding reductions in copper losses were calculated and tabulated. These reduction factors can be applied to three-phase, quarter-phase, and single-phase windings in general.

There is, however, one special type of single-phase winding which is not completely covered in that paper. Reference is made to the standard three-phase winding in which two phases are connected in series to form a single-phase winding, and the third phase is left idle. This connection has been applied to several large alternators in the last few years, and will, no doubt, find further use in the future. When high untransposed losses are encountered in this kind of winding, any one of the four types of inverted turn transposition can be utilized just as in standard windings, although the reduction factors will in general have different values. In the present paper the formulas and tables of the previous paper are extended to include this special single-phase winding.

Curves are presented in Figs. 8 to 12 inclusive which will decrease the work involved in making routine numerical calculations. These curves apply not only to windings with integral numbers of slots per pole per phase, but also to the general case of windings with fractional numbers of slots per pole per phase.

The second purpose of the paper is to describe the so-called "Twisted Lead Transposition." As the name suggests, this transposition consists of a 180 deg. twist in one lead of each armature coil. To make the inversion effective, the conductor laminations are insulated throughout each phase belt. Formulas are derived and tables showing reductions in extra copper losses are presented in the second part of the paper. Various types of windings and coil groupings are treated, including the special case of the three-phase winding connected single-phase with one leg idle.

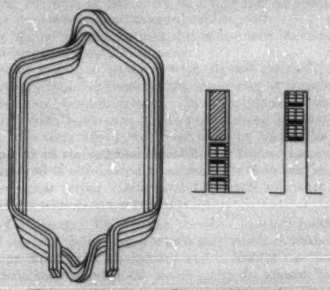

Fig. 1—Standard Barrel Type Coil
Showing successive positions in slot of a single strand—Type I, Table I

### II. General Theory

A brief review of the fundamental theory underlying

*Turbine Generator Engg. Dept., General Electric Co., West Lynn, Mass.

1. *Reduction of Armature Copper Losses*, by I. H. Summers, A. I. E. E. Trans., Vol. 46, 1927, p. 101.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*



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the determination of extra copper losses in rectangular conductors is essential to a complete discussion of the problem. The basic cause of extra copper losses in slot-wound conductors carrying alternating current is

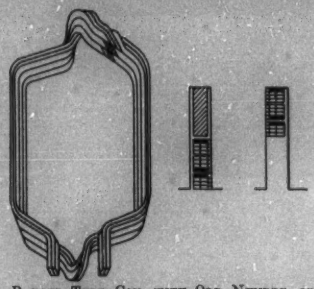

Fig. 2—Barrel Type Coil with Odd Number of Turns
All inverted at the end opposite connections—Type II, Table I

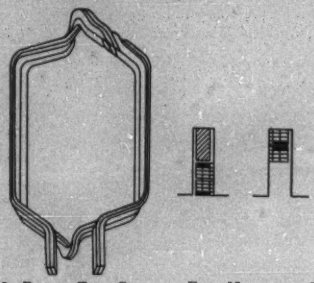

Fig. 3—Barrel Type Coil with Even Number of Turns
All inverted at the end opposite connections—Type II, Table I

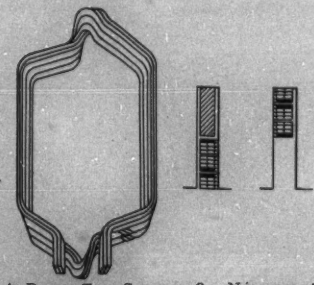

Fig. 4—Barrel Type Coil with Odd Number of Turns
All inverted at the connection end—Type III, Table I

the uneven distribution of the current over the cross-section. The flux linkages, and hence the reactance, are greatest at the bottom of the conductor, and least at the top. The current is in effect forced toward the top of the conductor, since the same voltage drop occurs along all the elements of the conductor between points where the elements are solidly joined. This means that the copper losses at the top are greatly in excess of the average, and while the losses at the bottom

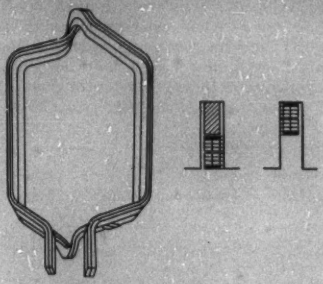

Fig. 5—Barrel Type Coil with Even Number of Turns
All inverted at the connection end—Type III, Table I

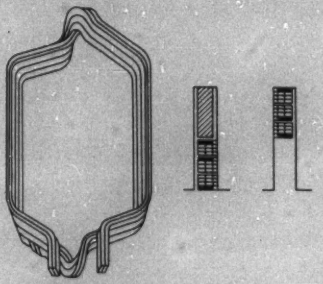

Fig. 6—Barrel Type Coil with Even or Odd Number of Turns
Top half turn in upper coil side only inverted at connection end—Type IV, Table I

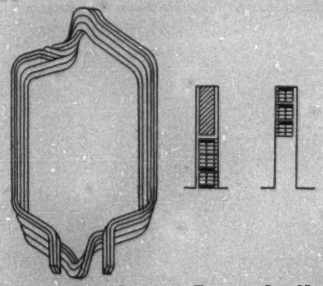

Fig. 7—Barrel Type Coil with Even or Odd Number of Turns
Bottom half turn in upper coil side only inverted at end opposite connections—Type V, Table I

are less than the average, the total losses in the conductor are greater than occur with the same total uniform current. Likewise, in the several turns in the slot, the extra loss is greatest in the top conductor and least in the bottom one.

Theories of this action have been worked out by various authors[2, 3], and equations for the variation in current density over a conductor have been developed. For practical use, formulas have been derived for calculating the ratio of a-c. copper loss to uniform current loss for solid conductors, infinitely laminated conductors, and laminations of finite thickness. The reader is referred to these papers for the complete derivations of the formulas, and for explanations of the

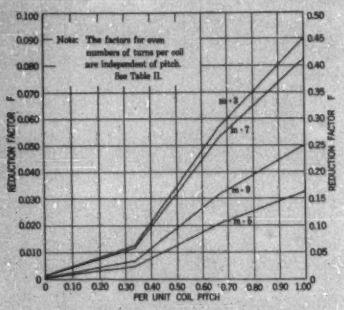


Fig. 8—Reduction Factors for Type II Transposition Single-Phase Connection

Use scale on right for $M = 3$ and $M = 5$
Use scale on left for $M = 7$ and $M = 9$

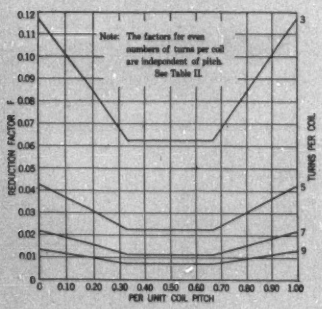


Fig. 9—Reduction Factors for Type III Transposition Single-Phase Connection

simplifying assumptions on which they are based. It is to be noted that four factors enter into all formulas and equations for current density and copper loss. These are: (1) frequency; (2) ratio of total copper width to slot width; (3) resistivity of copper; (4) total depth of conductor. These variables are generally collected into one factor $D$ according to the equation:

$$D = 1.19 \left[ \frac{f}{60/\text{sec.}} \right]^2 [b\, r\, c\, (n\, d/\text{in.})^2]^2 \qquad (1)$$

which holds good for copper at 75 deg. cent. The

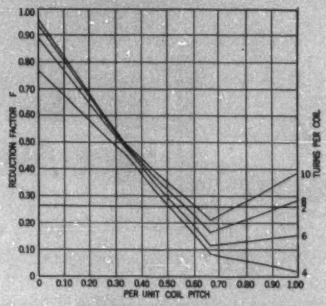


Fig. 10—Reduction Factors for Type IV Transposition Single-Phase Connection

Even number of turns per coil

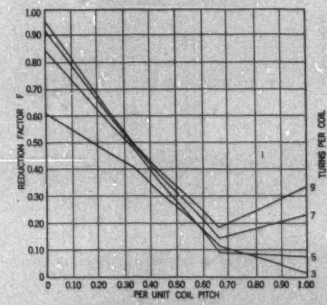


Fig. 11—Reduction Factors for Type IV Transposition Single-Phase Connection

Odd numbers of turns per coil

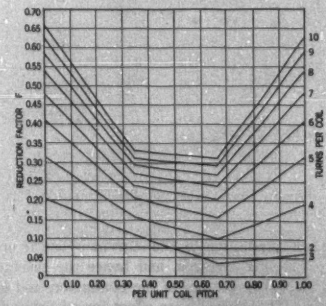


Fig. 12—Reduction Factors for Type V Transposition Single-Phase Connection

2. *Heat Losses in the Conductors of Alternating-Current Machines*, Waldo V. Lyon, A. I. E. E. Trans., Vol. 40, p. 1361.
3. Bibliography given in Reference 1.

meanings of the symbols are to be found in the table at the end of the paper. The ratio $b$ takes account of the fact that the uneven current distribution is due to flux linkages in the core portions of the coil, while the laminations are insulated throughout the whole length of each turn.

The copper loss in any conductor due to circulating currents depends not only on the current in that conductor, but also on the total current below it in the slot. Following the rules derived by Professor W. V. Lyon,[2] in order to find the average loss in a coil it is necessary to find a vector quantity $\mathbf{I}_e$ as follows. Let $\mathbf{I}_b$ be the vector total current in the slot below the given conductor, and let $\mathbf{I}_1$ be the vector current in the conductor. Then, for all conductors having laminations in a direct order (arbitrarily chosen), and for all solid conductors:

$$\mathbf{I}_e = \mathbf{I}_b \tag{2}$$

For conductors having laminations in the reverse order

$$\mathbf{I}_e = -\mathbf{I}_1 - \mathbf{I}_b \tag{3}$$

The average value of $\mathbf{I}_e$ over all the conductors in a coil must then be found and used in the equation

$$L = \frac{\mathbf{I}_e \cdot \mathbf{I}_e + \mathbf{I}_e \cdot \mathbf{I}_1}{\mathbf{I}_1 \cdot \mathbf{I}_1} \tag{4}$$

where the dot product stands for product of the magnitudes times the cosine of the angle between the vectors.

The formula for $L$ has not been presented before in the simple vector form of Equation (4). The vector form lends itself most readily to simplified derivations of the equations for $L$, and is to be generally preferred to scalar forms previously used.

The general formula for the ratio of a-c. copper loss to uniform current loss is

$$K = M_r + L\,N_r \tag{5}$$

$M_r$ and $N_r$ are the real parts of complex hyperbolic expressions, and relate to the copper loss due to current in a conductor, and to current below the conductor respectively. Using only the first terms in the series for the hyperbolic quantities, and subtracting the constant uniform current loss from the series for $M_r$, the following formula is derived for the ratio of extra loss to constant loss

$$k = (4 + 15\,L)\,D \tag{6}$$

This formula will be used to calculate all extra copper losses in this paper.

## III. Inverted Turn Transpositions in Single-Phase Windings

The quantity $L$, as defined in Equation (4), depends on the number of turns per coil and on the phase angle between the currents in the upper and lower coil sides. In the special single-phase winding with one phase idle there are three possibilities as regards the phase angle:

1. The current in the lower coil side is in phase with that in the upper coil side.

$$\mathbf{I}_2 = m\,\mathbf{I}_1$$

TABLE I

VALUES OF "L" FOR POLYPHASE AND SPECIAL SINGLE-PHASE WINDINGS

| Type | Description of winding | Turns per coil | Value of $L$ for polyphase winding | Value of $L$ for single-phase winding: $\mathbf{I}_2 = m\,\mathbf{I}_1$ | $\mathbf{I}_2 = -m\,\mathbf{I}_1$ | $\mathbf{I}_2 = 0$ |
|---|---|---|---|---|---|---|
| I | Multi-turn coil. Two coil sides per slot. Involute at each end. (Standard coil) | Either Even or Odd | $\frac{m^2-1}{4}$ | $\frac{m^2-1}{4}$ | $\frac{m^2-1}{4}$ | $-1/4$ |
| II | All turns inverted on end opposite connections | Even | $-1/4$ | $-1/4$ | $-1/4$ | $-1/4$ |
| | | Odd | $3/4 - \sin^2\left(\frac{\theta}{2}\right)$ | $3/4$ | $-1/4$ | $0$ |
| III | All turns inverted on connection end. | Even | $0$ | $0$ | $0$ | $0$ |
| | | Odd | $0$ | $0$ | $0$ | $-1/4$ |
| IV | Top half turn in upper coil side only inverted on connection end | Either Even or Odd | $\left[\frac{(m-1)(m-2)}{m}\right]\left[\frac{m^2-5m+2}{4m}\right]+2\sin^2\left(\frac{\theta}{2}\right)$ | $\left[\frac{(m-1)(m-2)}{m}\right]\left[\frac{m^2-5m+2}{4m}\right]$ | $\left[\frac{(m-1)(m-2)}{m}\right]\left[\frac{(m+1)(m+2)}{4m}\right]$ | $\frac{(3m-2)(m-2)}{4m^2}$ |
| V | Bottom half turn in upper coil side only inverted on end opposite connections | Either Even or Odd | $\left[\frac{m^4-4m^3+m^2+4m+1}{4m^2}+\frac{m-2}{m}\sin^2\left(\frac{\theta}{2}\right)\right]$ | $\left(\frac{m^4-4m^3}{4m^2}\right)+\left(\frac{m^2+4m+1}{4m^2}\right)$ | $\left(\frac{m^4-4m^3}{4m^2}\right)+\left(\frac{5m^2-4m+1}{4m^2}\right)$ | $\frac{1-m^2}{4m^2}$ |

Note: Top always refers to open end of slot.

2. The current in the lower coil side is 180 deg. out of phase with that in the upper coil side.

$$\mathbf{I}_2 = -m\,\mathbf{I}_1$$

3. The current in the lower coil side is zero.

$$\mathbf{I}_2 = 0$$

Table I gives all the possible values of $L$ in terms of turns per coil for standard coils, and for the four types of inverted turn transposition. Derivations of $L$ for a few typical cases are shown in Appendix A.

Referring to the table, the value of $L$ for standard multi-turn coils is

$$L = \frac{m^2 - 1}{4} \tag{7}$$

Substituting this value in Equation (6)

$$k = \frac{(15\,m^2 + 1)}{4}\,D \tag{8}$$

In a coil with any other value of $L$ the ratio of extra circulating current loss to the untransposed loss is, therefore

$$F = \frac{16 + 60\,L}{15\,m^2 + 1} \tag{9}$$

This formula was used in calculating the reduction factors of Table II and the supplementary curves of Figs. 8-12. The table and curves cover the four types of transposition listed in Table I and shown in Figs. 2-7. They cover all ordinary numbers of turns per coil and all coil pitches.

It is important to note that Equation (9) is used to compare the extra losses in transposed single-phase windings with the extra losses in normal untransposed three-phase double-layer windings having the same coil specifications. In other words the reduction factors are applied to the losses in standard windings of Type I, as calculated by the approximate formula given by Summers,[1] or by the exact equations derived by Professor Lyon.[2] The factors are not applied to the losses in the actual single-phase connection of the normal three-phase winding. The first method leads to simpler computations of extra losses, and at the same time gives the same results when comparing the loss reductions offered by the different transpositions.

Several significant facts can be seen from an inspection of the table and curves. In particular, Type II transpositions are most effective for coils with even numbers of turns. Type III transpositions are to be preferred for coils with odd numbers of turns, especially when the pitch lies between 33⅓ per cent and 66⅔ per cent. Types IV and V are not as effective in general as Types II and III, and are to be used only when space prohibits the use of Types II and III in coils with many turns.

The special case of single-layer windings with standard coils of Type I can easily be treated by referring to Table I. For all coils of this type of winding $\mathbf{I}_2 = 0$, and hence for standard coils without transposition

$$L = -1/4$$

For this value of $L$ the extra losses in a given winding with barrel-type coils are a minimum. No reductions can be made in the losses by any of the transpositions treated in this paper. Single-layer one-turn coils generally require reduction in extra losses, and such coils should be made up of half-turn bars with laminations transposed in the slot portion by well-known methods.

## IV. Strand Loss in Special Single-Phase Winding

The approximate formula for extra loss in the strands themselves, arising from the non-uniform distribution of current over each strand cross-section is

$$k_s = 6.0\,b\,\psi\,a\,v\left[\frac{f}{60/\text{sec.}}\right]^2 [r\,n\,(d/\text{in.})^2]^2 \tag{10}$$

This is the same equation as given in Reference (1). The variation of $\psi\,a\,v$ with coil pitch for the special single-phase winding is shown in Fig. 13.

TABLE II

REDUCTION FACTORS FOR CIRCULATING CURRENT LOSSES OBTAINED WITH INVERTED TURN TRANSPOSITIONS

Three-Phase Windings Connected Single-Phase with One Phase Idle

| | Type of Transposition | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | II | | | | III | | | | IV | | | | V | | | |
| | Pitch | | | | Pitch | | | | Pitch | | | | Pitch | | | |
| Turns per coil | 0 | 1/3 | 2/3 | 3/3 | 0 | 1/3 | 2/3 | 3/3 | 0 | 1/3 | 2/3 | 3/3 | 0 | 1/3 | 2/3 | 3/3 |
| 2 | 0.0164 | 0.0164 | 0.0164 | 0.0164 | 0.262 | 0.262 | 0.262 | 0.262 | 0.262 | 0.262 | 0.262 | 0.262 | 0.0778 | 0.0778 | 0.0778 | 0.0778 |
| 3 | 0.00736 | 0.0625 | 0.2833 | 0.449 | 0.1176 | 0.0625 | 0.0625 | 0.1176 | 0.607 | 0.405 | 0.114 | 0.0197 | 0.2035 | 0.112 | 0.0380 | 0.0564 |
| 4 | 0.00415 | 0.00415 | 0.00415 | 0.00415 | 0.0664 | 0.0664 | 0.0664 | 0.0664 | 0.768 | 0.456 | 0.0820 | 0.0197 | 0.319 | 0.1635 | 0.1015 | 0.195 |
| 5 | 0.00266 | 0.0226 | 0.1023 | 0.1620 | 0.0425 | 0.0226 | 0.0226 | 0.0425 | 0.845 | 0.475 | 0.0929 | 0.0809 | 0.411 | 0.208 | 0.160 | 0.315 |
| 6 | 0.00185 | 0.00185 | 0.00185 | 0.00185 | 0.0295 | 0.0295 | 0.0295 | 0.0295 | 0.891 | 0.485 | 0.1157 | 0.1525 | 0.482 | 0.242 | 0.205 | 0.408 |
| 7 | 0.00136 | 0.0115 | 0.0523 | 0.0828 | 0.0217 | 0.0115 | 0.0115 | 0.0217 | 0.920 | 0.491 | 0.1417 | 0.222 | 0.540 | 0.271 | 0.242 | 0.482 |
| 8 | 0.00104 | 0.00104 | 0.00104 | 0.00104 | 0.0166 | 0.0166 | 0.0166 | 0.0166 | 0.939 | 0.494 | 0.1659 | 0.283 | 0.586 | 0.294 | 0.270 | 0.539 |
| 9 | 0.00082 | 0.00695 | 0.0316 | 0.0501 | 0.01307 | 0.00695 | 0.00695 | 0.01307 | 0.950 | 0.495 | 0.1884 | 0.337 | 0.625 | 0.313 | 0.2935 | 0.586 |
| 10 | 0.00067 | 0.00067 | 0.00067 | 0.00067 | 0.01063 | 0.01063 | 0.01063 | 0.01063 | 0.960 | 0.497 | 0.2080 | 0.383 | 0.655 | 0.328 | 0.3125 | 0.624 |

## V. Reduction of Extra Circulating Current Losses by the Twisted Lead Transposition

The circulating currents in any winding can be reduced by increasing the length of path which they must

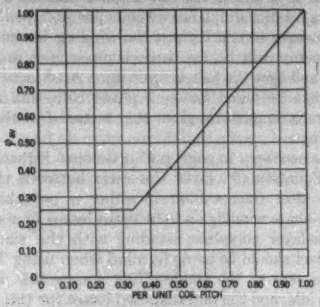


Fig. 13—The Factor $\psi_{cr}$ Used in Strand Loss Calculations

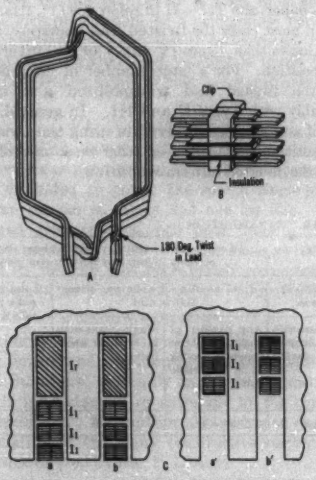


Fig. 14—Twisted Lead Transposition of Barrel Type Coils

A. Standard multi-turn coil with twisted lead
B. Simplified detail of insulated clip connections
C. Conventional slot cross-sections of two consecutive coils $a\,a^1$ and $b\,b^1$ in a phase belt

follow. For this reason, a coil with strands insulated from each other throughout the whole length of the coil suffers a lower extra copper loss than a coil with solid conductors, or with laminations solidly joined at the end of each half turn. If coils of the first type are clipped together so that the strands are insulated from each other throughout a phase belt, the extra loss is still further reduced. The reduction can be made comparable to the inverted turn transposition by making a 180 deg. twist in one lead of each coil, as illustrated in Fig. 14. The effect of the twist is to reverse the order of the laminations in corresponding half turns of successive coils, and thus partly to equalize the unbalanced voltages induced in the strands by the leakage fluxes.

The twisted lead transposition, described above, was suggested by Mr. M. A. Savage, one of the author's associates. It has been used successfully on large alternators, where space prohibited using the inverted turn transposition. Fig. 15 shows the application of this transposition to a synchronous condenser rated ATI-12-30,000-kv-a., 600-rev. per min., 11,000-volt, which was built in 1923. Approximately 15 machines have been built since then with armature windings

Fig. 15—Stator Coil Connections, Twisted Lead Transposition Showing Insulated Groups of Laminations Clipped Together

transposed by this method. Although this is a relatively small number compared to the number using the inverted turn transposition, it should be noted that in machines where the twisted lead method is applied it is indispensable in reducing extra losses. An added impetus has been given to its use by the development of methods of calculating the ratio of the circulating current loss in such a winding to the loss in the same winding untransposed. The formula which expresses this ratio is as follows:

$$F = \frac{15\,u\,(m/t)^2 + 1}{15\,m^2 + 1} \tag{11}$$

This is a remarkably simple formula considering the complexity of the problem. The development of this equation is detailed in Appendix C. In the formula, $m$ is the number of turns per coil, $t$ is the number of coils

in the phase belt considered, and $u$ is a factor depending on the way the phase belt is split up as regards phase angles between upper and lower coils sides. A complete mathematical definition of $u$ is given in Appendix C after the derivation of Equation (11). This factor can have any one of three values, namely, 0, 1, 2.

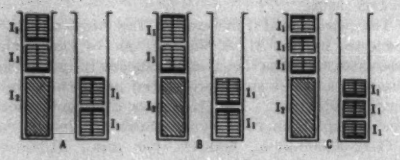


FIG. 16—TYPICAL SLOT CROSS-SECTIONS INVERTED TURN TRANSPOSITIONS

A. Standard coil—Type I
B. Type II transposition—Even number of turns per coil
C. Type V transposition—Even or odd number of turns per coil

Table III gives a summary of the possible groupings of the coils in single-phase, quarter-phase, and three-phase windings, with the corresponding values of $u$.

The reduction factors to be expected from the twisted lead transposition are shown in Table IV. The table covers only the usual range of turns per coil and coils per phase belt. The reduction factors for other conditions can easily be calculated from Table III and Equation (11). The procedure for finding reductions in circulating current losses in the twisted lead transposition reduces, therefore, to checking what part of Table III describes the winding or phase belt, noting the value of $u$, and going to Table IV or Equation (11) for the reduction factor corresponding to the given values of $m$ and $i$. In the general case of a winding with a fractional number of coils per pole per phase, it is necessary to first lay out the winding in order to see how many coils belong to each phase belt under each pole, and how the belt is split up. A reduction factor can then be found for each phase belt, and all these factors averaged to give the factor for the whole winding.

It is necessary to point out again that Equation (11), like Equation (9), gives the ratio between the extra losses after transposition in either a polyphase or a single-phase winding and the extra losses in a standard double-layer polyphase winding with the same coils. This fact should be borne in mind when using Table IV in the case of the single-phase connection with one phase idle, and the untransposed losses for this winding should be figured as though all coils were active.

Comparing Table IV with Table II, in the first part of this paper, and Table II in reference (1), it is apparent that in most cases the twisted lead transposition gives lower losses than Types IV and V of the inverted turn transposition. For a large number of coils per phase belt the twisted lead transposition also compares favorably with Types II and III. In general, there is little if any sacrifice involved in using the twisted lead transposition when space or other reasons prohibit the use of the inverted turn transposition.

TABLE III

VALUES OF "$u$" FOR TWISTED LEAD TRANSPOSITION

| Phase belt divided into two parts, each having a different phase angle between currents in top and bottom coil sides. | | | | | All coils in phase belt have same phase angle between currents in top and bottom coil sides. | | |
|---|---|---|---|---|---|---|---|
| Both parts have even number of coils. Any number of phases. | Both parts have odd number of coils | | One part has even number of coils. Other part has odd number. | | Total number of coils per phase belt is odd. | | Total number of coils per phase belt is even. |
| | Three-phase and special single-phase | Two-phase | Any number of phases except single-phase with the odd number of coils having $I_2 = 0$ | Single-phase with the odd number of coils having $I_2 = 0$ | Any number of phases except single-phase having $I_2 = 0$ in whole belt. | Single-phase with $I_2 = 0$ over whole belt. | |
| $u = 0$ | $u = 1$ | $u = 2$ | $u = 1$ | $u = 0$ | $u = 1$ | $u = 0$ | $u = 0$ |

TABLE IV

REDUCTION FACTORS TO BE APPLIED TO EXTRA CIRCULATING CURRENT LOSSES WHEN TWISTED LEAD TRANSPOSITION IS EMPLOYED

| Turns per coil | | $u = 1$ | | | | | | | | | | | | $u = 2$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Coils in phase belt | | | | | | | | | | | | Coils in phase belt | | |
| | $u = 0$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 2 | 6 | 10 |
| 2 | 0.0164 | 1.00 | 0.262 | 0.126 | 0.078 | 0.0557 | 0.0438 | 0.0365 | 0.0318 | 0.0285 | 0.0252 | 0.0245 | 0.0232 | 0.508 | 0.071 | 0.0361 |
| 3 | 0.00735 | 1.00 | 0.256 | 0.118 | 0.0694 | 0.0470 | 0.0349 | 0.0276 | 0.0229 | 0.0196 | 0.0173 | 0.0155 | 0.0143 | 0.504 | 0.0625 | 0.0272 |
| 4 | 0.00415 | 1.00 | 0.253 | 0.115 | 0.0664 | 0.0440 | 0.0318 | 0.0245 | 0.0197 | 0.0164 | 0.0141 | 0.0124 | 0.0111 | 0.502 | 0.0595 | 0.0241 |
| 5 | 0.00266 | 1.00 | 0.252 | 0.1135 | 0.0649 | 0.0426 | 0.0303 | 0.0230 | 0.0182 | 0.0150 | 0.0126 | 0.0109 | 0.0096 | 0.5015 | 0.0582 | 0.0226 |
| 6 | 0.00185 | 1.00 | 0.251 | 0.113 | 0.0641 | 0.0417 | 0.0296 | 0.0222 | 0.0174 | 0.0142 | 0.0118 | 0.0101 | 0.0088 | 0.501 | 0.0572 | 0.0218 |
| 7 | 0.00136 | 1.00 | 0.251 | 0.113 | 0.0638 | 0.0413 | 0.0291 | 0.0217 | 0.0170 | 0.0137 | 0.0113 | 0.0096 | 0.0083 | 0.5005 | 0.0568 | 0.0213 |
| 8 | 0.00104 | 1.00 | 0.251 | 0.112 | 0.0635 | 0.0410 | 0.0288 | 0.0214 | 0.0167 | 0.0134 | 0.0110 | 0.0093 | 0.0080 | 0.500 | 0.0565 | 0.0210 |
| 9 | 0.00082 | 1.00 | 0.251 | 0.112 | 0.0633 | 0.0408 | 0.0286 | 0.0212 | 0.0164 | 0.0132 | 0.0109 | 0.0091 | 0.0078 | 0.500 | 0.0564 | 0.0208 |
| 10 | 0.00067 | 1.00 | 0.251 | 0.112 | 0.0631 | 0.0406 | 0.0284 | 0.0210 | 0.0162 | 0.0130 | 0.0107 | 0.0089 | 0.0076 | 0.500 | 0.0564 | 0.0206 |

The objection of greater cost may be raised against this transposition because of the extra labor involved in clipping the coils together so that the laminations are insulated throughout a phase belt. However, the extra cost of connecting deep conductors with many strands can be reduced appreciably by bunching the laminations in groups of 2 and 3. Corresponding groups are then clipped together as illustrated in Fig. 15, which shows three center laminations grouped. Not more than three or four strand levels should be joined in this manner, since they are joined solidly at the ends of each coil, and an extra circulating current loss is thus developed. In Appendix F an approximate formula is worked out for this extra loss. The formula is:

$$k = \left\{ 4 + \frac{15}{4} \left[ (m + a)(m + a - 2) - 4\,m\,(a - 1) \sin^2\left(\frac{\theta}{2}\right) \right] \right\} D \qquad (12)$$

and the symbols are defined in the Table of Symbols. The factor $D$, as defined by Equation (1), varies as the fourth power of the number of strands in a group. Hence, the grouping should be a compromise between cost of connection and extra loss to be tolerated. The strand loss in a twisted lead winding is found from Equation (10) in the same manner as for untransposed windings.

## VI. Conclusion

The study of the inverted turn transposition, begun in the previous paper referred to in the Bibliography, has been extended to cover the special single-phase case of two phases in series and one leg idle. The twisted lead transposition has been described and analyzed to show its effect on extra losses, with the result that its use can now be definitely recommended in cases where other transpositions are impracticable.

## Acknowledgment

The author wishes to acknowledge with appreciation the many important contributions to this paper by Mr. I. H. Summers, especially in the development of the formula for reduction in extra loss by the twisted lead transposition. The author also wishes to express his appreciation of the many constructive suggestions and criticisms offered by Mr. P. L. Alger.

## Appendix A

Derivation of Formulas for $L$.

*Type I. Standard Coil.* Applying the general rules for finding the average value of $\mathbf{I}_e$ over a coil side, in the upper coil side

$$\mathbf{I}_e = -\frac{1}{m} \sum_{p=1}^{m} [\,(p-1)\,\mathbf{I}_1 + \mathbf{I}_1 + \mathbf{I}_2] \qquad (13)$$

where $p$ represents the number of the turn from the bottom of the coil side. In the lower coil side

$$\mathbf{I}_e = \frac{1}{m} \sum_{p=1}^{m} (p-1)\,\mathbf{I}_1 \qquad (14)$$

Averaging over both coil sides

$$\mathbf{I}_e = -\frac{1}{2\,m} \sum_{p=1}^{m} (\mathbf{I}_1 + \mathbf{I}_2) = -\left(\frac{\mathbf{I}_1 + \mathbf{I}_2}{2}\right) \qquad (15)$$

Equation (4) can also be written in this form

$$L = \frac{\mathbf{I}_e \,.\, (\mathbf{I}_e + \mathbf{I}_1)}{\mathbf{I}_1 \,.\, \mathbf{I}_1} \qquad (16)$$

Substituting for $\mathbf{I}_e$ from Equation (15), the following result is obtained:

$$L = -\frac{(\mathbf{I}_1 + \mathbf{I}_2) \,.\, (\mathbf{I}_1 - \mathbf{I}_2)}{4\,\mathbf{I}_1 \,.\, \mathbf{I}_1} \qquad (17)$$

which reduces to

$$L = \frac{I_2^2 - I_1^2}{4\,I_1^2} \qquad (18)$$

But $I_2 = m\,I_1$, and therefore

$$L = \frac{m^2 - 1}{4} \qquad (19)$$

If $\mathbf{I}_2 = 0$, as in the special single-phase winding

$$\mathbf{I}_e = -\frac{\mathbf{I}_1}{2} \qquad (20)$$

and

$$L = \frac{I_1^2 - 2\,I_1^2}{4\,I_1^2} \qquad (21)$$

$$L = -\frac{1}{4} \qquad (22)$$

*Type II. Even Number of Turns per Coil.* (See Table I and Fig. 8.) In the upper coil side

$$\mathbf{I}_e = \frac{1}{m} \left\{ \sum_{s=1}^{m/2} [\,(p-1)\,\mathbf{I}_1 + \mathbf{I}_2\,] \Bigg|_{p=2s} - \sum_{s=1}^{m/2} [\mathbf{I}_1 + (p-1)\,\mathbf{I}_1 + \mathbf{I}_2\,] \Bigg|_{p=2s-1} \right\} \qquad (23)$$

where $s$ = any integer except 0.

In the lower coil side

$$\mathbf{I}_e = \frac{1}{m} \left\{ -\sum_{s=1}^{m/2} [\mathbf{I}_1 + (p-1)\,\mathbf{I}_1] \Bigg|_{p=2s} + \sum_{s=1}^{m/2} (p-1)\,\mathbf{I}_1 \Bigg|_{p=2s-1} \right\} \qquad (24)$$

Substituting for $p$, and averaging over both coil sides

$$\mathbf{I}_o = \frac{1}{2m} \sum_{s=1}^{m/2} [\,(2s-1)\,\mathbf{I}_1 + \mathbf{I}_2 - \mathbf{I}_1 - (2s-2)\,\mathbf{I}_1$$

$$- \mathbf{I}_2 - \mathbf{I}_1 - (2s-1)\,\mathbf{I}_1 + (2s-2)\,\mathbf{I}_1\,] \quad (25)$$

$$\mathbf{I}_o = \frac{1}{2m} \sum_{s=1}^{m/2} -2\,\mathbf{I}_1 \quad (26)$$

$$\mathbf{I}_o = -\frac{\mathbf{I}_1}{2} \quad (27)$$

Substituting in the general equation for $L$

$$L = \frac{I_1^2 - 2\,I_1^2}{4\,I_1^2} \quad (28)$$

$$L = -\frac{1}{4} \quad (29)$$

This value of $L$ is independent of $\mathbf{I}_2$.

*Type V. Even or Odd Number of Turns.* In the upper coil side

$$\mathbf{I}_o = \frac{1}{m}\left[-(\mathbf{I}_1 + \mathbf{I}_2) + \sum_{p=2}^{m} \{\,(p-1)\,\mathbf{I}_1 + \mathbf{I}_2\}\right] \quad (30)$$

In the lower coil side

$$\mathbf{I}_o = -\frac{1}{m} \sum_{p=1}^{m} [\mathbf{I}_1 + (p-1)\,\mathbf{I}_1] \quad (31)$$

Averaging over both coil sides

$$\mathbf{I}_o = \frac{1}{2m}\left\{ \sum_{p=2}^{m} [\,(p-1)\,\mathbf{I}_1\,] + (m-1)\,\mathbf{I}_2 - m\,\mathbf{I}_1 \right.$$

$$\left. - \sum_{p=1}^{m} [\,(p-1)\,\mathbf{I}_1\,] - \mathbf{I}_1 - \mathbf{I}_2 \right\} \quad (32)$$

$$\therefore \mathbf{I}_o = \frac{(m-2)\,\mathbf{I}_2 - (m+1)\,\mathbf{I}_1}{2m} \quad (33)$$

$$\mathbf{I}_o + \mathbf{I}_1 = \frac{(m-2)\,\mathbf{I}_2 + (m-1)\mathbf{I}_1}{2m} \quad (34)$$

Substituting in the equation for $L$

$$L = \frac{(m-2)^2\,I_2^2 - (m^2-1)\,I_1^2 - 2\,(m-2)\,\mathbf{I}_1 \,.\, \mathbf{I}_2}{4\,m^2\,I_1^2} \quad (35)$$

which finally reduces to the form

$$L = \frac{m^4 - 4\,m^3 + m^2 + 4m + 1}{4\,m^2} + \frac{(m-2)}{m} \sin^2(\theta/2) \quad (36)$$

If $\mathbf{I}_2 = m\,\mathbf{I}_1 \qquad (\theta = 0)$

$$L = \frac{m^4 - 4\,m^3 + m^2 + 4\,m + 1}{4\,m^2} \quad (37)$$

If $\mathbf{I}_2 = -\,m\,\mathbf{I}_1 \qquad (\theta = 180 \text{ deg.})$

$$L = \frac{m^4 - 4\,m^3 + m^2 + 4\,m + 1 + 4\,m^2 - 8\,m}{4\,m^2} \quad (38)$$

$$= \frac{m^4 - 4\,m^3 + 5\,m^2 - 4\,m + 1}{4\,m^2} \quad (39)$$

If $\quad \mathbf{I}_2 = 0\ , \quad \mathbf{I}_o = -\,\frac{(1+m)}{2\,m}\,\mathbf{I}_1 \quad (40)$

$$\mathbf{I}_o + \mathbf{I}_1 = -\,\frac{(1-m)}{2\,m}\,\mathbf{I}_1 \quad (41)$$

$$L = \frac{1-m^2}{4\,m^2} \quad (42)$$

## Appendix B

### Sample Calculations of Reduction Factors for Inverted Turn Transposition of Single-Phase Windings

A. Assume Type II transposition, three-turn coils, two-thirds pitch, one pole being shown in Fig. 17.

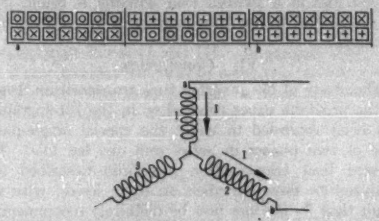

Fig. 17—Cross-Section, Double-Layer Single-Phase Winding

×—Coils of phase 1
+—Coils of phase 2
○—Coils of phase 3 (idle phase)

Considering the two active phase belts, the following tabulation can be constructed by the use of Table II:

| Number of coils | $\mathbf{I}_2$ | $L$ | $m$ | $F$ |
|---|---|---|---|---|
| 7 | $m\,\mathbf{I}_1$ | 3/4 | 3 | 0.449 |
| 7 | 0 | 0 | 3 | 0.1176 |

$\therefore F_{av} = 0.2833$

Since there are an integral number of slots per pole per phase this average ratio applies to the whole winding.

B. Assume Type II transposition, three-turn coils, 42 slots, 6 poles, 7/3 slots per pole per phase, four-sevenths pitch. See Fig. 18 where three poles are shown.

Considering the two active phases and the three

poles, the following tabulation can be made by means of Equation (9):

| Number of coils | $\mathbf{I}_2$ | $L$ | $m$ | $F$ |
|---|---|---|---|---|
| 5 | $m\,\mathbf{I}_1$ | 3/4 | 3 | 0.449 |
| 2 | $-m\,\mathbf{I}_1$ | $-1/4$ | 3 | 0.00736 |
| 7 | 0 | 0 | 3 | 0.1176 |

$$\mathbf{F}_{av} = 5/14\ (0.449) + 2/14\ (0.00736) + 1/2\ (0.1176) = 0.220$$

Since the winding repeats itself under the other three poles this ratio holds for the complete winding. The

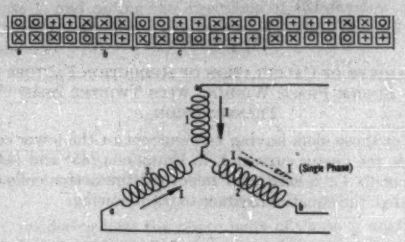


FIG. 18—CROSS-SECTION, DOUBLE-LAYER WINDING

Fractional number slots per pole per phase

×—Coils of phase 1
+—Coils of phase 2
○—Coils of phase 3 (idle for single phase)

value of $F_{av}$ will be found to check the curve Fig. 8 for Type II, three turns per coil, 57.2 per cent pitch. These illustrations show that the factors in Table II hold for any type of winding.

## Appendix C

### DERIVATION OF FORMULA FOR REDUCTIONS IN EDDY CURRENT LOSSES IN TWISTED LEAD WINDING

Referring to Fig. 14 in the body of the paper, each strand in a twisted lead winding is theoretically insulated throughout the length of the $m$ turns per coil and also throughout the $t$ coils in each phase belt. The order of the strands in corresponding conductors reverses from coil to coil, so that it is necessary to determine $\mathbf{I}_e$ separately for the even numbered coils and for the odd numbered coils. $\mathbf{I}_e$ is determined for each half turn in the usual way as described in Part II of the paper, and these values are then averaged over all the coils in the phase belt.

The determination of $\mathbf{I}_e$ in a phase belt where $t$ is even is as follows. Considering the odd numbered coils, which are assumed to have laminations in the direct order in the bottom coil side:

$$\mathbf{I}_e = \frac{1}{m\,t} \sum_{\substack{s=1 \\ r=2s-1}}^{t/2} \left\{ \sum_{p=1}^{m} (p-1)\,\mathbf{I}_1 - \sum_{p=1}^{m} [(p-1)\,\mathbf{I}_1 + \mathbf{I}_r + \mathbf{I}_1] \right\} \tag{43}$$

Considering the even numbered coils, which will have the laminations in the reverse order:

$$\mathbf{I}_e = \frac{1}{m\,t} \sum_{\substack{s=1 \\ r=2s}}^{t/2} \left\{ \sum_{p=1}^{m} [(p-1)\,\mathbf{I}_1 + \mathbf{I}_r] - \sum_{p=1}^{m} [(p-1)\,\mathbf{I}_1 + \mathbf{I}_1] \right\} \tag{44}$$

In the above equation $\mathbf{I}_r$ is the vector total current in the lower coil side in the $r$th slot of the phase belt being considered. Let

$$\mathbf{I}_r = m\,I_1\,\mathbf{v}_r \tag{45}$$

where $\mathbf{v}_r$ is a unit vector displaced from $\mathbf{I}_1$ by the phase angle between the currents in the upper and lower coil sides in the $r$th slot. Substituting this relation in Equations (43) and (44), and averaging $\mathbf{I}_e$ over all coil sides in the phase belt:

$$\mathbf{I}_e = I_1 \frac{m}{2\,t} \left[ \sum_{s=1}^{t/2} \mathbf{v}_r - \sum_{s=1}^{t/2} \mathbf{v}_r \right] - \frac{1}{2}\,\mathbf{I}_1 \tag{46}$$

$$r = 2\,s \quad r = 2\,s - 1$$

In the same way it can be shown that when $t$ is odd

$$\mathbf{I}_e = I_1 \frac{m}{2\,t} \left[ \sum_{s=1}^{(t-1)/2} \mathbf{v}_r - \sum_{s=1}^{(t+1)/2} \mathbf{v}_r \right] - \frac{1}{2}\,\mathbf{I}_1 \tag{47}$$

$$r = 2\,s \quad r = 2\,s - 1$$

Let

$$\sum_{r=2s} \mathbf{v}_r = \mathbf{v}_e \tag{48}$$

$$\sum_{r=2s-1} \mathbf{v}_r = \mathbf{v}_o \tag{49}$$

In words, $\mathbf{v}_e$ is the vector summation of the unit vectors $\mathbf{v}_r$ for all even numbered coils, and $\mathbf{v}_o$ is the vector summation of the unit vectors $\mathbf{v}_r$ for all the odd numbered coils.

Then Equations (46) and (47) can be reduced to one general form as follows:

$$\mathbf{I}_e = \frac{m}{2\,t}\,I_1\,(\mathbf{v}_e - \mathbf{v}_o) - \frac{1}{2}\,\mathbf{I}_1 \tag{50}$$

For simplicity let

$$\mathbf{v}_e - \mathbf{v}_o = \mathbf{v} \tag{51}$$

Referring to Equation (16)

$$L = \frac{\mathbf{I}_e \cdot (\mathbf{I}_e + \mathbf{I}_1)}{\mathbf{I}_1 \cdot \mathbf{I}_1}$$

Substituting the value of $\mathbf{I}_e$ from (50) and (51)

$$L = \frac{[\,(m/2\,t)\,I_1\,\mathbf{v} - 1/2\,\mathbf{I}_1\,]\,.\,[\,(m/2\,t)\,I_1\,\mathbf{v} + 1/2\,\mathbf{I}_1\,]}{I_1^2} \tag{52}$$

$$= \frac{(m/t)^2\,\mathbf{v}\,.\,\mathbf{v} - 1}{4} \tag{53}$$

Let $\mathbf{v}\,.\,\mathbf{v} = u$ (a scalar quantity) (54)

Then
$$L = \frac{u\,(m/t)^2 - 1}{4} \tag{55}$$

But the first order of eddy currents is proportional to

$$4 + 15\,L = \frac{15\,u\,(m/t)^2 + 1}{4} \tag{56}$$

For the standard untransposed winding

$$4 + 15\,L = \frac{15\,m^2 + 1}{4} \tag{57}$$

The reduction factor due to the twisted lead transposition is

$$F = \frac{15\,u\,(m/t)^2 + 1}{15\,m^2 + 1} \tag{58}$$

It is now necessary to define the factor $u$ which enters into all calculations of reductions in eddy current losses in twisted lead windings. A mathematical definition is all that can be given, as the factor has no apparent physical meaning. In brief, $u$ is the square of the magnitude of the vector difference between two vectors, one representing the sum of as many unit vectors as there are even numbered coils in a phase belt, and the other representing the sum of as many unit vectors as there are odd numbered coils in the belt. The angular displacement of each unit vector from the origin is equal to the phase angle between currents in the upper and lower coil sides in the slot to which it applies.

## Appendix D

### Example of Calculation of Reduction Factor for Twisted Lead Transposition in Three-Phase Winding

Assume the winding of Fig. 18 to be operating as a normal three-phase winding with the twisted lead transposition in the coils. Considering the coils of Phase 1 in each of the phase belts shown, and noting the directions of current flow in the three phases, the following tabulation can readily be made:

| Phase belt | $\mathbf{v}_e$ | $\mathbf{v}_o$ | $\mathbf{v}$ | $u$ |
|---|---|---|---|---|
| 1 | $\underline{1/60^\circ}$ | $\underline{1/60^\circ} + \underline{1/120^\circ}$ | $-\underline{1/120^\circ}$ | 1 |
| 2 | $\underline{1/60^\circ}$ | $\underline{1/60^\circ}$ | 0 | 0 |
| 3 | $\underline{1/60^\circ}$ | $\underline{1/120^\circ}$ | $\underline{1/0^\circ}$ | 1 |

The two phase belts in which $u = 1$ will have the following reduction factors:

(a) Phase belt No. 1 (3 coils)

$$F = \frac{15\,(3/3)^2 + 1}{15\,(3)^2 + 1} = 0.1176$$

(b) Phase belt No. 3 (2 coils)

$$F = \frac{15\,(3/2)^2 + 1}{15\,(3)^2 + 1} = 0.255$$

In the phase belt in which $u = 0$

$$F = \frac{1}{15\,(3)^2 + 1} = 0.00736$$

The average reduction factor for the whole winding is

$$F_{av} = \frac{1}{3}\,(.1176 + .255 + .00736)$$
$$= 0.127$$

## Appendix E

### Examples of Calculation of Reduction Factors in Single-Phase Winding with Twisted Lead Transposition

For those slots having zero current in the lower coil sides, the vector current $\mathbf{I}_e$ in Equations (43) and (44), Appendix C, is zero, and hence for the active coils so located, the equations reduce to the following.

$$\mathbf{I}_o = -\frac{1}{2}\,\mathbf{I}_1$$

$$L = -\frac{1}{4}$$

Comparing this with Equation (55) it is evident that for any group of coil sides having $\mathbf{I}_e = 0$

$$u = 0$$
$$\mathbf{v} = \mathbf{v}_e - \mathbf{v}_o = 0$$

This result simplifies the calculations of loss reduction factors in the various phase belts of single-phase windings having the twisted lead transposition. In those phase belts having some of the lower coil sides carrying no current it is only necessary to consider the slots with active lower coil sides in forming the vector difference $\mathbf{v}$, and determining the factor $u$ for the phase belt. If all the lower coil sides in the phase belt carry zero current, the factor $u$ is zero for that group.

As an example, consider the single-phase winding of Fig. 17 with the twisted lead transposition, each coil having three turns. In the phase group lying over the coils of the idle phase

$$u = 0$$

In the other active phase belt all slots have the same phase angle between currents in upper and lower coil sides. Since the phase group has an odd number of coils, there is one more of the odd numbered coils than of the even numbered coils, and hence

$$\mathbf{v}_e - \mathbf{v}_o = -1$$
$$u = 1$$

With the aid of Table IV the following tabulation can be made:

| Phase | $u$ | $m$ | $l$ | $F$ |
|---|---|---|---|---|
| 2 | 0 | 3 | 7 | 0.00735 |
| 1 | 1 | 3 | 7 | 0.0276 |

$$F_{av} = 0.0175$$

Since the winding repeats under the other pole this factor holds for the whole armature.

As a second example, consider the single-phase connection of the winding shown in Fig. 18, and assume three turn coils. Considering only the phase belts of phase 1, and noting the directions of current flow, the following tabulation can be made with the aid of Table IV:

| Phase belt | $v_s$ | $v_o$ | $v$ | $u$ | $m$ | $l$ | $F$ |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 0 | 3 | 3 | 0.00735 |
| 2 | 1 | 1 | 0 | 0 | 3 | 2 | 0.0164 |
| 3 | 1 | 0 | 1 | 1 | 3 | 2 | 0.256 |

The average reduction factor for phase 1 is

$$F_{av} = 0.0784$$

Considering next the phase belts of phase 2, another tabulation can be made as follows:

| Phase belt | $v_s$ | $v_o$ | $v$ | $u$ | $m$ | $l$ | $F$ |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | −1 | 1 | 3 | 2 | 0.256 |
| 2 | .. | .. | .. | 0 | 3 | 2 | 0.00735 |
| 3 | 0 | 1 | −1 | 1 | 3 | 3 | 0.118 |

The average reduction factor for phase 2 is

$$F_{av} = 0.1258$$

The resultant factor for determining the extra loss in the whole winding is

$$F = 0.1021$$

It is interesting to note the possibility that the effective resistance and extra loss in one phase of a single-phase winding with the twisted lead transposition can be greater than in the other phase.

The preceding calculation is typical of that to be followed in the general case of fractional slots per pole per phase. The values of $u$ in Table III were found in this way.

## Appendix F

### Extra Circulating Current Loss in Group of Laminations Joined at Coil Ends in Twisted Lead Winding

Assume uniform current density over each conductor. This assumption is justifiable where the twisted lead transposition is used, since it approximately produces this effect. Also, let

$n$ = number of laminations vertically per conductor.
$n_e$ = number of laminations vertically in group.
$n_b$ = number of laminations vertically from bottom of conductor to bottom of group in one coil side.

Then, because of inversion of the conductors $n - (n_b + n_e)$ = number of laminations vertically from bottom of conductor to bottom of group in other coil side.

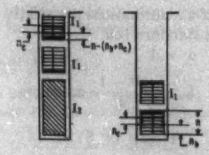

Fig. 19—Slot Cross-Sections Showing Lamination Grouping—Twisted Lead Transposition

Referring to Fig. 19, in the upper coil side

$$\mathbf{I}_o = -\frac{1}{m}\sum_{p=1}^{m}\left[\left(\frac{n_e}{n}\right)\mathbf{I}_1 + \left(\frac{n-n_b-n_e}{n}\right)\mathbf{I}_1 + (p-1)\,\mathbf{I}_1 + \mathbf{I}_2\right] \tag{59}$$

In the lower coil side

$$\mathbf{I}_o \frac{1}{m}\sum_{p=1}^{m}\left[\left(\frac{n_b}{n}\right)\mathbf{I}_1 + (p-1)\,\mathbf{I}_1\right] \tag{60}$$

Averaging over the whole coil

$$\mathbf{I}_o = \frac{1}{2m}\sum_{p=1}^{m}\left[\left(\frac{2\,n_b}{n}\right)\mathbf{I}_1 - \mathbf{I}_1 - \mathbf{I}_2\right] \tag{61}$$

$$= -\frac{\mathbf{I}_1}{2}\left(\frac{n-2\,n_b}{n}\right) - \frac{\mathbf{I}_2}{2} \tag{62}$$

Let

$$\left(\frac{n-2\,n_b}{n}\right) = a \tag{63}$$

Then

$$\mathbf{I}_o = -a\,\frac{\mathbf{I}_1}{2} - \frac{\mathbf{I}_2}{2} \tag{64}$$

$$\mathbf{I}_o + \mathbf{I}_1 = -\frac{(a-2)}{2}\,\mathbf{I}_1 - \frac{\mathbf{I}_2}{2} \tag{65}$$

$$L = \frac{a\,(a-2)\,I_1^2 + m^2\,I_1^2 + 2\,(a-1)\,\mathbf{I}_1 \cdot \mathbf{I}_2}{4\,I_1^2} \tag{66}$$

which can be reduced to the form

$$L = \frac{(m+a)\,(m+a-2) - 4\,m\,(a-1)\sin^2(\theta/2)}{4} \tag{67}$$

The value of $L$ so found can then be put into the usual formula

$$k = (4 + 15\,L)\,D \tag{6}$$

in order to find the extra loss produced in the group

being considered. The value of $D$ to be used for the lamination group is

$$D = 1.19 \left[ \frac{f}{60/\text{sec.}} \right]^2 [b\, r\, c\, (n_c\ d/\text{in.})^2]^2 \quad (68)$$

If $n_b = 0$, or if all laminations are solidly joined at each coil end as in a standard coil,

$$a = 1$$

and $$L = \frac{m^2 - 1}{4} \text{ as before.}$$

### Table of Symbols

$D$ A numeric depending on the slot and conductor dimensions and assembly, and on the frequency.

$F$ Reduction factor representing the ratio of the extra circulating current loss in any transposed coil, group of coils, or winding to the loss in the same coil, group of coils, or winding untransposed.

$\mathbf{I}_1$ The vector current in any conductor.

$\mathbf{I}_2$ The total vector current in the bottom coil side.

$\mathbf{I}_b$ The resultant vector current in the slot below any conductor.

$\mathbf{I}_e$ A vector current defined by Equations (2) and (3).

$\mathbf{I}_r$ The vector total current in the lower coil side in the $r$th slot of a phase belt.

$K$ Ratio of total heat loss in a winding with alternating current to loss with uniform current.

$L$ A numeric defined by Equation (4).

$a$ The ratio $(n - 2\, n_b)/n$

$b$ A ratio $= \left( \dfrac{2 \times \text{core length}}{\text{mean length of turn}} \right)$

$c$ $\left[ \dfrac{\text{gross depth of strand}}{\text{net copper depth of strand}} \right]^2$

$d$ Net depth of copper in a strand.

$f$ Frequency of alternating current.

$k$ Ratio of extra circulating current loss to uniform current loss.

$k_e$ Ratio of extra loss due to uneven current distribution in strands to uniform current loss.

$m$ Turns per coil.

$n$ Number of strands depthwise per conductor.

$n_b$ Number of strands depthwise below a group of laminations in a twisted lead transposition.

$n_c$ Number of strands depthwise in the group of laminations.

$p$ The order of a conductor, numbered from the bottom of a coil side. For the first conductor $p = 1$.

$r$ The ratio of total copper width to slot width.

$r$ (As a subscript) The order of a coil in a phase belt in a twisted lead winding, the numbering beginning at the start of the phase belt with $r = 1$.

$s$ Any integer, except 0.

$t$ Number of coils in a phase belt throughout which the conductor laminations are insulated from each other depthwise.

$u$ A scalar quantity used in twisted lead transposition formulas. It depends on the way the $t$ coils in a phase belt are split up as regards phase angles between upper and lower coil sides.

$\mathbf{v}$ The vector difference $\mathbf{v}_e - \mathbf{v}_o$.

$\mathbf{v}_e$ The vector sum of as many unit vectors $\mathbf{v}_r$ as there are even numbered coils in a phase belt in a twisted lead winding.

$\mathbf{v}_o$ The vector sum of all the unit vectors $\mathbf{v}_r$ in the odd numbered coils in the phase belt.

$\mathbf{v}_r$ A unit vector in phase with $\mathbf{I}_r$.

$\theta$ Phase angle between currents in upper and lower sides in a slot.

$\psi_{av}$ The average of the quantity $[1 - 3/4 \sin^2 (\theta/2)]$ over all coils in a winding.

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## Discussion

**I. H. Summers:** I should like to point out that the formulas, tables, and equations which Mr. Lyons has presented are not merely of theoretical interest. In Schenectady for the past four or five years in practically all the large water wheel generators built the inverted turn transposition has been used with the exception of those having a large number of turns which do not need it and those using the twisted lead transposition, which is also covered in Mr. Lyons' paper. These latter have been built over a period of approximately the last two years, and there have been about 15 machines built with this transposition. As a result of this practise no large water wheel alternators are now built in Schenectady having a parasitic eddy current loss of greater than about 15 per cent of the legitimate copper loss.

**J. M. Lyons:** I wish to thank Mr. Summers for pointing out the extent to which the transpositions described in this paper have been applied on large water wheel generators. The inverted turn and twisted lead transpositions naturally find their greatest use in such machines having multi-turn coils with fairly deep conductors. The reduction of extra copper loss to 15 per cent of the ohmic loss obviously represents a very worth while saving.

The problem of predicting loss reductions due to the twisted lead transposition having been simplified by the development of Equation (11) and the corresponding tables, it would seem that this transposition should find a relatively larger number of applications than in the past.

The scheme of transposition described by Mr. Palueff as being used on heavy transformer coils is apparently very effective in securing a uniform current density and low extra copper loss. This method is essentially different from those described in this paper in that the strands are transposed relative to each other at regular intervals around each turn instead of being twisted all together at one point. Such a transposition would be very difficult to apply on multi-turn coils of generator windings, while for large one-turn generator coils there is available a more effective method. I am referring to the Roebel Transposition for which each coil is made up of two half-turn bars. The laminations are offset and bent in the slot portion so that in the assembled bar every strand passes twice through every level in the bar. In this way the current density over the bar cross-section becomes practically uniform and the extra loss is reduced to a negligible value.

There is seldom any need of transposing generator armature coils in machines smaller than 5000 kw. because of the relatively shallow conductors characteristic of these machines. For all larger ratings the Roebel or one of the twisted conductor transpositions will meet the call for reduction of extra copper losses in any winding.

# Effect of Armature Resistance Upon Hunting of Synchronous Machines

BY C. F. WAGNER*
Member, A. I. E. E.

***Synopsis.***—*The ability of systems to withstand shocks, such as faults or switching operations, is much greater for small operating angles. The present paper has to do with system stability for small oscillations as contrasted with the more usual concept of stability as being its ability to withstand shocks.*

*The analysis shows that synchronous machines without amortisseur windings and with no resistance in the armature are inherently stable for small oscillations in prime mover input or load output. With resistance in the armature, stability for such conditions is dependent upon load.*

*A new proof is given for the relation previously derived by Nickle and Pierce which states that the limiting angle at which a machine becomes stable is* $\tan^{-1}\frac{r}{x_q}$.

*Arguments are presented which show that any standard type of damper which may have been installed in generators for other incidental reasons, possesses the property of preventing spontaneous hunting except for the most abnormal conditions met in practise.*

* * * * *

FROM time to time cases of spontaneous hunting arise, the cause of which can be traced to an excessive proportion of resistance in the armature circuit, namely in the transmission line. This phenomenon was particularly evident in the early days of rotary converters. A rough working rule in use at that time was to limit the line resistance to 25 per cent of the reactance. In 1911 Dreyfus[1] in Germany showed that the tendency toward hunting decreased with increasing load and that the presence of damper windings tended to stabilize the conditions. In 1924, reporting stability tests made in the works of the Westinghouse Company, Evans and Bergvall[2] likewise demonstrated this same effect using salient pole generators and condensers. More recently Wennerberg[3] in Sweden and Nickle and Pierce[4] in this country, have extended the analysis, developing the results into more usable form. The writer has been working on this same problem and has used a somewhat different method of attack which he believes gives a somewhat clearer conception of the mechanism involved.

## I. Qualitative Analysis

To get a picture of what occurs when a machine becomes unstable, and begins to hunt because of the presence of an excessive amount of resistance in its armature circuit, consider a synchronous generator without damper windings and having constant exciter voltage, and connected to an infinite bus through a transmission line. The analysis of transients of synchronous machines may be expedited by the use of the so-called "transient reactance" ($x_d'$), and the "transient internal voltage" ($e_d'$). The transient reactance is the reactance to be used in connection with the determination of current flow for sudden changes. It includes not only the armature leakage reactance but also the effects due to the field leakage. The subscript $d$ signifies that the reactions are taken with reference to the direct axis. The voltage $e_d'$ for zero power factor will be defined as the arithmetic sum of the terminal voltage and the transient reactance drop, and for any other power factor, as the arithmetic sum of the component of the terminal voltage in the direct axis and the transient reactance drop due to the component of armature current in the direct axis. This is the fictitious voltage corresponding to flux linkages in the field and for any sudden change in circuit condition the flux linkages and this voltage remain fixed. The voltage $e_d$ will be defined in a similar manner except that the synchronous reactance $x_d$ must be used. It follows, therefore, that $e_d$ and $e_d'$ for steady state conditions differ only by the magnitude of the two drops and that

$$e_d - e_d' = x_d i_d - x_d' i_d$$

or

$$e_d' = e_d - (x_d - x_d') i_d \qquad (1)$$

in which $i_d$ is the component of armature current in the direct axis, that is, it is the demagnetizing component of current for $i_d$ positive. The quantity $(x_d - x_d')$ takes something of the nature of a reactance corresponding to armature reaction. It is clear then from the above equation and also from the physical conception of the quantities, that for constant exciter voltage, which is equivalent to constant $e_d$, that the voltage $e_d'$ which is proportional to flux linkages in the field winding should decrease as the demagnetizing component of current, $i_d$, increases.

In Fig. 1a is shown the familiar power circle diagram showing the output characteristics of the machine for constant internal voltage assuming no resistance in the armature. This diagram is not strictly correct as it does not introduce the distortion due to the saliency of the poles. It is, however, sufficiently correct for this preliminary analysis. For any operating point such as $p$ the abscissa gives the power output of the machine and the ordinate, the demagnetizing kv-a. The angle $\theta$ is the angle between the generated voltage and the voltage of the infinite bus at the receiving end. The particular circle drawn assumed constant voltage $e_d$ so that the circle represents the steady state characteristics.

Now assuming that the generator is operating at a

*Transmission Engineer, Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

1. For reference see Bibliography.

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30-61

mean angle $\theta$ and that in some manner, the exact nature of which is, at present, of no importance, the rotor is made to oscillate sinusoidally about $\theta$ with an amplitude $\Delta\,\theta_m$ and a frequency $f$. The amplitude of these oscillations is indicated in Fig. 1A, from which it will be observed that for $\Delta\,\theta$ positive the demagnetizing kv-a. or the demagnetizing current $i_d$ increases. But from Equation (1) it was shown that if $i_d$ increases $e_d'$ decreases. It follows, therefore, that for positive increments in $\theta$ that the increment of $e_d'$ is negative and for negative increments of $\theta$ the increment of $e_d'$ is positive. This result is shown graphically by the straight line in Fig. 1b. However, this relation merely shows how $\Delta\,e_d'$ would vary if $\theta$ were increased an amount $\Delta\,\theta$ and kept there or the manner in which $\Delta\,e_d'$ would vary for very slow oscillations. Due to the inductance associated with the field circuit $e_d'$ cannot change instantly so that the variations of $\Delta\,e_d'$ instead of oscillating along the straight line will form an elliptical loop (Lissajous figure) of the form shown. The direction of rotation of the generating point around this loop is extremely important. It will be observed that if $\Delta\,\theta$ be increasing positively from its value $-\,\Delta\,\theta_m$, the operating point $a$ in generating the loop must lag, that is, it must pass through zero at a later time than when $\Delta\,\theta$ passes through zero. This determines the direction of rotation as being clockwise. With very low frequency the loop degenerates into the straight line $b\,c$ and for extremely high frequencies degenerates into a straight line along the horizontal axis.

The power-angle diagram for the machine including

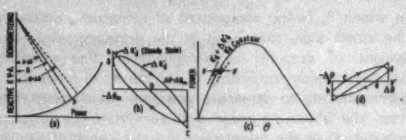

Fig. 1—Pure Reactance Line

a. Demagnetizing current increases with $+\,\Delta\,\theta$, so that $\Delta\,e_d'$ tends to decrease
b. Log of instantaneous value of $\Delta\,e_d'$ behind value which it would attain for steady state conditions
c. Power loop obtained from instantaneous values of $\Delta\,e_d'$. System stable for clockwise loops
d. Enlargement of power loop

the effect of saliency is shown in Fig. 1c. This curve was drawn for a constant value of $e_d'$. For small positive increments in $e_d'$ the resultant curve will, in general, for almost all cases met in practise, lie above the one for $e_d'$ and for negative increments of $e_d'$ will lie below the curve for $e_d'$. The loop of Fig. 1B gives the instantaneous values of $\Delta\,e_d'$ as a function of the angle so that using these instantaneous values it can be seen that a similar power loop is obtained on the power angle diagram and following the point-by-point substitution it will be observed that the rotation of this movement is also clockwise. Assuming constant input into the prime mover of the value corresponding to the generator power output for the mean value of $\theta$, the instantaneous acceleration is determined by the distance between the curves of instantaneous power and the line $p\,p'$. Starting at the point $b$ of maximum negative travel (see Fig. 1d) where the relative velocity between the rotor of the machine and the voltage of the infinite bus is zero, the velocity of oscillation under the assumed conditions of constant input increases until the point $c$ is reached, at which point the acceleration is zero. At this point the rotor has accumulated an amount of stored kinetic energy proportional to the area of the

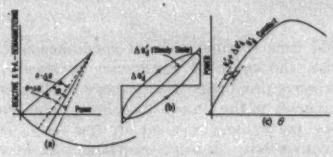

Fig. 2—Line with Resistance

a. Demagnetizing current decreases with $+\,\Delta\,\theta$, so that $\Delta\,e\,d'$ tends to increase
b. Log of instantaneous value of $\Delta\,e_d'$ behind value which it would attain for steady state conditions
c. Power loop obtained from instantaneous value of $\Delta\,e_d'$. System unstable for counter-clockwise loop

triangle $b\,p\,c$, so that the rotor overshoots this point. The relative velocity is again brought to zero at the point $d$, but it will be observed that the area representing the energy available to retard this velocity—area $d\,p'\,c$—is greater than the area $b\,p\,c$. The significance of this observation is that, left free to oscillate from point $b$ with constant prime mover input, the generating point will not move all the way to $p'$, but will be damped; or if the generating point does move actually along the locus $b\,c\,d$, then the assumption of constant prime mover is incompatible with the results, the prime mover input represented by the line $p\,p'$ must be altered so that the two areas are equal. In moving from $b$ to $d$, the excess energy tending to produce damping is proportional to the difference of the areas $d\,p'\,c$ and $b\,p\,c$; but since area $b\,p\,c$ is equal to area $d\,p'\,e$, this difference is equal to the area $c\,d\,e$. Similarly in moving from $d$ to $b$, the excess energy tending to produce damping is proportional to the area $e\,b\,c$, or during one complete cycle, to the area of the loop.

The system may be said to be stable. It will be observed that this condition holds for all values of $\theta$ when the armature resistance is zero.

An entirely different condition may prevail when the armature and line resistance is other than zero. Consider the conditions when such a system is operating at the angle $\theta$ shown in Fig. 2a on the power-reactive power circle diagram. Due to the presence of the resistance, the center of the circle is shifted from the axis of reactive kv-a. to the position shown. For positive increments in $\theta$, the demagnetizing current decreases,

thus increasing the value $\Delta e_d'$ attains for steady state increments of $\Delta \theta$. This relation is shown in Fig. 2b. During system oscillations $\Delta e_d'$ cannot attain the value corresponding to the steady state value, but lags forming the loop shown, which is generated in a counter-clockwise sense. The voltage loop can be converted to the power loop in Fig. 2c, which is also generated in a counter-clockwise sense. Pursuing the same argument as used previously, the area of this loop is proportional to the energy given out,—the system is unstable.

This condition follows from the fact that for small angles the demagnetizing current decreases with increasing angle, but it will be noted that for larger angles this same relation no longer obtains. As the load increases a point is finally reached beyond which the system becomes stable. The qualitative treatment thus shows the mechanism of the phenomena involved and why a machine without damper windings becomes more stable, from the standpoint of hunting, with increasing load.

This phenomenon should not be confused with energy absorbed thermally by the series resistance, which is not effective in damping oscillations between machines. The truth of this statement may be verified by assuming that the oscillations are so fast or that the time constant of the field is so large as to justify the assumption that $e_d'$ is constant. Any effect of the series resistance should still be present. In this case the operating point in the power-angle diagram generates the same locus with increasing angles as with decreasing angles. The area of the loop and the decrement of the oscillations must therefore be zero. For constant prime mover input and constant load output, the energy absorbed by the series resistance is supplied by the stored kinetic energy of rotation, resulting in a decrease of mean system frequency.

## II. Salient Pole Machine without Amortisseur Winding

In the mathematical treatment which follows, the case of a salient pole machine without amortisseur windings will be discussed. A number of simplifying assumptions has been made which agree with those used by Nickle and Pierce.[4]

It has been shown by a number of investigators that transients in synchronous machines involving symmetrical armature conditions can be resolved into a unidirectional component in the field winding (and associated with it a transient of synchronous velocity in the armature) and a unidirectional component in the armature (and associated with it a transient of synchronous velocity in the field winding). These components have very little effect upon each other so that small error is introduced into the calculations effecting the unidirectional component of the field by neglecting entirely the unidirectional component of the armature. For the case under consideration the machine is assumed to be connected to an infinite bus, that is, to a source of e. m. f., $E$, which will not change in phase position or magnitude by any alteration in the machine or the circuit. Small angular oscillations of the rotor of frequency $f$ are superposed upon the operating angle. These oscillations produce a superposed oscillation of field current of frequency $f$ and a modulation of the armature current of the same frequency. In addition a current of frequency $f$ appears in the armature and a fundamental frequency current, modulated at frequency $f$, appears in the field circuit. Arguing from the above considerations affecting transients it should be clear that these latter have very little influence upon the magnitude of the former. Further, while the former pair of currents produces variations in torque and power of the first order (since the modulated alternating current in the armature reacts with the average value of the field), the second pair of currents produces variations of the second order. In this analysis the assumption will be made that all currents in the armature but the modulated component of fundamental frequency will be neglected. Thus the instantaneous torque and power will be determined by inserting the instantaneous value of field current in the usual vector diagrams of the machine, depicting the steady state characteristics.

Saturation is neglected to the extent that the impedances of the machine are assumed to be independent of the current flow, that is, the constants may be altered somewhat to take saturation into effect.

The per unit system of notation will be used, by which is meant that units will be used as bases instead of 100 per cent. For example, terminal voltage will be expressed as a fraction of rated terminal voltage, field current will be expressed as a fraction of the field current required to produce rated terminal voltage at no load, and other quantities similarly.

Assume a salient pole machine without amortisseur windings and the absence of other paths which might permit circulating currents in the quadrature axis and thus prevent the change of flux in that axis. Let such a machine be connected to an infinite bus. The plan of attack shall be to first obtain an expression for the flux linkages with the field winding and the time rate of change of these flux linkages in terms of the constants of the machine. A small sinusoidal variation of angle will then be superposed upon the operating angle and the resultant variation of flux linkages and internal voltages determined. These incremental values may be converted to power increments and the area of the loop obtained.

Following the method of Blondel the reactions within the machine will be resolved into the two components, one in phase and one in quadrature to the axis of the main field structure. The nomenclature used will be the same, with some few exceptions, as that used by Doherty and Nickle in their excellent papers on *Synchronous Machines*.

### Transient Reactance and Transient Voltage

In Fig. 3 let $e_{dl}$ be the no load excitation curve with abscissa representing the field current. In the "per unit system" unit field current will be defined as that current required to produce unit terminal voltage at no load. Also, defining unit air-gap flux as that required to produce unit voltage, $e_{dl}$ will also represent air-gap flux. The component of armature current in phase with the field structure, $i_d$, is directly demagnetizing. Its effect in field terms is $x_a i_d$, indicated by the line $p - n$, in which $x_a$ converts the armature current to its field equivalent. The total field current required then to produce the air-gap voltage $e_{dl}$ is $e_{dl} + x_a i_d$. But this is numerically equal to $e_d$, the nominal voltage due to excitation in the direct axis. Therefore

$$e_d = e_{dl} + x_a i_d \tag{2}$$

In addition to the air-gap flux, the field windings are

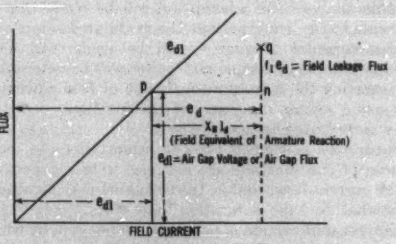


Fig. 3—Flux Relations in Direct Axis

also linked with a field leakage flux* which is directly proportional to the field current $e_d$. Defining the field leakage, $f_l$, as a fraction of the air gap flux at no load, the field leakage will be $f_l e_d$. This is indicated in the figure by the line $n - q$. The total flux linking the field winding is then

$$e_{dl} + f_l e_d$$

Now defining unit flux linkages as the flux linkages at no load normal voltage, and since the flux linking the field winding at no load normal voltage is $(1 + f_l)$, the flux linkages $\psi_d$ in per unit values are

$$\psi_d = \frac{e_{dl} + f_l e_d}{1 + f_l} \tag{3}$$

Inserting $e_{dl}$ from (2), $\psi_d$ is also

$$\psi_d = e_d - \frac{x_a}{1 + f_l} i_d \tag{4}$$

The "transient reactance" of a synchronous machine is that reactance which when divided into the normal voltage gives the maximum r. m. s. symmetrical current (neglecting the additional component having a very rapid decrement) at the occurrence of a three-phase short circuit at the terminals of the machine which had been operating at no load. Its value can be obtained by the aid of Fig. 3 as follows.

For unit armature current with a three-phase short circuit at the terminals, the air-gap voltage is equal to the armature leakage reactance $x_l$ and the armature reaction expressed in terms of field current is $x_a$. To maintain this flux and armature current the total field current required is $x_l + x_a$, which is equal to the synchronous reactance $x_d$. The field leakage corresponding to this current is $f_l x_d$. The total field linkages per unit armature current are then, in per unit terms,

$$\frac{x_l + f_l x_d}{1 + f_l}.$$

For any sudden change in circuit conditions, the flux linkages with the field winding at the first instant remain constant. Since, by definition, the flux linkages with the field winding at normal no load voltage is unity, for any transition from this condition the flux linkages at the first instant for the new condition must remain unity. Knowing then the linkages per unit armature current and the total linkages, the armature current is equal to $\dfrac{1 + f_l}{x_l + f_l x_d}$.

From the previous definition of the transient reactance, $x_d'$, it may be seen that $x_d'$ is the reciprocal of this quantity.

$$x_d' = \frac{x_l + f_l x_d}{1 + f_l} \tag{5}$$

Remembering that $x_d = x_l + x_a$, other forms of this expression are

$$x_d' = x_l + \frac{f_l}{1 + f_l} x_a \tag{6}$$

$$x_d' = x_d - \frac{1}{1 + f_l} x_a \tag{7}$$

Expression (6) is interesting in that it gives a better picture of the nature of $x_d'$ as being the armature leakage reactance plus a term proportional to the field leakage and the relative strengths of field and armature ampere turns.

From (7)

$$\frac{x_a}{1 + f_l} = x_d - x_d' \tag{8}$$

Inserting in (4)

$$\psi_d = e_d - (x_d - x_d') i_d \tag{9}$$

or

$$e_d - \psi_d = (x_d - x_d') i_d \tag{10}$$

From Equation (10) it will be observed that the difference between $e_d$ and $\psi_d$ in the per unit system is equal to the difference in synchronous reactance and transient

*Leakage flux turns weighted so that they may be replaced by a leakage flux which links all of the turns.

reactance drops. It follows, therefore, that $\psi_d$ has all the characteristics of a fictitious voltage, which shall be designated the "transient" voltage, $e_d'$, and which is obtained in the same manner as $e_d$ for steady state conditions, except that $x_d$ is replaced by $x_d'$. The flux linkages $\psi_d$ or $e_d'$ can be obtained during transients by the same kind of formula as that used to determine $e_d$ for steady state conditions.

### Time Rate of Change of $e_d'$

In per unit terms, the unit of instantaneous value of exciter voltage $e_x$ will be defined as the voltage required to circulate unit current in the field circuit. The value of $e_d$ has already been defined as the nominal voltage in the direct axis, that is, the internal voltage of the machine obtained by using the synchronous reactance $x_d$, and is also numerically equal to the instantaneous value of field current or instantaneous resistance drop in the field circuit. The voltage applied to the field must at any instant be equal to the resistance drop plus the inductive drop, which latter is proportional

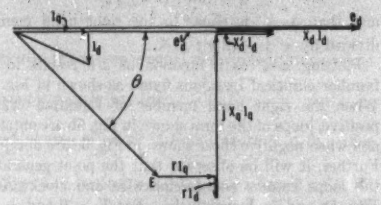


Fig. 4—Vector Diagram of Salient Pole Synchronous Machine without Amortisseur Winding

to the rate of change of flux linkages. In per unit terms the voltage equation may, therefore, be written

$$e_x = e_d + T_{do} \frac{d\,\psi_d}{d\,t} \tag{11}$$

The coefficient, $T_{do}$, is the no load time constant of the machine and, since the units of $e_x$, $e_d$, and $\psi_d$ have already been defined this coefficient is introduced to convert the time rate of change of linkages in "per unit" values to "per unit" values of e. m. f. in the field circuit.

Equation (11) may also be written

$$e_x = e_d + T_{do} \frac{d\,e_d'}{d\,t} \tag{12}$$

In what follows, incremental values will be designated by the prefix $\Delta$, and when this prefix is not used the mean operating values will be understood unless specifically stated otherwise. Since constant exciter voltage is assumed, Equation (12) may be written

$$0 = \Delta\, e_d + T_{do} \frac{d\,\Delta\, e_d'}{d\,t} \tag{13}$$

In Fig. 4, the vector diagram of the machine is shown in which

$E$ = Voltage of the infinite bus
$e_d$ = Nominal voltage in direct axis
$e_d'$ = Transient voltage in direct axis
$\theta$ = Angle between direct axis of machine and voltage $E$
$r$ = Resistance in armature circuit
$x_q$ = Synchronous reactance in quadrature axis.

Equating reals and imaginaries and using $x_d'$ and $e_d'$

$$E \sin\theta + r\, i_d - x_q\, i_q = 0 \tag{14}$$

$$E \cos\theta + r\, i_q + x_d'\, i_d = e_d' \tag{15}$$

Solving for $i_d$

$$i_d = \frac{1}{r^2 + x_d'\, x_q} [x_q\, e_d' - x_q\, E \cos\theta - r\, E \sin\theta] \tag{16}$$

As indicated previously and shown graphically in Fig. 4

$$e_d = e_d' + i_d\,(x_d - x_d') \tag{17}$$

Substituting (16)

$$e_d = \frac{1}{r^2 + x_d'\, x_q} [(r^2 + x_d\, x_q)\, e_d' - (x_d - x_d')\, E\,(x_q \cos\theta + r \sin\theta)] \tag{18}$$

and

$$\Delta\, e_d = \frac{1}{r^2 + x_d'\, x_q} [(r^2 + x_d\, x_q)\, e_d' + (x_d - x_d')\, E\,(x_q \sin\theta - r \cos\theta)] \tag{19}$$

Now substituting (19) in (13),

$$(r^2 + x_d\, x_q)\, \Delta\, e_d' + (r^2 + x_d'\, x_q)\, T_{do} \frac{d\,\Delta\, e_d'}{d\,t} = (x_d - x_d')\, E\,(-\,x_q \sin\theta + r \cos\theta)\, \Delta\,\theta \tag{20}$$

Dividing through by $(r^2 + x_d\, x_q)$ and letting

$$T_d = \frac{r^2 + x_d'\, x_q}{r^2 + x_d\, x_q}\, T_{do} \tag{21}$$

Equation (20) becomes

$$\Delta\, e_d' + T_d \frac{d\,\Delta\, e_d'}{d\,t} = \frac{x_d - x_d'}{r^2 + x_d\, x_q}\, E(-x_q \sin\theta + r \cos\theta)\Delta\,\theta \tag{22}$$

It may be observed in passing that $T_d$ is the time constant of the field winding for the particular circuit condition. Equation (21) is similar to the expression derived by Park and Robertson[8] showing how the time constant of the unidirectional transient in the field varies with the reactance in the short circuited armature, except that Equation (21) goes one step further and includes the effect of the resistance. When $r$, $x_d'$, $x_d$, and $x_q$ refer specifically to machine constants, the effect of external constants $R$ and $X$ may be included as follows:

$$T_d = \frac{(r + R)^2 + (x_d' + X)\,(x_q + X)}{(r + R)^2 + (x_d + X)\,(x_q + X)} \tag{23}$$

### Variation of $\Delta e_d'$ for Small Sinusoidal Variations of Angle

Equation (22) enables one to determine the time rate of change of $\Delta e_d'$ for instantaneous values of $\Delta e_d'$ and $\Delta \theta$ for the condition of constant exciter voltage. Now let small sinusoidal variations of $\theta$ of frequency $f$ and magnitude $\Delta \theta_m$ be superposed upon the main operating angle,—the mechanism whereby this may be accomplished is immaterial at this point. Then

$$\Delta \theta = \Delta \theta_m \sin 2 \pi f t \tag{24}$$

Since these oscillations are assumed to be sustained, $e_d'$ will also attain some form of sinusoidal oscillation of the same frequency. Let the value of $\Delta e_d'$ be

$$\Delta e_d' = \Delta e_{dm}' \sin (2 \pi f t + \alpha) \tag{25}$$

in which $\Delta e_{dm}'$ and $\alpha$ are to be determined.

$$\frac{d \Delta e_d'}{d t} = 2 \pi f \Delta e_{dm}' \cos (2 \pi f t + \alpha) \tag{26}$$

Inserting (24), (25), and (26) in (22)

$$\Delta e_{dm}' \sin (2 \pi f t + \alpha) + 2 \pi f T_d \Delta e_{dm}' \cos (2 \pi f t + \alpha) = \frac{x_d - x_d'}{r^2 + x_d x_q} E(-x_q \sin \theta + r \cos \theta) \Delta \theta_m \sin 2 \pi f t \tag{27}$$

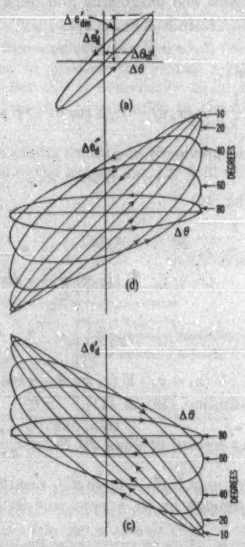


Fig. 5—Voltage Loops Showing Effect of Lag upon Shape and Direction of Generation

Since the above relations must be satisfied for all value of $t$, $\Delta e_{dm}'$, and $\alpha$ can be determined by letting $2 \pi f t = 0$ and $\pi/2$, producing the two following equations:

$$\Delta e_{dm}' \sin \alpha + 2 \pi f T_d \Delta e_{dm}' \cos \alpha = 0 \tag{28}$$

$$\Delta e_{dm}' \cos \alpha - 2 \pi f T_d e_{dm}' \sin \alpha = \frac{x_d - x_d'}{r^2 + x_d x_q} E (- x_q \sin \theta + r \cos \theta) \Delta \theta_m \tag{29}$$

As will be shown later, it will not be necessary to determine $\alpha$ and $\Delta e_{dm}'$, but rather the quantity $\Delta e_{dm}' \sin \alpha$. This quantity can be obtained from (28) and (29)

$$\Delta e_{dm}' \sin \alpha = -\frac{2 \pi f T_d}{1 + (2 f T_d)^2} \cdot \frac{x_d - x_d'}{(r^2 + x_d x_q)} E(-x_q \sin \theta + r \cos \theta) \Delta \theta_m \tag{30}$$

By analogy with the ordinary a-c. circuit it is possible to see immediately from Equation (22) that $\Delta e_d'$ lags behind $\Delta \theta$ by an angle

$$\alpha = \tan^{-1} (2 \pi f T_d)$$

and that $\Delta e_{dm}'$ is equal to the right hand member divided by $\sqrt{1 + (2 \pi f T_d)^2}$.

Plotting $\Delta e_d'$ as a function of $\Delta \theta$ results in the familiar elliptical Lissajous figure as shown in Fig. 5a. When the right hand member of Equation (22) is positive, loops of the form shown in Fig. 5b are obtained and when negative those shown in Fig. 5c are obtained. Further, it will be observed that the point generating the loops rotates counterclockwise and clockwise in Figs. 5b and 5c, respectively. For $T_d = 0$ and $\infty$ the loops become a diagonal straight line and a horizontal straight line, respectively.

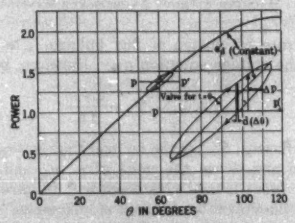


Fig. 6—Power-Angle Diagram with Angular Oscillation Superposed

### Power Loop

Equation (107) in Appendix I determines the total power output of the generator in terms of $e_d$, $e_q$, and $\theta$. Letting $e_d$ equal to $e_d'$, $x_q$ equal to $x_q'$, and $e_q$ equal to zero, the power output as a function of $\theta$ for a constant value of $e_d'$ may be plotted as shown in Fig. 6.

Having obtained the variation in $\Delta e_d'$ with respect to $\Delta \theta$, the corresponding increment in power output

above the value corresponding to $e_d'$ constant is, for small values of $\Delta\,\theta$,

$$\Delta\,P = \frac{d\,P}{d\,e_d'}\,\Delta\,e_d' \tag{31}$$

This differential has been derived in Appendix I and is given by Equation (**116**). Now since the variation of $\Delta\,e_d'$ with $\Delta\,\theta$ forms an elliptical loop, the increment in $\Delta\,P$ will likewise form an elliptical loop about the curve of power output for $e_d'$ constant. When $\frac{d\,P}{d\,e_d'}$ is positive, the direction of generation is the same as the voltage loop.

As shown in the qualitative treatment, the energy per cycle is proportional to the area of the power loop and the system is stable for clockwise generation of the loop. The quantitative evaluation of the energy absorbed per cycle follows. $\Delta\,P$ varies in time phase relation with $\Delta\,e_d'$ so that

$$\Delta\,P = \frac{d\,P}{d\,e_d'}\,\Delta\,e_{dm}'\sin\,(2\,\pi\,f\,t + \alpha) \tag{32}$$

The area of the loop is equal to the integration around one complete cycle, say from $t = 0$ to $t = \frac{1}{f}$, of the incremental area of height $\Delta\,P$ and width $d\,(\Delta\,\theta)$. (See Fig. 6)

$$d\,(\Delta\,\theta) = d\,(\Delta\,\theta_m \sin 2\,\pi\,f\,t) = \Delta\,\theta_m\,2\,\pi\,f \cos 2\,\pi\,f\,t\,.\,d\,t \tag{33}$$

$$W/\sim = \text{Area} = \int_0^{\frac{1}{f}} \frac{d\,P}{d\,e_d'}\,\Delta\,e_{dm}'\sin\,(2\,\pi\,f\,t + \alpha)\,\Delta\,\theta_m\,2\,\pi\,f \cos 2\,\pi\,f\,t\,.\,d\,t$$

$$= \pi\,f\,\Delta\,e_{dm}'\,\Delta\,\theta_m \frac{d\,P}{d\,e_d'}\left\{\int_0^{\frac{1}{f}} \sin\,(4\,\pi\,f\,t + \alpha)\,d\,t + \int_0^{\frac{1}{f}} \sin\,\alpha\,d\,t\right\} = \pi\,\Delta\,\theta_m \frac{d\,P}{d\,e_d'}\,\Delta\,e_{dm}'\sin\,\alpha \tag{34}$$

Insert Equation (**30**)

$$W/\sim = -\frac{2\,\pi\,f\,T_d}{[1 + (2\,\pi\,f T_d)^2]}\,\frac{\pi\,(x_d - x_d')}{(r^2 + x_d\,x_q)}\,E\,(-\,x_q \sin\,\theta + r \cos\,\theta)\,\frac{d\,P}{d\,e_d'}\,(\Delta\,\theta_m)^2 \tag{35}$$

This expression gives the excess of power output per cycle of oscillation, $\frac{d\,P}{d\,e_d'}$, being defined by Equation (**116**) in the appendix and $T_d$ by Equation (**21**), for constant prime mover input. The expression thus represents the energy that is absorbed per cycle of oscillation,—a positive value indicating a stable condition and negative value an unstable operating condition; or in the event of cyclic variations in prime mover input it represents the energy per cycle that can be absorbed without producing hunting.

The differential $\frac{d\,P}{d\,e_d'}$ for practically all conditions met in practise is positive for generators as also is $(x_d - x_d')$.

It follows, therefore, that the sign of the quantity is dependent upon the expression $(-\,x_q \sin\,\theta + r \cos\,\theta)$. Therefore, for

$$\theta > \tan^{-1}\frac{r}{x_q} \tag{36}$$

the energy per cycle is positive and the machine is stable. This relation was first pointed out by Nickle and Pierce.

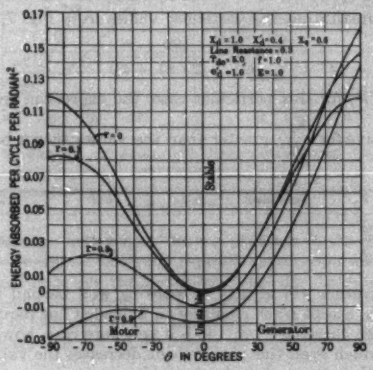


FIG. 7—ENERGY ABSORBED PER CYCLE OF SYSTEM OSCILLATION

No amortisseur windings

$$\text{Energy per cycle} = -\frac{2\,\pi\,f\,T_d}{[1 + (2\,\pi\,f\,T_d)^2]}\,\frac{\pi\,(X_d - X_d')}{(r^2 + X_d\,X_q)}\,E\,(-\,X_q \sin\,\theta + r \cos\,\theta)\,\frac{d\,P}{d\,e_d'}\,(\Delta\,\theta_m)^2$$

in which

$$T_d = \frac{r^2 + X_d'\,X_q}{r^2 + X_d\,X_q}\,T_{do}$$

$$\frac{d\,P}{d\,e_d'} = \frac{1}{(r^2 + X_d'\,X_q)^2}\,\{2\,r\,(r^2 + X_q^2)\,e_d' + [r^2\,(2\,X_d' - X_q) + X_d'\,X_q^2]\,E \sin\,\theta - r\,[r^2 + X_q\,(2\,X_q - X_d')]\,E \cos\,\theta\}$$

To form an idea of the relative importance of the operating angle and armature resistance, the curves in Fig. 7 have been calculated for the particular machine constants designated in the figure. The constants were chosen for a typical machine with an external reactance of 0.3. Positive angles indicate a generator action and negative angles motor action. As will be seen, the angle for which $W/\sim$ is equal to zero increases with

increasing angle following the relation expressed by Equation (**36**). Observe also that the machine is more stable for a given $e_d'$ (flux linkages with the field winding) when operating as a generator than when operating as a motor. This difference becomes very pronounced for the larger values of armature resistance.

It was stated that $\frac{d\,P}{d\,e_d'}$ is usually positive for generators. Actually the sign of this quantity is dependent upon the excitation. It is difficult to conceive a case in which the coefficient of sin $\theta$ of Equation (**116**) in Appendix I is negative, so that if the quantity within the brackets is positive for $\theta = 0$ it will be positive for all positive values of $\theta$. Now to show that the function is positive for $\theta = 0$ it is only necessary to show that

$$2\,(x_q^2 + r^2)\,e_d' > [x_q\,(2\,x_q - x_d') + r^2]\,E \qquad (37)$$

or substituting the particular values from Fig. 7, that

$$\frac{e_d'}{E} > \frac{.99 + r^2}{2\,(.81 + r^2)}$$

that is, for this particular case, the expression will be positive for $\frac{e_d'}{E}$ greater than the values shown below.

| $r$ | very small | 0.1 | 0.2 | 0.3 |
|---|---|---|---|---|
| $\frac{e_d'}{E}$ | 0.611 | 0.617 | 0.606 | 0.60 |

Generators will always be working well beyond these limits, except when charging an unloaded line requiring a large charging kv-a. It is a very rare case, however, for which even this requirement decreases the value of $e_d'$ below those given in the table.

For values of $\frac{e_d'}{E}$ below those indicated in the table it is possible that $\frac{d\,P}{d\,e_d'}$ may be negative but, due to the sine term, $\frac{d\,P}{d\,e_d'}$ again turns positive for larger angles.

To get an idea of the relative importance of the various terms, the constants given in Fig. 7 were substituted for $r = 0.1$ with the following result

$$\frac{d\,P}{d\,e_d'} = 0.164\,e_d' + 0.572\,E \sin\theta - 0.1\,E \cos\theta$$

The effect of excitation upon spontaneous hunting was verified by an experiment described in the Evans and Bergvall[2] paper referred to previously. A 425-kv-a., 2300-volt condenser (without damper winding) was connected to the 2300-volt shop circuit through an impedance of 6.66 + j 0 ohms (0.53 + j 0 per unit). This is equivalent to a generator operating at practically $\theta = 0$. For low excitations the system was stable. However, when the excitation was increased to four amperes (7 amperes = N. L. excitation) the system became unstable.

## III. Salient Pole Machine with Amortisseur Windings

The effect of the amortisseur winding in the quadrature axis is to prevent the change of flux linked therewith. The rate of change of the cross flux with respect to angle is greater for small operating angles, that is, for light loads, so that under small sustained angular oscillations the currents induced in the quadrature axis should be greater for small operating angles. One should expect, therefore, that the energy absorbed per cycle should be greater for the small operating angles.

The problem is further complicated by the presence of two windings in the direct axis, namely, the main field winding itself and the amortisseur. Several simplifying assumptions suggest themselves with respect to the windings in the direct axis.

a. The presence of the amortisseur winding in the direct axis may be neglected, the currents in the main field only being taken into consideration.

b. The resistance of the main field may be assumed to be zero so that the flux linkages with it remain constant, with the effect of the amortisseur winding taken into consideration.

c. The presence of the amortisseur winding in the direct axis may be neglected and the main field resistance assumed to be equal to zero.

Any of these sets of assumptions render the problem readily susceptible to analysis; the complete derivation of the expressions giving the energy absorbed per cycle of system oscillation being given in the Appendix. In Fig. 8 are given two sets of curves for the above assumptions for a typical machine equipped with copper amortisseur (upper set) and with brass amortisseurs (lower set). The constants of the machine and line utilized are also given in the figure. The line resistance for this case is zero. It will be observed that for both the copper and the brass amortisseurs the three curves comprising a set coincide for $\theta = 0$ and then diverge slowly reaching a maximum divergence for $\theta = \pm 90$ deg. The coincidence for $\theta = 0$ becomes clear when one considers that for small angular oscillations about $\theta = 0$, the demagnetizing component of armature current in the direct axis is not altered, so that the flux in the direct axis has no tendency to change. The phenomenon must of necessity, therefore, be independent of the assumptions as to the characteristics of the windings in the direct axis, the entire energy loss being due to current flow in the quadrature axis. It will be observed that for large angles the energy absorbed is, for copper, larger under assumption (b) than assumption (a) but that for brass, larger under assumption (a) than assumption (b). The best assumption to employ is therefore dependent upon the character of the amortis-

seur in question. As a matter of fact, all of the simplifying assumptions stated introduce considerable error at large angles, the correct value of energy absorbed being very near to the value for assumption (c) plus the difference for assumptions (a) and (c) plus the difference for assumptions (a) and (b). The justification for this statement is that the currents in the field winding and in the amortisseur winding in the direct axis, because of the large difference in their time constants, are very nearly in time quadrature and consequently do not react upon each other to any considerable extent. This hypothesis has been checked by analysis and calculation for the copper amortisseur and found to be substantiated. It therefore follows that one cannot

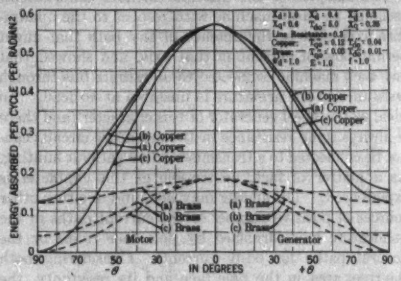


FIG. 8—ENERGY ABSORBED PER CYCLE OF SYSTEM OSCILLATION WITH ARMATURE RESISTANCE = 0 FOR THE MACHINE EQUIPPED WITH COPPER AND BRASS AMORTISSEURS FOR THE FOLLOWING ASSUMPTIONS:

| Assumption | Amortisseur in quad. axis | Amortisseur in direct axis | Resistance of main field |
|---|---|---|---|
| a | Yes | No | Normal |
| b | Yes | Yes | Zero |
| c | Yes | No | Zero |

say without giving consideration to the particular type of amortisseur which assumption will give the best results. Fortunately, however, as will be seen later, this question is usually not of much importance. In most cases the problem is to determine whether the machine is stable or unstable, so that unless other periodic power impulses, such as prime mover pulses, enter the problem and require a quantitative evaluation of the energy absorbed per cycle of system oscillation, it is adequate to determine only the sign of $W/\sim$.

## EFFECT OF ARMATURE RESISTANCE

To determine the effect of armature resistance, Figs. 9 and 10 were prepared, the former showing the energy absorbed per cycle for copper amortisseurs using assumption (b) and the latter for brass amortisseurs using assumption (a). It will be observed that the machine, equipped either with brass or copper amortisseurs, should be stable for any normal operating angle or line resistance. The machine is somewhat more stable operating as a generator than as a motor. While resistance decreases the stability of the machine, a very considerable amount will be required to make it unstable within the normal operating range.

The dotted curves in Figs. 9 and 10 were added to further demonstrate the effect of the particular assump-

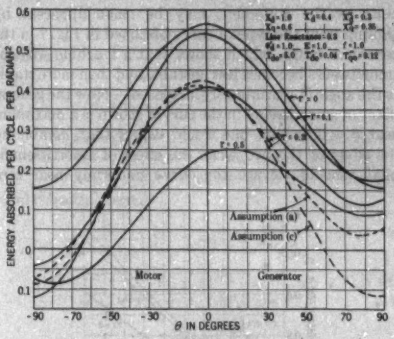


FIG. 9—EFFECT OF ARMATURE RESISTANCE WITH COPPER AMORTISSEURS

Using assumption (b) of Fig. 8. Dotted curves using assumptions (a) and (c) of Fig. 8

tions chosen with respect to the windings in the direct axis. It will be observed that the assumption chosen matters little for the motoring range but becomes of increasing importance, in a quantitative sense, as the angle is increased in the generating range. It is clear, however, that for either copper or brass amortisseurs,

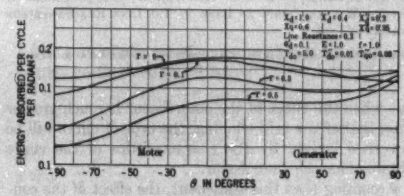


FIG. 10—EFFECT OF ARMATURE RESISTANCE WITH BRASS AMORTISSEURS

Using assumption (a) of Fig. 8. Dotted curves used assumptions (b) and (c) of Fig. 8

the true curve would result in a positive value of $W/\sim$. For smaller machines in which $T_{do}$ is smaller, the assumption of neglecting the amortisseur in the direct axis becomes more justifiable.

## GENERAL DISCUSSION

In general, as previously pointed out by Nickle and Pierce, for practical machines, if a generator is stable

at zero load it will be stable for all loads. Of course, theoretical machines may be imagined for which this is not true; machines in which the resistance of field winding is very small and in which the amortisseur winding is connected for the quadrature axis only, resulting in characteristic curves such as that for similar assumptions in Figs. 9 and 10 in which the lower curve passes through zero near 60 deg. The plausibility of the statement may be made apparent by arguing from the type of curve obtained in Fig. 7 in the generator range, which shows that a machine without amortisseurs becomes less unstable and then more stable as the angle is continuously increased. Now the general effect of amortisseurs in the curves shown is a maximum near $\theta = 0$ so that one would expect that, combining the effect of the two when the effect of amortisseur is small, should elevate the curve uniformly near zero

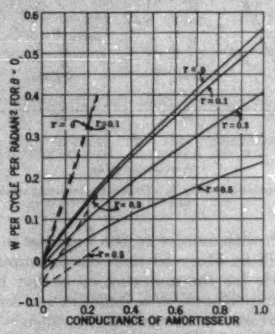


FIG. 11—ENERGY ABSORBED PER CYCLE AS A FUNCTION OF THE CONDUCTANCE OF THE AMORTISSEUR FOR DIFFERENT VALUES OF LINE RESISTANCE AND REACTANCE. CONDUCTANCE OF COPPER WINDING USED AS BASE = 1.0. LINE REACTANCE FOR FULL LINES = 0.3

Line reactance for dotted lines = 0. Same constants used as for Figs. 9 and 10

but when the effect of the amortisseur is much greater than that of the field winding, the type of curve will be governed largely by the characteristics of the curve obtained for the amortisseur.

Accepting then this statement, the effect of the conductivity of the amortisseur is illustrated in Fig. 11, which shows the energy loss for $\theta = 0$ plotted as a function of the conductance of the amortisseur, using the copper amortisseur as unity. The variation in conductance may be obtained either by changing the quantity or quality of the material employed. Brass dampers for the same section will have about 20 to 30 per cent of the conductance of copper. The curves are plotted for different values of armature resistance and two values of line reactance, the full lines for 0.3 and the dotted for 0. It would appear from these curves that even for such a large value of armature resistance as 0.5, so long as the reactance external to the machine is 0.3, an amortisseur of 4 per cent of the conductance of a copper amortisseur is all that is necessary to prevent spontaneous hunting. Almost any kind of amortisseur installed for the purpose for which it is normally installed will incidentally be of sufficiently low conductance to take care of all but the most abnormal cases giving rise to hunting of this nature. As the series reactance in the armature circuit decreases, the curves show that the need for the amortisseurs to stabilize the system, increases, that is, a higher conductance for the amortisseurs is required, but even this value is still quite small.

The analysis of the machine without amortisseurs assumed an ideal machine with respect to the quadrature axis, that is, the absence of any path that might permit flow of current in that axis, and showed that any such machine connected to an infinite bus through resistance in the armature is unstable at no load. An ideal water wheel generator of this character (and there is always some resistance in the armature circuit) cannot be connected to a transmission line without hunting. As a matter of fact, no trouble of this character is experienced. The answer may be found in either other sources of positive damper or the current paths in the quadrature axis furnished by pole face rivets or the natural paths for eddy currents. Considering both the rivet area in the pole face and its resistivity, the conductance of the rivets may be of the order of 5 per cent of the conductance of the copper damper and since they are surrounded by a complete iron magnetic circuit their time constant is still greater. Of course to offset this effect the subtransient reactance will be greater. In general, however, the stable operation of generators without amortisseurs at no load may well be attributed to the currents in the rivets.

## CONCLUSIONS

Theoretically, an ideal machine without amortisseurs should hunt, when operating at light loads. The lack of such hunting in modern transmission systems is explained by the presence of current paths in the quadrature axis afforded by rivets and parts of the field structure. Except for very abnormal conditions any normal design of amortisseur, that is installed for other purposes, will be found adequate incidentally to prevent spontaneous hunting.

# Appendix I

## POWER EQUATION

The vector diagram for a salient pole machine with the excitation $e_d$ and $e_q$ in the direct and quadrature axes, respectively, is shown in Fig. 12. The reactances in the two axes are $x_d$ and $x_q$.

Equating the reals and imaginaries

$$E \sin \theta + r i_d - x_q i_q + e_q = 0 \qquad (101)$$

$$E \cos \theta + r\, i_q + x_d\, i_d - e_d = 0 \qquad (102)$$

From (1)

$$i_q = \frac{1}{x_q}\,(e_q + E \sin \theta + r\, i_d) \qquad (103)$$

Substituting in (102)

$$E \cos \theta + \frac{r}{x_q}\, e_q + \frac{r}{x_q}\, E \sin \theta + \frac{r^2}{x_q}\, i_d + x_d\, i_d - e_d = 0$$

From which

$$i_d = \frac{1}{r^2 + x_d\, x_q}\,[x_q\, e_d - r\, e_q - r\, E \sin \theta - x_q\, E \cos \theta] \qquad (104)$$

and substituting in (103)

$$i_q = \frac{1}{r^2 + x_d\, x_q}\,[r\, e_d + x_d\, e_q + x_d\, E \sin \theta - r\, E \cos \theta] \qquad (105)$$

The power output, that is, the power at $E$ is equal to

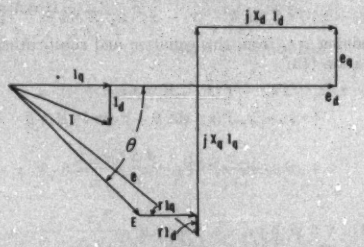


FIG. 12—VECTOR DIAGRAM OF SALIENT POLE SYNCHRONOUS MACHINE WITH EXCITATION IN BOTH THE DIRECT AND QUADRATURE AXES

the sum of the products of the in phase components of $E$ and $I$. To get the total power, including the loss in the resistance, it is necessary to use the sum of the products of the in phase components of $I$ and $e$, the latter including the resistance drop.

$$P = (e_d - x_d\, i_d)\, i_q + (-\, e_q + x_q\, i_q)\, i_d$$
$$= e_d\, i_q - e_q\, i_d + (x_q - x_d)\, i_d\, i_q \qquad (106)$$

Substituting (104) and (105)

$$P = \frac{1}{(r^2 + x_d\, x_q)^2}\,\{\, e_d\,(r\, e_d + x_d\, e_q$$
$$+ x_d\, E \sin \theta - r\, E \cos \theta)\,(r^2 + x_d\, x_q)$$
$$- e_q(x_q\, e_d - r\, e_q - r\, E \sin \theta - x_q\, E \cos \theta)(r^2 + x_d\, x_q)$$
$$+ (x_q\, e_d - r\, e_q - r\, E \sin \theta - x_q\, E \cos \theta)(r\, e_d + x_d\, e_q$$
$$+ x_d\, E \sin \theta - r\, E \cos \theta)\,(x_q - x_d)\,\} \qquad (107)$$

The increment in power for small increments in $e_d$ and $e_q$ is

$$P = \frac{\partial P}{\partial e_d}\,\Delta e_d + \frac{\partial P}{\partial e_q}\,\Delta e_q \qquad (108)$$

But

$$\frac{\partial P}{\partial e_d} = \frac{1}{(r^2 + x_d\, x_q)^2}\,\{\,(2\, r\, e_d + x_d\, e_q$$
$$+ x_d\, E \sin \theta - r\, E \cos \theta)(r^2 + x_d\, x_q) - x_q\, e_q(r^2 + x_d\, x_q)$$
$$+ x_q(r\, e_d + x_d\, e_q + x_d\, E \sin \theta - r\, E \cos \theta)(x_q - x_d)$$
$$+ r(x_q\, e_d - r\, e_q - r\, E \sin \theta - x_q\, E \cos \theta)(x_q - x_d)\,\}$$

which, after collecting terms becomes

$$\frac{\partial P}{\partial e_d} = \frac{1}{(r^2 + x_d\, x_q)^2}\,\{\, 2\, r(r^2 + x_q^2)\, e_d - 2\, r^2\,(x_q - x_d)\, e_q$$
$$+ [r^2\,(2\, x_d - x_q) + x_d\, x_q^2]\, E \sin \theta - r\,[r^2$$
$$+ x_q\,(2\, x_q - x_d)]\, E \cos \theta\,\} \qquad (109)$$

Similarly,

$$\frac{\partial P}{\partial e_q} = \frac{1}{(r^2 + x_d\, x_q)^2}\,\{\, x_d\, e_d\,(r^2$$
$$+ x_d\, x_q) - (x_q\, e_d - 2\, r\, e_q - r\, E \sin \theta - x_q\, E \cos \theta)(r^2$$
$$+ x_d\, x_q) - r(r\, e_d + x_d\, e_q + x_d\, E \sin \theta - r\, E \cos \theta)(x_q - x_d)$$
$$+ x_d(x_q\, e_d - r\, e_q - r\, E \sin \theta - x_q\, E \cos \theta)\,(x_q - x_d)\,\}$$

and collecting terms

$$\frac{\partial P}{\partial e_q} = \frac{1}{(r^2 + x_d\, x_q)}\,\{\, - 2\, r^2\,(x_q - x_d)\, e_d$$
$$+ 2\, r\,(r^2 + x_d^2)\, e_q + r\,[r^2 - x_d\,(x_q - x_q)]\, E \sin \theta$$
$$+ [r^2\,(2\, x_q - x_d) + x_q\, x_d^2]\, E \cos \theta\,\} \qquad (110)$$

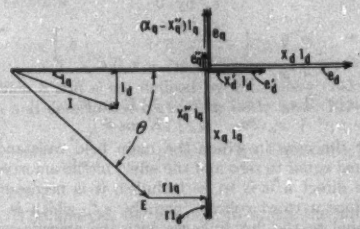


FIG. 13—VECTOR DIAGRAM OF SALIENT POLE SYNCHRONOUS MACHINE SHOWING THE RELATION BETWEEN $e_d$ AND $e_d'$ AND $e_q$ AND $e_q''$

The rate of change of power with respect to $e_d'$ and $e_q''$ may be obtained by replacing

$e_d$ by $e_d'$
$e_q$ by $e_q''$
$x_d$ by $x_d'$
and $x_q$ by $x_q''$

giving

$$\frac{\partial P}{\partial e_d'} = \frac{1}{(r^2 + x_d'\, x_q'')^2}\,\{\, 2\, r(r^2 + x_q''^2)\, e_d' - 2\, r^2(x_q'' - x_d')\, e_q''$$
$$+ [r^2\,(2\, x_d' - x_q'') + x_d'\, x_q''^2]\, E \sin \theta$$
$$- r\,[r^2 + x_q''\,(2\, x_q'' - x_d')]\, E \cos \theta\,\} \qquad (111)$$

$$\frac{\partial P}{\partial e_q''} = \frac{1}{(r^2 + x_d'\, x_q'')^2}\,\{\, -2r^2(x_q'' - x_d')\, e_d' + 2\, r(r^2 + x_d'^2)\, e_q''$$
$$+ r\,[r^2 - x_d'\,(2\, x_d' - x_q'')]\, E \sin \theta$$
$$+ [r^2\,(2\, x_q'' - x_d') + x_q''\, x_d'^2]\, E \cos \theta\,\} \qquad (112)$$

in which $e_q''$ is given below by Equation (115) which is derived as follows. From Fig. 13 which shows a more

complete vector diagram of the machine, it can be seen that

$$e_q'' = e_q - (x_q - x_q'')\, i_q \tag{113}$$

From Equation (105), replacing

$x_d$ by $x_d'$
$e_d$ by $e_d'$
and $e_q$ by 0

one obtains

$$i_q = \frac{1}{r^2 + x_d'\, x_q}\,[r\, e_d' + x_d'\, E \sin\theta - r\, E \cos\theta] \tag{114}$$

which when substituted in (113) gives

$$e_q'' = -\frac{x_q - x_q''}{r^2 + x_d'\, x_q}\,[r\, e_d' + x_d'\, E \sin\theta - r\, E \cos\theta] \tag{115}$$

In considering the machine without amortisseur windings $e_q''$ can change instantaneously so that the characteristics of the machine with respect to the quadrature axis can be determined by the constants which are used for determining the steady state performance. Therefore replacing in Equation (109)

$e_d$ by $e_d'$
$e_q$ by 0
and $x_d$ by $x_d'$

$$\frac{\partial P}{\partial e_d'} = \frac{1}{(r^2 + x_d'\, x_q)^2}\,\{\, 2\, r\, (r^2 + x_q^2)\, e_d' + [r^2\,(2\, x_d' - x_q) + x_d'\, x_q^2\,]\, E \sin\theta - r\,[r^2 + x_q\,(2\, x_q - x_d')\,]\, E \cos\theta \,\} \tag{116}$$

For the case in which the main field resistance is assumed equal to zero and the effect of the amortisseur in the direct axis is to be included, it is necessary to introduce a third voltage, namely, $e_d''$, which is proportional to the flux linkages with the amortisseur in the direct axis. The "subtransient reactance" in the direct axis, $x_d''$, must be used with $e_d''$. Equations (111) and (112) for this condition become

$$\frac{\partial P}{\partial e_d''} = \frac{1}{(r^2 + x_d''\, x_q'')^2}\,\{2\, r\, (r^2 + x_q'')\, e_d'' - 2\, r^2 (x_q'' - x_d'')\, e_q'' + [r^2\,(2\, x_d'' - x_q'') + x_d''\, x_q''^2\,]\, E \sin\theta - r\,[r^3 + x_q''\,(2\, x_q'' - x_d'')\,]\, E \cos\theta \tag{117}$$

$$\frac{\partial P}{\partial e_q''} = \frac{1}{(r^2 + x_d''\, x_q'')^2}\,\{-2\, r^2 (x_q'' - x_d'')\, e_d'' + 2\, r\, (r^2 + x_d''^2)\, e_q'' + r\,[r^2 - x_d''\,(2\, x_d'' - x_q'')\,]\, E \sin\theta + [r^2\,(2\, x_q'' - x_d'') + x_q''\, x_d''^2\,]\, E \cos\theta \,\} \tag{118}$$

in which $e_q''$ is determined by Equation (115) and $e_d''$ by the following Equation (121) which is derived as follows.

$$e_d'' = e_d' - (x_d' - x_d'')\, i_d \tag{119}$$

But $i_d$ from Equation (104) inserting the appropriate constants is

$$i_d = \frac{1}{r^2 + x_d'\, x_q}\,[x_q\, e_d' - r\, E \sin\theta - x_q\, E \cos\theta] \tag{120}$$

Substituting in (119)

$$e_d'' = \frac{1}{r^2 + x_d'\, x_q}\,[(r^2 + x_d''\, x_q)\, e_d' + (x_d' - x_d'')\,(r \sin\theta + x_q \cos\theta)\, E\,] \tag{121}$$

## Appendix II

### Energy per Cycle Including Effect of Windings in Both Axes

1. Analysis will first be made of a salient pole machine with an amortisseur winding in the quadrature axis only.

Equation (17) gives the instantaneous value of $e_d$ and substituting $i_d$ from Equation (104) of the appendix in terms of $e_d'$, $e_q''$, $x_d'$, and $x_q''$, there results

$$e_d = \frac{1}{r^2 + x_d'\, x_q''}\,[(r^2 + x_d\, x_q'')\, e_d' - r\,(x_d - x_d')\, e_q'' - (x_d - x_d')\, r\, E \sin\theta - (x_d - x_d')\, x_q''\, E \cos\theta] \tag{122}$$

Obtaining $\Delta e_d$ from this equation and substituting in Equation (13)

$$(r^2 + x_d\, x_q'')\, \Delta e_d' - r\,(x_d - x_d')\, \Delta e_q'' + (x_d - x_d')\,(x_q'' \sin\theta - r \cos\theta)\, E\, \Delta\theta + (r^2 + x_d'\, x_q'')\, T_{do}\, \frac{d\, \Delta e_d'}{d\, t} = 0$$

or

$$\Delta e_d' + T_d\, \frac{d\,(\Delta e_d')}{d\, t} - \frac{r\,(x_d - x_d')}{r^2 + x_d\, x_q''}\, \Delta e_q'' = -\frac{(x_d - x_d')}{r^2 + x_d\, x_q''}\,(x_q'' \sin\theta - r \cos\theta)\, E\, \Delta\theta \tag{123}$$

in which $T_d$ is defined by

$$T_d = \frac{r^2 + x_d'\, x_q''}{r^2 + x_d\, x_q''}\, T_{do} \tag{124}$$

In Fig. 13 is shown the vector diagram including the nominal quadrature voltage, $e_q$. The nominal voltage is numerically equal to the instantaneous value of current in the quadrature axis; the positive sense being taken for values leading $e_d'$. The voltage $e_q''$ is the subtransient voltage in the quadrature axis and is called so because it corresponds to flux linkages associated with the damper winding, the double prime being used to correspond with subtransient reactances $x_d''$ and $x_q''$. For steady state conditions $e_q = 0$ and $e_q''$ is negative when the machine is operating as a generator.

Since there is no source of e. m. f. in the amortisseur winding, the voltage equation may be written

$$0 = e_q + T_{qo}''\, \frac{d\, \psi_q}{d\, t} \tag{125}$$

But since $\psi_q$ may be shown to be equal to $e_q''$ in a manner analogous to relation $e_d' = \psi_d$ for the direct axis,

$$0 = e_q + T_{qo}'' \frac{d\, e_q''}{d\, t}$$

or

$$0 = e_q + T_{qo}'' \frac{d\, \Delta\, e_q''}{d\, t} \qquad (126)$$

But from Fig. 13 it may be seen that

$$e_q = e_q'' + (x_q - x_q'')\, i_q \qquad (127)$$

Substituting $i_q$ from Equation (105) of the appendix, in terms of $e_d'$, $e_q''$, and $x_q''$,

$$e_q = \frac{1}{r^2 + x_d'\, x_q''} [r\, (x_q - x_q'')\, e_d' + (r^2 + x_q\, x_d')\, e_q'' + (x_q - x_q'')\, E\, (x_d' \sin\theta - r \cos\theta)\,] \qquad (128)$$

Obtaining $\Delta\, e_q$ from this equation and substituting in Equation (126)

$$(r^2 + x_q\, x_d')\, \Delta\, e_q'' + r\, (x_q - x_q'')\, \Delta\, e_d' + (x_q - x_q'')\, (x_d' \cos\theta + r \sin\theta)\, E\, \Delta\, \theta + (r^2 + x_d'\, x_q'')\, T_{qo}'' \frac{d\, \Delta\, e_q''}{d\, t} = 0$$

or

$$\Delta\, e_q'' + T_q'' \frac{d\, \Delta\, e_q''}{d\, t} + \frac{r\, (x_q - x_q'')}{r^2 + x_q\, x_d'} \Delta\, e_d' = - \frac{(x_q - x_q'')}{r^2 + x_q\, x_d'} (x_d' \cos\theta + r \sin\theta)\, E\, \Delta\, \theta \qquad (129)$$

in which

$$T_q'' = \frac{r^2 + x_q''\, x_d'}{r^2 + x_q\, x_d'} \qquad (130)$$

Now if $\Delta\, \theta$ varies sinusoidally, $\Delta\, e_d'$ and $\Delta\, e_q''$ will also vary sinusoidally. Representing these quantities vectorially as $\underline{\Delta\, \theta}$, $\underline{\Delta\, e_d'}$, and $\underline{\Delta\, e_q''}$, and substituting in (123) and (129), there results

$$(1 + j\, 2\, \pi\, f\, T_d')\, \underline{\Delta e_d'} - \frac{r\, (x_d - x_d')}{r^2 + x_d\, x_q''}\, \underline{\Delta\, e_q''} = - \frac{(x_d - x_d')}{r^2 + x_d\, x_q''} (x_q'' \sin\theta - r \cos\theta)\, \underline{E\, \Delta\, \theta} \qquad (131)$$

and

$$(1 + j\, 2\, \pi\, f\, T_q'')\, \underline{\Delta\, e_q''} + \frac{r\, (x_q - x_q'')}{r^2 + x_q\, x_d'}\, \underline{\Delta\, e_d'} = - \frac{(x_q - x_q'')}{r^2 + x_q\, x_d'} (x_d' \cos\theta + r \sin\theta)\, \underline{E\, \Delta\, \theta} \qquad (132)$$

It will be observed that for $r = 0$, the second terms on the left hand numbers are zero so that $\underline{\Delta\, e_d'}$ and $\underline{\Delta\, e_q''}$ are independent of each other and may be solved separately. For other values of $r$, $\Delta\, e_d'$ and $\Delta\, e_q''$ will be dependent upon each other. Let the solution of the simultaneous Equations (13) and (132), be

$$\underline{\Delta\, e_d'} = (a + j\, b)\, \underline{\Delta\, \theta} \qquad (133)$$

and

$$\underline{\Delta\, e_q''} = (c + j\, d)\, \underline{\Delta\, \theta} \qquad (134)$$

Now

$$\Delta\, P = \frac{\partial\, P}{\partial\, e_d'} \Delta\, e_d' + \frac{\partial\, P}{\partial\, e_q''} \Delta\, e_q'' \qquad (135)$$

in which $\frac{\partial\, P}{\partial\, e_d'}$ and $\frac{\partial\, P}{\partial\, e_q''}$ are given by Equations (111) and (112), respectively.

The energy absorbed per cycle is obtained by inserting the instantaneous values of $\Delta\, e_d'$ and $\Delta\, e_q''$ and integrating the quantity $\Delta\, P \frac{d\, (\Delta\, \theta)}{d\, t}$ around one complete cycle. This has been done before and it was seen (Equation (34)) to be proportional to $\Delta\, e_{dm}' \sin\alpha$. In the case at hand this quantity is equal to be $\Delta\, \theta_m$ for $\Delta\, e_d'$ and $d\, \Delta\, \theta_m$ for $\Delta\, e_q''$. The energy per cycle thus becomes

$$W/\sim = \pi \left[ b \frac{\partial\, P}{\partial\, e_d'} + d \frac{\partial\, P}{\partial\, e_q''} \right] (\Delta\, \theta_m)^2 \qquad (136)$$

in which $b$ and $d$ are defined by Equations (133) and (134) and determined by solving (131) and (132) and $\frac{\partial\, P}{\partial\, e_d'}$ and $\frac{\partial\, P}{\partial\, e_q''}$ are obtained by Equations (111) and (112).

2. The analysis for the case in which the amortisseurs in both axes are included and the resistance of the main field is assumed equal to zero will be discussed next. With zero resistance field, the flux linkages associated with the field winding, must remain constant. This is equivalent to assuming $e_d'$ constant. The voltage corresponding to the flux linkages with the amortisseur winding in the direct axis will be designated $e_d''$ and the associated reactance $x_d''$. It follows, therefore, that the analysis will follow the same lines as for the case of the amortisseur winding in the quadrature axis only and finite field resistance, except that $e_d'$ will be replaced by $e_d''$, $x_d'$ by $x_d''$, and $x_d$ by $x_d'$.

The equations determining $\underline{\Delta\, e_d''}$ and $\underline{\Delta\, e_q''}$ become, from (131) and (132)

$$(1 + j\, 2\, \pi\, f\, T_d'')\, \underline{\Delta\, e_d''} - \frac{r\, (x_d' - x_d'')}{r^2 + x_d'\, x_q''}\, \underline{\Delta\, e_q''} = - \frac{(x_d' - x_d'')}{r^2 + x_d'\, x_q''} (x_q'' \sin\theta - r \cos\theta)\, \underline{E\, \Delta\, \theta} \qquad (137)$$

$$(1 + j\, 2\, \pi\, f\, T_q)\, \underline{\Delta\, e_q''} + \frac{r\, (x_q - x_q'')}{r^2 + x_q\, x_d''}\, \underline{\Delta\, e_d''}$$

$$= -\frac{(x_q - x_q'')}{r^2 + x_q x_d''} (x_d'' \cos\theta + r \sin\theta) \underline{E \Delta \theta} \quad (138)$$

and

$$T_q'' = \frac{r^2 + x_d'' x_q''}{r^2 + x_d'' x_q} T_{qo}'' \quad (139)$$

$$T_d'' = \frac{r^2 + x_q'' x_d''}{r^2 + x_q'' x_d'} T_{do}'' \quad (140)$$

Now if $\underline{\Delta e_d''} = (g + j h) \underline{\Delta \theta}$ (141)

and $\underline{\Delta e_q''} = (k + j m) \underline{\Delta \theta}$ (142)

the energy absorbed per cycle is

$$W/\sim = \pi \left[ h \frac{\partial P}{\partial e_d''} + m \frac{\partial P}{\partial e_q''} \right] (\Delta \theta_m)^2 \quad (143)$$

in which $\frac{\partial P}{\partial e_d''}$ and $\frac{\partial P}{\partial e_q''}$ are defined by Equations (117) and (118).

## Appendix III

### Machine with Field Resistance = 0 and Amortisseur Winding in Quadrature Axis Only

With a field winding having a resistance equal to zero the flux linking the winding in the direct axis must remain constant. The flux in the quadrature axis is still permitted to vary, the amount of which can be obtained from Equation (132) by letting $\underline{\Delta e_d'} = 0$, giving,

$$\Delta e_q'' = -\frac{1 - j 2 \pi f T_q''}{1 + (2 \pi f T_q'')^2} \frac{(x_q - x_q'')}{r^2 + x_q x_d'} (x_d' \cos\theta + r \sin\theta) E \Delta \theta \quad (144)$$

Since $b$ in Equation (136) is zero and $d$ is equal to the imaginary part of Equation (135), then

$$W/\sim = \frac{2 \pi f T_q''}{1 + (2 \pi f T_q'')^2} \frac{(x_q - x_q'')}{(r^2 + x_q x_d')} (x_d' \cos\theta + r \sin\theta) E \frac{\partial P}{\partial e_q''} (\Delta \theta_m)^2 \quad (145)$$

in which $\frac{\partial P}{\partial e_q''}$ is determined by Equation (112).

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## Discussion

**H. E. Edgerton:** The person who has never had experience with, or heard of self-sustained oscillation of synchronous machines is at first disturbingly puzzled by the idea. Why should the currents that are induced in the stator and rotor by momentary departures from synchronism tend to drive the machine further from synchronism? It appears to be a contradiction to Lenz's law which tells us that the induced currents set up a force that tends to stop the motion producing them. The induced currents in the rotor of an induction motor obey Lenz's law and tend to bring the rotor to synchronous speed and we would think that the induced currents in the field of the synchronous machine should be of the same nature.

There is however an important difference between the rotor of an induction motor and the field of a synchronous machine which, I believe, is the cause for self-sustained oscillations. The induction motor has a *polyphase* winding on the rotor while the field winding of the synchronous machine appears as a

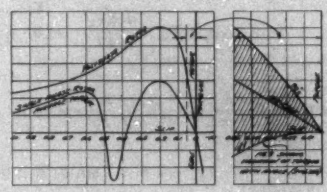

Fig. 1 Fig. 2

Fig. 1—Slip-Torque Curves for an Induction Motor with a Polyphase Rotor and with a Single-Phase Rotor

Fig. 2—Diagram showing Instantaneous Range of Variation of Slip-Torque Curve for an Induction Motor with a Single-Phase Rotor

*single-phase* winding to the stator. An amortisseur winding tends to introduce a winding in the quadrature axis, thus allowing the rotor winding to approach a polyphase combination. In this discussion I wish to show how the theory of the single-phase rotor induction motor can be used to explain the phenomena of self oscillation of synchronous machines.

Fig. 1 herewith shows the speed torque curve of an induction motor with a polyphase rotor. If one rotor phase is opened the resulting curve will be that indicated also in Fig. 1 (see for instance, Arnold and La Cour "Die Induktionsmaschinen," pages 186-196). The characteristic has the well-known dip at half speed. I wish to point out that this torque curve is, however, only an *average*. As the single-phase rotor winding rotates it alternately grabs and releases its hold on the rotating magnetic field at double slip frequency. The torque, we must then realize, is a function of *angular displacement* between the terminal potential and the axis of the single-phase winding as well as of slip. This is shown in Fig. 2 for the region from zero to 5 per cent slip. The instantaneous torque varies with the angle making an excursion over the shaded area between the boundaries and giving an average torque which is shown by the curve marked "average" on Fig. 2 and is shown over the complete range in Fig. 1. The effect of stator resistance is to cause the instantaneous

torque to give generator action for small values of motor slip and angle.

Fig. 4 shows the wiring diagram for a test to show the effect of a single-phase rotor on the induction motor effect. A Westinghouse instantaneous polyphase-power oscillograph element recorded the power at the terminals of the motor with the external resistance between the infinite bus and the oscillograph. Other elements were used to record stator and rotor current, voltage of an open-circuited synchronous machine on the shaft, and a voltage from which angle could be computed.

The oscillogram, Fig. 5, shows that for part of the time the motor is acting as a generator and is actually delivering power. From this oscillogram were measured power input and angular

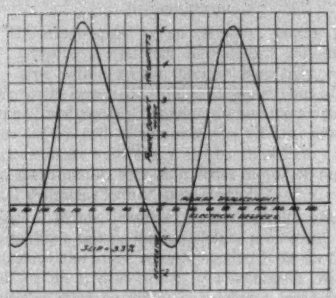

Fig. 3—Experimental Input-Angle Curve from Oscillogram (Fig. 5) of an Induction Motor With a Single-Phase Rotor Circuit. Slip = 3.3%

displacement. These are plotted against each other in Fig. 3. For the no-load region about zero degrees of angular displacement the damping tendency of the induced currents is such as to cause an increase in slip rather than retard its progress. This action is the source of self-oscillation.

The frequency of oscillation of a synchronous machine depends upon the inertias of the rotating machines and upon the synchronous torque-angle relations. This frequency depends upon what portion of the torque-angle curve is being used and upon

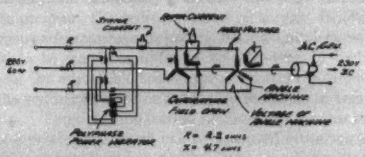

Fig. 4—Wiring Diagram for Oscillogram (Fig. 5) to show Instantaneous Variation of Input to a Polyphase Induction Motor with a Single-Phase Rotor

the amplitude of the oscillation. The angle-time curves are not sinusoidal if the variation is large.

The damping has very little effect on the frequency of oscillation. The damping, however, determines how fast transient oscillations are to decrease to zero or increase. Mr. Wagner shows very clearly how the energy per cycle from damping action is negative for the case where oscillations increase and positive for cases where the oscillations damp out. For sustained oscillations the energy per cycle of oscillation must be zero. That is if the damping is negative part of the time it must oscillate over enough degrees to include just enough positive damping to keep the total energy per cycle equal to zero.

If the machine oscillates about no-load it is important to notice that the maximum slip occurs at small angular displacements and so the negative damping effect, if any, will be accentuated. As the rotor swings into angular displacements which give positive damping the slip is much smaller and so the swing will need to be greater.

If the excitation is obtained from a constant voltage d-c. source, increasing the excitation has two effects: (a) It increases the frequency of oscillation because it stiffens the synchronizing torque thus influencing the manner in which the slip varies; (b) It causes the slip-torque characteristic to change because the external field resistance is decreased. A change in inertia also affects the range of self-oscillation because it causes a different variation of the slip by changing the period of oscillation.

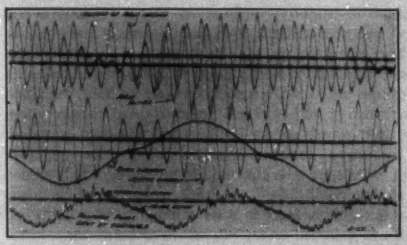

Fig. 5—Oscillogram showing Variation of Induction Motor (with Single-Phase Rotor) Input with Angular Displacement. Connections Fig. 4. Values from Oscillogram Fig. 3

As Mr. Wagner points out the practical elimination of the self-oscillation phenomena depends upon the use of quadrature or amortisseur windings which tend to make the rotor appear as a balanced polyphase winding to the stator.

**R. C. Bergvall:** Mr. Wagner's analysis of hunting phenomena of synchronous machines has been interesting to me on account of accidentally having had experience which checks his analysis. In 1923, Mr. Evans and I wrote a paper covering tests on a miniature transmission system on which hunting was actually produced by increasing the field current with relatively high resistance in the lines. These tests were made at no load and the severity of the hunting was found to increase with an increase in field current. The same machine was tested both with and without damper windings and it required more field current to produce the same degree of hunting with damp windings. A couple of years ago while experimenting with high-speed excitation applied to a 150-kv-a. synchronous condenser which was connected to a large bus through about 15 per cent reactance, severe enough hunting to cause the condenser to pull out of step with the system was produced by the application of five times normal field current. This should not indicate that there is much possibility in actual practise of producing hunting with high-speed excitation even though five times normal voltage is applied to the slip rings during emergencies, because this high voltage is only used to obtain a rapid build-up of the field current and is dropped down when the field current reaches the proper value.

**C. F. Wagner:** I am very greatly interested in Mr. Edgerton's point of view regarding this problem and look foward to the time when I can analyze his method in more detail.

The 1923 tests to which Mr. Bergvall referred illustrated quite clearly the effect of excitation in armature resistance. The machine under test had no dampers and had considerable resistance in the armature circuit. We found during the test that with low excitation the machine was stable and as the excitation was increased the machine became unstable. It was unfortunate at the time that we did not continue the tests to bring out the complete cycle as we might have done. We could have increased the load on the machine and again made the machine stable after which, by decreasing the excitation, the machine could again be made unstable. Decreasing the load would have made the machine stable again. This procedure would have illustrated quite plainly the effect of both load and excitation.

# The Synchronous-Repulsion Motor

## A Special Development for the Photophone

BY H. C. SPECHT*

Member, A. I. E. E.

*Synopsis.—This paper describes a motor which is developed specially for the operation of photophone machinery. The characteristics of this motor are analyzed and demonstrated by oscillograms. Since the well-known theory of synchronous and repulsion motor can easily be applied for this double motor, no equations are given. For illustration of the characteristics various oscillograms and test curves are given.*

* * * * *

### INTRODUCTION

THE exact speed of an ordinary motion picture projector is relatively unimportant provided it is kept within certain limits. Not only can the projector be operated at different speeds, but also it is possible, and usually desirable, to be able to vary the speed at the will of the operator. These simple requirements are quite easily met by an ordinary adjustable speed motor, such as a series motor or repulsion motor with some form of speed control.

Such a motor, however, would be quite unsuitable for driving a talking motion picture projector. In the first place, the sound record, whether it be on the film itself or on a disk driven synchronously with the projector, must be run at one definite speed in order that the musical sounds be reproduced at their correct pitch. Even more important than the fact that the record be run at the proper speed is the fact that once the speed is set, it must not be changed suddenly, for while only a few may have an ear for "absolute pitch," practically every one experiences a disagreeable sensation if the pitch suddenly changes. However, these requirements are easily met by a synchronous motor for the frequency of a modern power system is substantially constant.

However, a synchronous motor is not entirely satisfactory, for sometimes a theater will have mixed into its program, the ordinary silent pictures. In order to keep performances on schedule, these silent pictures must often be run at a different speed,—usually higher,—and the adjustable speed characteristics desirable with the ordinary projector are highly desirable in this case, too. Thus, the application requirement for this service is a driving set which can be operated either as a synchronous motor when desired, or as an adjustable speed motor which speeds up to, say, one and one-half times synchronous speed. These requirements could be met by a synchronous motor and an adjustable speed repulsion motor on the same shaft, but limited space requirements in a projection booth and simplicity in operation make it highly desirable to have this dual service provided by a single machine. Such a machine, which may well be styled a synchronous-repulsion motor, has been developed for this service and will be described in this paper.

Suppose two separate motors, a synchronous motor and a repulsion motor mechanically coupled in tandem to drive an external load, and further suppose both machines to be connected to a proper source of power, an external resistance or other speed-controlling means being provided for the repulsion motor. The repulsion motor can be used to bring the load and synchronous motor up to synchronous speed where the set will pull into step and operate in synchronism, provided of course that the torque of the repulsion motor at synchronous speed is less than the break-down torque of the synchronous machine as a generator plus the load torque, and more than the difference between the load torque and the breakdown torque of the synchronous machine as a motor. It is hardly necessary to mention that if the repulsion motor torque is less than the load torque, the synchronous machine will act as a synchronous motor, drawing power from the line and developing mechanical torque to assist the repulsion motor; if the repulsion motor develops torque in excess of that required by the load, the synchronous machine acts as a generator, absorbing the excess torque of the repulsion motor and feeding power back into the line.

However, a synchronous machine and a repulsion motor can be combined into a single machine using the same magnetic circuit and the same windings. Such a motor is shown diagrammatically in Fig. 1.

When the switch *g* is thrown to the upper position, the machine will operate as an ordinary repulsion motor, speed control being effected by means of the rheostat *h*, though of course this could be done by control of the line voltage by means of a transformer, resistance or reactance in the line circuit, etc. When the switch *g* is thrown to its lower position, the motor, for reasons to be explained later, will come up to speed, pull into step and operate as a synchronous motor. A flywheel is provided to prevent hunting during synchronous operation. Thus, the control of this motor is so simple that an inexperienced person can readily operate it.

*Consulting Engineer, Westinghouse Elec. & Mfg. Co., Springfield, Mass.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*



30-63

### Determination of the Size of Motor Required

As already mentioned, the projector must be run at speeds above synchronism. The power requirements at the highest speed fix the size of the motor for it can be designed as an ordinary repulsion motor, ample in size to carry this load at this speed as if there were no other considerations. The design of the motor being fixed, nothing remains to be determined except the direct current excitation necessary for satisfactory synchronous operation which can either be calculated or found experimentally.

### Characteristics of the Synchronous Repulsion Motor

The characteristics of this motor are somewhat different from those of any conventional single machine, but closely resemble the characteristics of two machines in tandem as previously described.

It is generally known that when the slip-rings of such

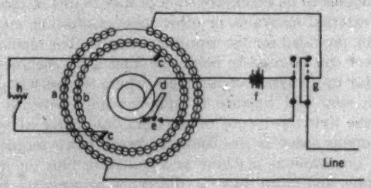


Fig. 1—Combined Synchronous and Repulsion Motor

a. Stator winding
b. Repulsion armature and d-c. exciting winding
c. Brushes on the commutator
d. Slip-rings and brushes on them
e. Centrifugal or automatic switch of some sort
f. Storage battery or other source of direct current
g. Double-pole, double-throw switch
h. Rheostat

a motor are short-circuited, the armature will run at synchronous speed under certain conditions. As the action of this motor is easier to understand if the latter be excited by direct current, let us consider this case. Since the direct current is introduced into the armature winding at two points which are fixed with respect to the armature, the direct current will set up magnetomotive forces tending to set up a flux which is fixed in space with respect to the armature; that is, the direct current sets up magnetic poles similar to the poles set up in a non-salient pole turbo alternator. These poles lock in with the rotating field set up by the repulsion motor and thus the armature rotates at synchronous speed.

Although the rotating member is excited from a direct current source, the exciting current and flux set up by the rotating member will pulsate strongly, mainly due to the high reaction of the a-c. field caused by the small air-gap, the low permeance of the laminated iron, and the distribution of the armature winding. The frequency of this pulsation is twice the line frequency, just as it is in an ordinary synchronous motor. A further pulsation is caused by a periodic short-circuiting of the slip-rings through the repulsion brushes. However, this effect is not very great since the contact resistance of the repulsion brushes is fairly high.

If the slip-rings be merely short-circuited, somewhat similar effects will be obtained, for the motor will run in synchronism with the line frequency under certain conditions and there will be pulsations of twice the line frequency in the slip-ring circuit due to having a winding rotating in the a-c. stator field. In this case, however, the effect is somewhat similar to that of a synchronous brake, as if the synchronous machine in the two-motor set used for illustration could not develop sufficient mechanical power and therefore could act only as a generator. The pull-out torque is approximately equal to the repulsion torque at synchronous speed. At light loads, the repulsion torque will overpower the synchronous braking torque, so to speak, and the machine will pull out of step and run above synchronous speed; if the slip-rings are merely short-circuited, the range of torques at which the motor will operate synchronously is rather limited and moreover the motor is unstable, tending to hunt, both of which facts make it unsuitable for photophone service. With d-c. excitation, the motor synchronizes more readily, is more stable over a larger range of loads and does not tend to hunt. Moreover with d-c. excitation, the pull-out torque will be approximately equal to the breakdown torque as a synchronous motor plus the repulsion torque at synchronous speed.

The d-c. excitation has another important effect, that of reducing the line current. The reasons for this are two-fold: First, the magnetizing component of the stator current is decreased, since the direct current sets up all or a portion of the revolving field which would normally be set up by the stator windings; that is, the repulsion motor, in effect, becomes armature-excited. Another effect, which becomes more important at light loads, is the reduction of the repulsion armature current. Perhaps an easy way to grasp the fundamental reason for this is to consider that at light loads, where the torque required by the load is less than the repulsion torque at synchronous speed, either the working flux or armature current must be less than it would be for repulsion operation at synchronous speed; the flux is essentially constant and therefore the repulsion armature current, and to some extent the stator current on account of reduced losses, is smaller than it would be if the motor were operating as a straight repulsion motor at synchronous speed.

The performance of this unusual motor can be figured from the theory of the synchronous motor and the theory of the repulsion motor. However, the many irregularities will make it difficult to obtain accurate results.

### Test Data

Various oscillograms were taken on one of the photophone motors built. Fig. 2 shows the direct-

current, line voltage, and stator current when the motor was run as a straight synchronous motor with the repulsion brushes lifted from the commutator. The oscillogram shows in a very pronounced manner the pulsation of the direct current and the distortion in the stator current. The applied a-c. voltage, of course, was not distorted.

FIG. 2—AS SYNCHRONOUS MOTOR

12 amperes, d-c. excitation, repulsion brushes lifted, load = 12 oz-ft., 1.55 stator amperes. Top curve, stator a-c. amperes; middle, the line voltage; bottom = exciting current

In Fig. 3 are shown oscillograms of the direct voltage, direct current, and the alternating current through the short-circuited repulsion brushes when the motor was run as a synchronous-repulsion motor. Due to the short-circuited repulsion brushes, the pulsation of the direct current is slightly greater than shown in Fig. 2. The rotor current, or current through the brushes, shows some distortion.

In Fig. 4 are shown oscillograms of the line voltage, and of the stator and rotor currents, with the same load

FIG. 3—AS REPULSION SYNCHRONOUS MOTOR

12 oz-ft. load, 220 volts, 1.6 amperes a-c., 1800 rev. per min. Top-d-c. volts across brushes of sling-rings; middle, d-c. amperes; bottom, rotor a-c. amperes.

conditions as in Fig. 3. It will be noted that the stator current is distorted much more than the alternating rotor current, and that this distortion is quite different from that in Fig. 2 where the machine is run as a synchronous motor. This difference, of course, is due to repulsion motor action. In addition to the distortion caused by the pulsation in the exciting current, the curves show smaller ripples which are probably caused by the teeth and commutator bars. In Fig. 5 are shown oscillograms taken with the motor operated as a plain repulsion motor delivering the same output torque at a higher speed.

Figs. 6 to 11 show a few test curves of the same motor which was a ¼-hp., 60-cycle, 220-volt, 4-pole, single-phase machine. In Fig. 6 is shown the no-load saturation curve, the motor being externally driven at 1800 rev. per min. In Fig. 7 are plotted the input amperes

FIG. 4—AS REPULSION SYNCHRONOUS MOTOR

12 oz-ft. load, 1800 rev. per min. Top curve, stator a-c. amperes; middle 220-volt line volts; bottom, rotor a-c. amperes

and watts at different exciting currents when the machine was operated at no-load as a straight synchronous motor. At 15 amperes excitation, the alternating current has assumed its lowest value, and this checks with Fig. 6 where at 15 amperes the generated voltage is 220; *i. e.*, equal to the line voltage.

Fig. 8 shows the results of a brake test as a synchronous motor with 12 amperes d-c. excitation, the repulsion brushes being lifted from the commutator. Fig. 9 shows the result of a brake test as a straight

FIG. 5—AS REPULSION MOTOR

12 oz-ft. load, 220 volts, 2230 rev. per min., 2.74 stator amperes and 112.2 rotor amperes. Top, stator amperes; middle, line volts; bottom, rotor amperes

repulsion motor and Fig. 10 the result of a brake test as a synchronous-repulsion motor with 12 amperes excitation. Finally, Fig. 11 shows the results of a brake test as a synchronous-repulsion motor without d-c. excitation, the leads of the collector rings being short-circuited.

In these curves, the efficiency and watt input do not include the watts supplied from the d-c. source for excitation. The measured pull-out torque as a synchronous motor was found to be 20 oz.-ft. and the repulsion motor torque at 1800 rev. per min. was 26 oz.

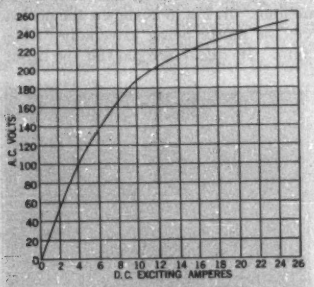


Fig. 6—Saturation Curve at 1800 Rev. per Min.

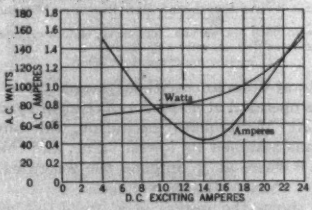


Fig. F—Saturation as a Synchronous Motor with Brushes Up

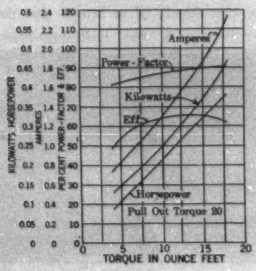


Fig. 8—Brake Test as Synchronous Motor at 1800 Rev. per Min., 12 Amperes Direct Current

ft. These two torques added together give 46 oz-ft., and it was noted from test that the pull-out torque as a synchronous-repulsion motor was 50 oz-ft. This small difference may have been due partly to errors in test, for it is difficult to obtain accurate pull-out torque readings on a motor with a brake-arm.

Further, it will be noted that under a heavy load, the performance as a synchronous-repulsion motor is the best; under a light load the efficiency as a synchronous motor is better because there are no brush friction losses nor losses in coils short-circuited by brushes as the latter are raised from the commutator. A brake test as a synchronous motor was also taken with the repulsion brushes down on the commutator and in this test,

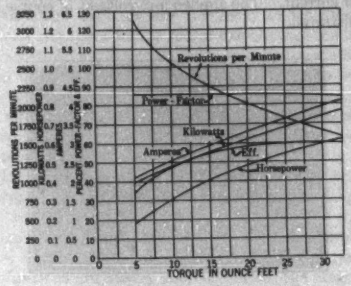


Fig. 9—Brake Test as Repulsion Moror

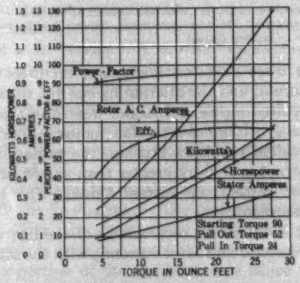


Fig. 10—Brake Test as Synchronous Repulsion Motor at 1800-Rev. per Min., 12 Amperes Direct Cuentrr

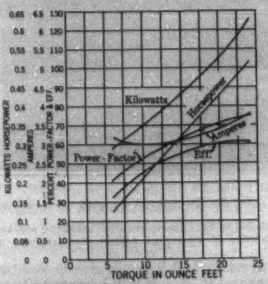


Fig. 11—Brake Test at 1800-Rev. per min., as Synchronous-Repulsion Motor without D-C. Excitation

the watt input at lighter loads were as high as on the synchronous-repulsion motor test.

The pull-in torque as a synchronous-repulsion motor was observed to be 24 oz-ft. With d-c. excitation, the speed was very steady when in synchronous operation from no-load up to about pull-out, whereas, when the

d-c. leads were short-circuited, the motor fell out of step at either 6 oz-ft. or 25 oz-ft.; *i. e.*, if the load torque were less than 6 oz-ft., the motor would pull out and run above synchronous speed, and at loads in excess of 25 oz-ft., the motor would pull out and run below synchronous speed. This demonstration shows quite clearly that without d-c. excitation, the machine cannot carry such a high overload torque as a synchronous motor as it can with d-c. excitation. Moreover, without d-c. excitation, hunting was quite noticeable. These conditions could have been improved somewhat by inserting some resistance between the repulsion brushes. Furthermore, it was observed that the commutator bars to which the slip-rings were connected, had a tendency to burn.

## Conclusion

This photophone motor is very simple in operation, synchronizes readily at all loads, and can carry considerable overload. Furthermore, it is quite efficient and has a particularly good power factor. It is therefore quite satisfactory for photophone drives.

The author wishes to acknowledge gratefully the valuable assistance rendered him by Messrs. H. E. Newhouse and C. G. Veinott in performing the tests described and in preparing this paper.

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## Discussion

**S. Newman, Jr.:** The Electric Specialty Company of Stamford, Connecticut, has recently developed a motor which combines the features of the repulsion type and the salient pole synchronous type of motor. This motor does not have any variable speed features and does not require any d-c. excitation. It is used for talking motion picture work or any application requiring synchronous operation where a small load is always connected to the motor. The small load is necessary because between no load and about 15 per cent of full load the motor runs above synchronous speed. From 15 per cent to 140 per cent of full load synchronous speed is maintained. The load at which slipping occurs, both over and under synchronism, can be controlled by shifting the position of the brushes.

The motor has very desirable characteristics as far as power factor and efficiency are concerned. The ¼ hp. and ½ hp. motors of the repulsion synchronous type have an apparent efficiency, *i. e.*, product of power factor and efficiency, of about 43 per cent as compared with about 20 per cent for split-phase salient pole synchronous motors of the same ratings.

The starting current on the repulsion synchronous motor of ¼ hp. is less than 15 amperes as compared with about 40 amperes for the split-phase type. This feature is especially important since the N. E. L. A. requirements allow 20 amperes starting current for motors of this size.

**R. E. Hellmund:** Mr. Specht has described in his paper a very interesting motor combination which is well suited for the particular application and possibly for others where similar requirements have to be met. The only drawback of this arrangement is that common to all synchronous motor arrangements, namely, the necessity for a source of d-c. power for the field excitation. For the size of motor involved, a battery as shown in Fig. 1 would serve the purpose, but it necessitates either the periodic replacement of dry batteries or means for charging a storage battery. It would therefore be much more desirable to use a copper-oxide rectifier, if the d-c. power requirements could be kept low enough to permit of the economical use of such a rectifier. In so far as the torque supplied by the motor during its synchronous repulsion operation is much in excess of the requirements, it would seem that operation at reduced voltage would give sufficient torque and at the same time permit a considerable reduction in the d-c. power requirements.

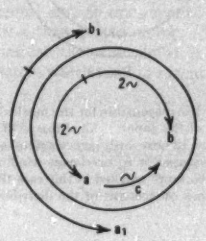


Fig. 1

The paper shows a number of oscillograms for the motor in its various operating conditions. Fig. 2, applying to the straight synchronous operation, indicates in particular a very marked third harmonic in the primary current curve. The reason for this is that the d-c. excited rotor represents at the same time a single-phase a-c. circuit. The secondary carries the double-frequency current common to motors with single-phase primaries. Since the secondary is also single-phase, the magnetomotive forces set up by the double-frequency currents can be represented in the usual way by two polyphase magnetomotive forces rotating in opposite directions relative to the rotor at double-frequency speed, as indicated by the arrows (*a*) and (*b*) in Fig. 1 herewith. Since the rotor has a mechanical synchronous speed corresponding to the line frequency, as indicated by the arrow (*c*), the

speed of the rotating field ($a$) with regard to the stator is increased to three times synchronous speed, as indicated by the arrow ($a_1$), and the speed of the rotating field ($b$) with regard to the stator is reduced to the line frequency, as indicated by the arrow

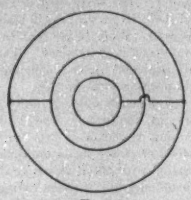

Fig. 2

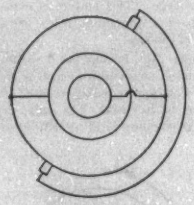

Fig. 3

($b_1$). The field ($a_1$) is responsible for the marked third harmonic indicated in Fig. 2 of the paper. All of this is, of course, qualitatively the same as in any ordinary single-phase synchronous machine without damper or squirrel-cage windings in the rotor. It may, however, be more marked in this case than in the usual salient-pole machines on account of the distributed windings in the rotor and the small air-gap, both of which tend to reduce the leakage coefficient and therefore the tendency of the leakage reactance to smooth out the higher harmonics.

As soon as a change is made from the pure synchronous operation to the synchronous repulsion operation, the short-circuited commutator brushes establish a second circuit through the rotor as shown in Fig. 3 herewith, and therefore a polyphase condition for all rotor positions except those for which the slip-ring taps happen to coincide with the commutator brush position. As a consequence, the backwardly rotating double-frequency magnetomotive force in the rotor is materially reduced, and so the third harmonic in the primary current of Fig. 4 is much less noticeable.

**H. C. Specht:** The synchronous repulsion motor mentioned by Mr. Newman is an ordinary repulsion motor with the exception that the periphery of the rotor possesses cutouts in the same way as is the general practise on synchronous induction motors. These cutouts are in number equal to the number of poles and the remaining projections make the salient poles. Such synchronous repulsion motors have occasionally been used for special applications for which a high starting and pull-in torque is required. The motor stays in synchronism very well at certain load and considerable overload. However, at light load, *i. e.*, at higher than synchronous speed it has a tendency to run out of step. For the application of photophone drive where the motor has to run occasionally at higher speed with greater load, the ordinary synchronous replusion motor is not adaptable.

Mr. Hellmund has mentioned the use of a rectifier for the d-c. supply, and this is certainly very desirable and there is no objection to the use of it. He also called attention to the fact that the motor I have described has considerable torque in excess when operated as synchronous repulsion motor. As a matter of fact this has been eliminated on the later motors, by a smaller d-c. excitation and by inserting a choke coil in the line supply circuit in order to reduce the applied a-c. voltage when operating as synchronous repulsion motor. By proper arrangement, the simple switching with the double throw switch is not affected. This scheme has naturally improved the performance of the motor.

# Synchronous Motor Effects in Induction Machines[1]

BY E. E. DREESE[2]

*Synopsis.—Many induction motors do not have the smooth speed torque curves which are to be expected from elementary theory. Many motors at no load show a tendency to run at some speed way below that normally expected. This is sometimes called "sub-synchronous" speed, or the motor is said to be "crawling." In the present paper one cause of this phenomenon is explained. It is found that certain combinations of phases, rotor slots, and poles cause the motor to run as a synchronous motor at some intermediate speed between zero and normal no-load induction motor speed. This effect has been christened the "synchronous motor effect" in induction machines and is shown to be due to the locking of harmonic fields, generated by the stator winding with similar harmonic fields, generated by the rotor windings. The method of avoiding this trouble by the proper selection of the number of rotor slots is given.*

FROM time to time those responsible for the design of induction motors are disappointed when a new design proves to be noisy or develops what is called a sub-synchronous speed. The present paper will present a new cause for this phenomenon which will explain some cases of sub-synchronous speeds hitherto not understood.

The speed-torque characteristic of the classical

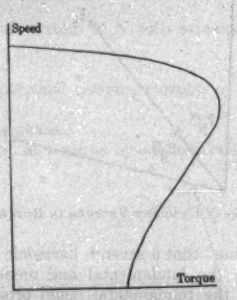


FIG. 1—THE SPEED-TORQUE CURVE OF AN ORDINARY INDUCTION MOTOR AS USUALLY DRAWN

induction motor is a smooth curve usually shown as in Fig. 1.

Various investigators have found from time to time that seldom (if ever) is the actual curve smooth as shown in Fig. 1. They find instead curves more like Fig. 2.

Still more careful investigation reveals that the curves are actually very "rough" near zero speed and Fig. 3 more nearly represents the true performance diagram.

In all the above curves the torque is shown as a single-valued function of the speed. This paper will show that in some cases the torque *is not* such a single-valued function and that none of the curves, such as the above, represents the true state of affairs.

The most plausible explanations advanced for these rough curves ascribe them to the presence of harmonics in the flux wave of the machine. As an example of this, consider a machine which has a prominent seventh harmonic in its flux wave. This harmonic, if due to the stator winding, will be revolving in the same direction as the fundamental and at one-seventh of the fundamental speed in a three-phase motor. It is then illuminating to consider that the motor is really a composite of two motors which tend to run at full speed and

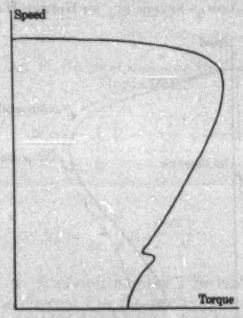


FIG. 2—THE SPEED-TORQUE CURVE SHOWING SUBSYNCHRONOUS "HOOK" DUE TO INDUCTION MOTOR EFFECT OF A HARMONIC

at one-seventh speed respectively. This might be shown as in Fig. 4.

This is a plausible explanation of some of the sub-synchronous speeds observed and without doubt the presence of harmonics will produce effects as shown in this figure. It will also serve to explain the roughness of the curves in the lower speeds because of the presence of higher harmonics. This effect will henceforth be called the "induction motor effect" of the harmonics.

1. This paper was submitted to the University of Michigan in partial fulfilment of the requirements for the E. E. Degree.

2. Chairman, Electrical Engg. Dept., The Ohio State University, Columbus, Ohio.

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30-62

From this point the development will be chronological as the calculations and experiments were made.

The work started on a squirrel-cage induction motor wound for the three-phase four-pole operation. The rotor had 28 bars. The motor showed a tendency to develop zero torque at one-seventh speed. The conclusion was therefore jumped at that this sub-synchronous speed was due to the "induction motor effect" of the seventh harmonic of the stator. Working with

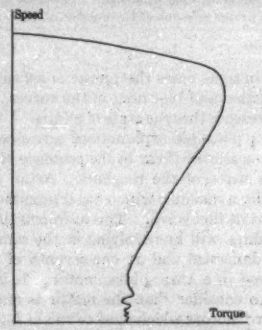


FIG. 3—SPEED-TORQUE CURVE SHOWING ROUGHNESS USUALLY FOUND IN LOWER SPEEDS DUE TO HIGHER HARMONICS

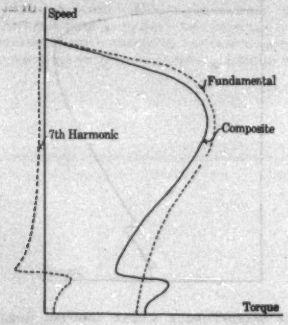


FIG. 4—SHOWING THE INDUCTION MOTOR EFFECT OF A FORWARD ROTATING 7TH HARMONIC

this in mind the reasonableness of this assumption was checked by making a mathematical check on the magnitude of the seventh harmonic in this particular motor by the use of Fourier's methods. Since these methods are well known they will not be gone into here and results only will be stated.

The stator in the present case had 24 slots. For three-phase and four poles this makes two slots per phase per pole. Now for a full pitch winding of one slot per pole per phase the relative magnitudes of the fundamental and seventh harmonic magnetomotive-forces in the stator are:

| fundamental | 7th harmonic |
|---|---|
| 1 | $\frac{1}{7} = 0.143$ |

The relative magnitudes for two slots per phase per pole are:

| fundamental | 7th harmonic |
|---|---|
| 1 | 0.038 |

In addition the coils had been short spanned one slot and the two sides of a coil were 150 electrical degrees apart so that the relative magnitudes as they actually existed in the stator m. m. f. were

| fundamental | 7th harmonic |
|---|---|
| 1 | 0.010 |

As the result of this calculation it did not seem reason-

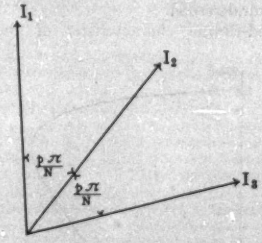


FIG. 5—$N$ CURRENT VECTORS IN ROTOR RODS

able to "assume" that a seventh harmonic of 1/100 the magnitude of the fundamental and revolving at 1/7 the speed of the fundamental could produce enough torque by the induction motor effect to overcome the torque of the fundamental at 1/7 speed.

Attention was then turned to the mathematical analysis of the rotor harmonics and after some false starts the magnitude, order, and speed of the harmonics originating in the rotor were worked out. The analysis follows.

## ROTOR HARMONICS

Consider a squirrel-cage rotor of $N$ bars being energized by a sinusoidal rotating field of $p$ poles. The currents in the rods will then be $\frac{p\pi}{N}$ radians apart and the vector diagram of currents would be as shown in Fig. 5, in which $I_1$, $I_2$, and $I_3$ designate the currents in rods numbered 1, 2, and 3 respectively. For the purpose of analysis let the system of rods be replaced by $N$ single-turn coils spanning 1 rotor slot pitch. Let the currents in the coils be $i_1$, $i_2$, and $i_3$ respectively (see Fig. 6). For the vector relations see Fig. 7.

It can then be seen that the actual rotor of $N$ bars

carrying currents of $I$ magnitude $\frac{p\pi}{N}$ radians apart may be replaced by a rotor of $N$ single-turn coils carrying currents of magnitude $i$ and $\frac{p\pi}{N}$ radians apart provided,

$$I = 2\,i \sin \frac{p\,\pi}{2\,N}$$

It is now necessary to determine the m. m. f. waves

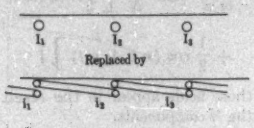


FIG. 6—SHOWING ROTOR RODS REPLACED BY COILS

set up by this system of $N$ coils separated by $\frac{2\,\pi}{N}$ radians in space and carrying currents $\frac{p\,\pi}{N}$ radians apart in time phase.

First the m. m. f. set up by one such coil will be found.

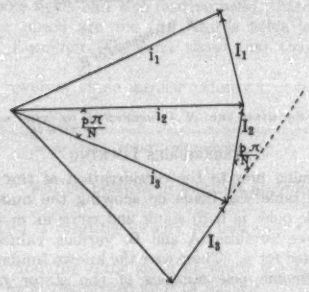


FIG. 7—SHOWING ROD CURRENTS REPLACED BY COIL CURRENTS

$I_1 = L_1 - L_2$ $\qquad$ $I_2 = L_2 - L_3$ etc.

The form of the m. m. f. wave set up by one such coil due to an instantaneous current $i$ is shown in Fig. 8.

The m. m. f. due to $i$ will be divided between the two portions of the magnetic circuit in the ratio

$$\frac{\frac{2\,\pi}{N}}{2\,\pi - \frac{2\,\pi}{N}} = \frac{1}{N-1}$$

the high portion will be $\frac{N-1}{N}\,i$ and the low portion $-\frac{1}{N}\,i$. The space wave-shape shown in Fig. 8 can be expressed as a trigonometric series,

$$H = \frac{1}{2}\,b_0 + b_1 \cos\theta + b_2 \cos 2\,\theta + \ldots b_m \cos m\,\theta + \ldots$$

in which $b_0$ is obviously zero since the positive areas in Fig. 8 equal the negative areas. $m$ is any positive integer. From the method of Fourier

$$b_m = \frac{2}{\pi}\int_0^{\frac{\pi}{N}} \left(\frac{N-1}{N}\,i \cos m\,\theta\right) d\,\theta$$

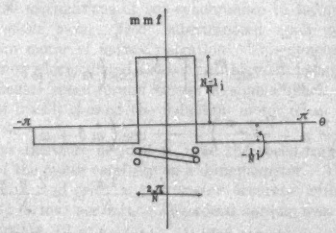


FIG. 8—M. M. F. DISTRIBUTION DUE TO CURRENTS IN ONE ROTOR COIL

$$+\frac{2}{\pi}\int_{\frac{\pi}{N}}^{\pi} \left(-\frac{1}{N}\,i \cos m\,\theta\right) d\,\theta$$

whence

$$b_m = \frac{2\,i}{m\,\pi} \sin \frac{m\,\pi}{N}$$

If the m. m. f. of coil number 1 be referred to as $H_1$ in which the current $i$ is the instantaneous value of $i_1$ $i = \sqrt{2}\,i_1 \cos \omega\,t$ (here $i_1$ is the magnitude only)

$$H_1 = \sum b_m \cos m\,\theta$$

$$= \sum \frac{2\,\sqrt{2}\,i_1}{m\,\pi} \sin \frac{m\,\pi}{N} \,.\, \cos m\,\theta \,.\, \cos \omega\,t$$

$$= \sum \frac{2\,\sqrt{2}\,i_1}{m\,\pi} \sin \frac{m\,\pi}{N} \left[\frac{1}{2} \cos (m\,\theta - \omega\,t) + \frac{1}{2} \cos (m\,\theta + \omega\,t)\right]$$

Thus each coil produces backward and forward moving waves since expressions of the type

$$\cos (m\,\theta - \omega\,t)$$

represent traveling waves of $2\,m$ poles.

Waves of the type $\cos(m\,\theta - \omega\,t)$ will be called forward rotating and of the type $\cos(m\,\theta + \omega\,t)$ will be called backward rotating. In like manner the m. m. f. wave of the second and succeeding coils will be, $\left(\text{remembering that coils are separated by } \frac{2\,\pi}{N}\right.$ and carry currents $\left.\frac{p\,\pi}{N} \text{ apart}\right)$:

$$H_2 = \frac{2\sqrt{2}\,i_2}{m\,\pi}\sin\frac{m\,\pi}{N}\left[\frac{1}{2}\cos\left(m\,\theta - \omega\,t + \frac{2\,\pi}{N}m - \frac{p\,\pi}{N}\right) + \frac{1}{2}\cos\left(m\,\theta + \omega\,t + \frac{2\,\pi}{N}m + \frac{p\,\pi}{N}\right)\right]$$

and

$$H_3 = \frac{2\sqrt{2}\,i_3}{m\,\pi}\sin\frac{m\,\pi}{N}\left[\frac{1}{2}\cos\left(m\,\theta - \omega\,t + \frac{4\,\pi}{N}m - \frac{2\,p\,\pi}{N}\right) + \frac{1}{2}\cos\left(m\,\theta + \omega\,t + \frac{4\,\pi}{N}m + \frac{2\,p\,\pi}{N}\right)\right]$$

The resultant field is obtained by superposing m. m. fs. $H_1$ to $H_N$ inclusive. Thus the rotating field of $2\,m$ poles consists of $N$ superimposed fields of equal magnitude since

$$i_1 = i_2 = i_3 = \ldots = i_n$$

For forward rotating fields these $N$ superimposed fields of equal magnitude are arrayed with a phase difference between adjacent fields of

$$\frac{2\,\pi\,m}{N} - \frac{p\,\pi}{N} \text{ radians (see Fig. 9)}$$

The total angle for the $N$ vector fields is

$$N\left(\frac{2\,\pi\,m}{N} - \frac{p\,\pi}{N}\right) = 2\,\pi\,m - p\,\pi$$

Since $m$ is always an integer and $p$ (the number of inducing poles) is always an even number, the pencil of vectors is always spread through an integral number of complete revolutions and the sum is therefore zero—with one exception.

That exception is the case when

$$\frac{2\,\pi\,m}{N} - \frac{p\,\pi}{N} = 2\,K\,\pi$$

where $K$ is any positive or negative integer including zero. Hence forward rotating m. m. f. of $2\,m$ poles are produced by the rotor if

$$2\,m - p = 2\,K\,N$$

and

$$2\,m = 2\,K\,N + p \qquad \textbf{(A)}$$

In like manner the backward rotating m. m. fs. form pencils, whose adjacent fields are separated by

$$\frac{2\,\pi\,m}{N} + \frac{p\,\pi}{N} \quad \text{Radians}$$

and in like manner, after the superposition, all those backward rotating fields vanish except those for which

$$2\,m = 2\,K\,N - p \qquad \textbf{(B)}$$

The magnitude of the rotor harmonic of the $2\,m$ poles is

$$H_m = N\left(\frac{2\sqrt{2}\,i}{m\,\pi}\sin\frac{m\,\pi}{N}\left[\frac{1}{2}\cos(m\,\theta - \omega\,t) + \frac{1}{2}\cos(m\,\theta + \omega\,t)\right]\right) \qquad \textbf{(C)}$$

since only those fields appear in the result which are in phase in the $N$ components.

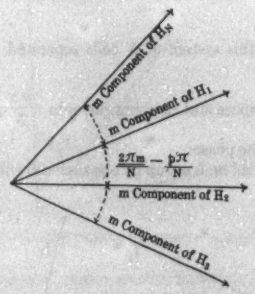


Fig. 9—Showing the $N$ Components of the $m$ Field

## Synchronous Locking

Returning now to the consideration of the 28-slot rotor, a table was made up showing the number of harmonic poles in both stator and rotor m. m. fs. In the above formulas, **A** and **B**, various values were substituted for $p$. These were the known fundamental and harmonic pole numbers of the stator m. m. f. In the present three-phase four-pole case, $p$ may be 4, 20, 28, 44, 52, etc., for the fundamental fifth, seventh, eleventh, and thirteenth harmonics respectively. Then upon substituting various values for $K$, the various rotor harmonic pole numbers were found. These are shown in Table I.

TABLE I
28 SLOT ROTOR HARMONICS
Stator Poles $P$

| 4 | | 20 | | 28 | | 44 | | 52 | | 68 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| For. | Back. | For. | Back. | For. | Back. | For. | Back. | For. | Back. | For. | Back. |
| 4 | 52 | 20 | 36 | 28 | 28 | 44 | 12 | 52 | 4 | 68 | 44 |
| 60 | 108 | 76 | 92 | 84 | 84 | 100 | 68 | 108 | 60 | 124 | 100 |
| 116 | 164 | 132 | 148 | 140 | 140 | 156 | 114 | 164 | 116 | 180 | 156 |
| | | | | | | | | | | 12 | |

Soon after the above table was made up it was noticed that the four-pole stator field acting upon the 28-slot rotor produces a 52-pole backward rotating rotor harmonic (the 13th). There is also present in the stator a forward rotating 13th harmonic of the 52 poles. The question naturally arose as to how do these independently produced 52-pole fields react upon each other.

It was only a step to regard the 52-pole rotor field as the revolving field of a synchronous machine getting its excitation from the stator fundamental flux instead of from a d-c. source.

The next natural step was to find at what rotor speed

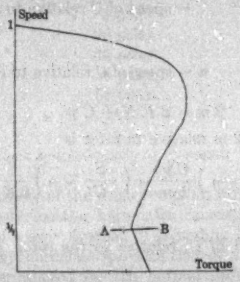


Fig. 10—Showing the Constant Speed-Torque Curve due to Synchronous Motor Effect

these 52-pole fields had zero relative speed, that is, at what rotor speed are the two 52-pole fields locked together. Equation (**C**) above shows that the $2m$-pole field revolves at an angular velocity $\frac{\omega}{m}$ *relative to the rotor*. Where

$$\omega = 2\pi \text{ (rotor frequency)}$$

Now $\frac{\omega}{m}$ will be positive or negative according as the $2m$ field is rotating forward or backward *relative to the rotor*.

Now to find the rotor speed at which the 52-pole fields will lock, the procedure is as follows:

Let $S$ = synchronous speed of stator 4-pole fundamental flux relative to the stator

$n$ = speed of rotor relative to the stator

Then $\frac{S}{13}$ = speed of 52-pole stator harmonic relative to the stator

And $S - n$ = speed of fundamental stator flux relative to the rotor

Also $S - n$ = speed of fundamental rotor flux relative to the rotor

$-\frac{S-n}{13}$ = speed of 52-pole rotor harmonic relative to the rotor

$-\frac{(S-n)}{13} + n$ = speed of 52-pole rotor harmonic relative to the stator

If the speeds of the two 52-pole fields are now set equal to each other

$$\frac{S}{13} = -\frac{(S-n)}{13} + n$$

$$\frac{n}{S} = \frac{1}{7}$$

*The two thirteenth harmonics lock at* $\frac{1}{7}$ *speed which is the observed sub-synchronous speed with the 28-slot 4-pole rotor.* If this effect accounted for the observed performance of this motor is would differ from previously published explanations of sub-synchronism in being a *"synchronous motor effect"* superimposed upon the induction motor of normal operation. This synchronous motor effect suffered a setback at this point because experimental speed-torque curves available (such as those of Stiehl) showed the induction motor effect as in Fig. 4.

It was therefore decided to take the speed-torque curve of the motor carefully on a dynamometer. The speed was read with a tachometer accurate within probably 5 rev. per min. The speed torque was as shown in Fig. 10.

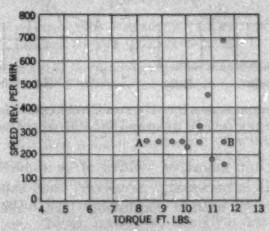


Fig. 11—Showing Actual Test Points at Constant Speed due to Synchronous Motor Effect

Within the limits of accuracy of the tachometer *there was* a synchronous motor effect evidenced here. Some representative points in the neighborhood of $\frac{1}{7}$ speed (257 rev. per min.) are shown in Fig. 11. *It appeared to be possible to vary the torque by 32 per cent at 257 rev. per min. without changing the speed.*

To make certain, the motor shaft was fitted with a stroboscopic disk with seven marks spaced at equal distances about the circumference. This was viewed through another disk with a slit in it revolving so as to give 1800 exposures per minute. See Fig. 12.

With the stroboscope the flat portion of the speed-

torque curve was observed to be *absolutely flat*. The motor was running as a synchronous motor superimposed on an induction motor. The only effect on the stationary image of the seven-point disk as the load was varied was that a slight shift in the coupling angle was observed, as in a pure synchronous motor. As the torque approached points $A$ or $B$ in Fig. 10, the rotor would show hunting and would vibrate erratically and then drop out of step. The proof of the existence of synchronous motor effect was definitely established thereby.

At this point some definite experimental proof of the locking of the 13th harmonics was sought and a check-up on the mathematical work showed that not only were the 13 harmonics locking but a *whole infinite series of harmonics was locking at* $\frac{1}{7}$ *speed.*

This is shown as follows. In formulas **A** and **B** where

$$2m = 2KN + p \qquad \textbf{(A)}$$

and

$$2m = 2KN - p \qquad \textbf{(B)}$$

negative values of $m$ have been inadmissible. A little study will reveal that the expression

$$2m = 2KN + p$$

will cover both Equations (**A**) and (**B**) if it be further

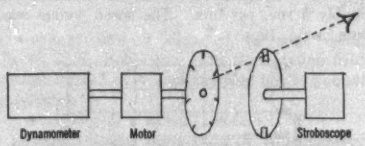


FIG. 12—STROBOSCOPE SET-UP FOR CHECKING THE CONSTANCY OF SPEED IN THE SYNCHRONOUS MOTOR EFFECT

stipulated that negative values of $m$ denote negative rotation. It is necessary, however, that this new convention should satisfy Equation (**C**). We see that Equation (**C**) is satisfied since $\frac{1}{m}\sin\frac{m\pi}{N}$ is not changed by a change in the sign of $m$. The only change is in the direction of rotation as shown in $\frac{1}{2}\cos(m\theta - \omega t)$.

## PROOF OF EXISTENCE OF INFINITE NUMBER OF LOCKING HARMONICS

Let $C$ be the stator harmonic which is acting on the rotor.

If $C$ is negative it denotes negative rotation.

Now $$2m = 2KN + cp$$

If $C_1$ is any other stator harmonic with which $2m$ locks then

$$2m = \pm C_1 p$$

$$\pm C_1 p = 2KN + cp$$

$$\pm C_1 - C = \frac{2KN}{p} \qquad \textbf{(D)}$$

If any pair of harmonics of the stator can satisfy Equation (**D**) there will be stator and rotor harmonics of the same number of poles. Another condition is necessary for the synchronous motor effect; the relative speeds of the stator and rotor equi-polar fields must be zero.

$$\frac{S}{C} = \text{speed of } C \text{ relative to stator}$$

$$\frac{S}{C} - n = \text{speed of } C \text{ relative to rotor}$$

Now $$2m = 2KN + Cp$$

Speed of $2m$ relative to rotor is

$$\left(\frac{S}{C} - n\right)\frac{Cp}{2m} = \left(\frac{S}{C} - n\right)\frac{Cp}{2KN + Cp}$$

The speed of $C_1$ relative to the rotor $= \frac{S}{C_1} - n$.

Equating these speeds

$$\frac{S}{C_1} - n = \left(\frac{S}{C} - n\right)\frac{Cp}{2KN + cCp} \qquad \textbf{(12)}$$

$$\frac{S}{C_1} - n = \left(\frac{S}{C} - n\right)\frac{Cp}{\pm C_1 p}$$

$$\frac{S}{C_1} - n = \frac{S - nC}{\pm C_1}$$

Using (+) signs $$-n = -n\frac{C}{C_1}$$

Whence $C = C_1$. This gives the ordinary induction motor effect.

Using (−) signs $$2\frac{S}{C_1} = n\left(\frac{C}{C_1} + 1\right)$$

$$\frac{n}{S} = \frac{2}{C + C_1} \qquad \textbf{(E)}$$

This gives the synchronous motor effect and we use only (−) sign of **D**.

Therefore $$C + C_1 = -\frac{2KN}{p} \qquad \textbf{(F)}$$

If the stator harmonic numbers satisfy (**F**) there will be a synchronous motor effect at $\frac{2}{C + C_1}$ speed.

There will be as many synchronous motor effects at

$\frac{2}{C + C_1}$ speed as there are pairs of values for $C$ and $C_1$ which will satisfy (F). The number is infinite. As an example, take the 28 slot case considered here. The pair of values already considered were

$$C = 1 \text{ and } C_1 = 13$$

Other pairs are

| | | | | | | |
|---|---|---|---|---|---|---|
| $C$ | 13 | 19 | 25 | 31 | 37 | etc. |
| $C_1$ | 1 | −5 | −11 | −17 | −23 | |

We thus see that there is an infinite series of locking pole numbers. The members of this series are

4 poles
20 poles
44 poles
56 poles
68 poles,
etc.

*and they all lock synchronously at* $\frac{1}{7}$ *speed.*

The discovery of the existence of an infinite series of synchronously locking harmonics caused a change in the point of view. Instead of regarding the operation at the sub-synchronous speed as that of a synchronous motor superimposed on the normal induction motor it is now necessary to consider the effect as due to *an infinite series* of synchronous motors superimposed upon the normal induction motor, all of these motors having the same synchronous speed. Some conception of what is going on may be obtained by imagining an induction motor and an infinite number of synchronous motors connected to the same shaft.

All experiments conducted up to this point had been with the use of a skewed rotor. Various rotors with different skews were then tried and it was found that the length of the synchronous portion of the speed-torque curves was very sensitive to skew, (see $A - B$, Fig. 10). With a reduction in skew the length $A - B$ increased until the point $A$ crossed to the negative torque side of the speed axis. Under this condition the motor, when started under its own power, would not come up to full speed but would run at $\frac{1}{7}$ speed when started.

It was therefore decided that a rotor built in such a way that the skew could be *varied* should definitely establish whether or not the synchronous motor effect was due to one pair of harmonics or to a plurality of pairs. This can be shown by a little consideration of the nature of skewing.

## Effect of Skew

If a rotor were skewed through two complete pole pitches there would be no voltage generated in the rod and as a consequence the rotor would act as though it had no winding for that particular pole pitch.

In an analogous manner it is possible to "skew out" any particular harmonic by the single expedient of skewing the rotor rod through two (or any multiple of two) poles of that harmonic. The word "analogous" is used advisedly because it is at this point where another difference between induction motor effect and synchronous motor effect is shown.

Suppose, for example, that the rotor were skewed to skew out the 13th harmonic. The skew would be through two poles of the 52-pole field. This amounts to 2/52 of the periphery of the rotor. Now with the rotor so skewed the rotor is inactive to the 13th harmonic of the stator and all rotor harmonics of which the 13th

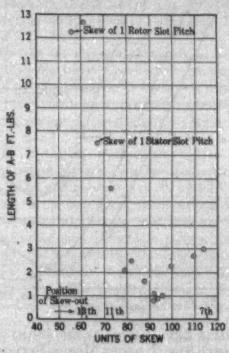


Fig. 13—Showing the Effect of Skew on the Torque Length of the Constant-Speed Line

(Note. Accuracy of ordinates not greater than 0.5 ft. lb. Accuracy of units of skew within 2 units)

of the stator is the parent, ($C$) will not appear. But the rotor still has a 13th harmonic of which the stator fundamental is the parent, (see Table I). So there still exists a 13th stator harmonic rotating forward and the 13th rotor harmonic rotating backward in reference to the rotor. Now, however, the 13th harmonic of the rotor is skewed through a double pole pitch. It is just the same as if a salient pole synchronous machine had the salient poles skewed through a double pole pitch. It is obvious that under this condition no torque can be exerted between the two fields; they cannot lock.

So with the rotor with variable skew it was only necessary to plot the length of the synchronous portion $A - B$ of the speed-torque against skew. If the synchronous motor effect were due to only one pair of harmonics the length of $A - B$ must go to zero when that particular harmonic was skewed out. The results of this experiment are shown in Fig. 13.

The result in Fig. 13 shows that no single harmonic is causing the synchronous torque. The minimum length for $A - B$ occurs between the points where the 11th and 7th harmonics are skewed out. There is indeed

*qualitative* proof here that there are several synchronous motor effects overlaid. This is shown as follows.

Consider the theoretical effect of skew on each harmonic. As the skew is varied the length of *that portion* of $A - B$ due to a particular harmonic should vary as an attenuated sine wave. If such waves are superimposed as in Fig. 14, it is seen that the composite curve may look very much like the actual curve in Fig. 13. The 7th harmonic is neglected because of its low magnitude.

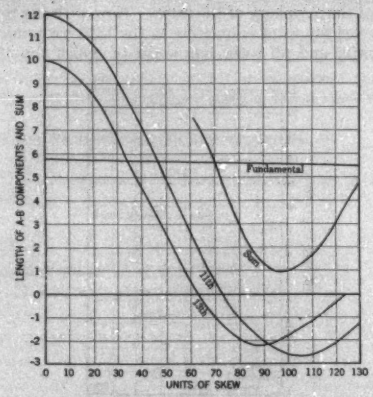


FIG. 14—POSSIBLE EXPLANATION OF FIG. 13 INVOLVING SUPERIMPOSED SYNCHRONOUS MOTOR EFFECTS

Equations for ordinates are of forms:

$A - B = \frac{\beta}{\alpha} \sin \frac{\alpha}{2}$ where $\beta$ = a constant and $\alpha$ = angle of skew

## DESIGNING TO AVOID SYNCHRONOUS MOTOR EFFECTS

It remains to predict the synchronous motor effect for other motors. It may be predicted from Equation (F).

$$C + C_1 = -\frac{2KN}{p}$$

Now in a three-phase motor

$$C = 6h + 1$$

where $h$ is any integer and negative values of $C$ denote negative rotation as before. Also

$$C_1 = 6h_1 + 1$$

and $$C + C_1 = 6(h + h_1) + 2 = -\frac{2KN}{p}$$

Replacing $h + h_1$ by $L$, any integer, and dividing by 2

$$3L + 1 = -\frac{KN}{p}$$

and $$\frac{N}{p} = -\frac{3L+1}{K} \qquad \text{(G)}$$

The above formula gives the number of rotor bars per pole to be avoided to eliminate the synchronous motor effect. In this formula $L$ and $K$ are any integers. A few values are given in Tables II and III.

VALUES OF $\frac{N}{P}$ WHICH GIVE SYNCHRONOUS MOTOR EFFECTS

TABLE II

| $K$ \ $L$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| −1 | 4 | 7 | 10 | 13 | 16 |
| −2 | 2 | $3^1/_2$ | 5 | $6^1/_2$ | 8 |
| −3 | $1^1/_3$ | $2^1/_3$ | $3^1/_3$ | $4^1/_3$ | $5^1/_3$ |
| −4 | 1 | $1^3/_4$ | $2^1/_4$ | $3^1/_4$ | 4 |
| −5 | $^4/_5$ | $1^3/_5$ | 2 | $2^3/_5$ | $3^1/_5$ |

TABLE III

| $K$ \ $L$ | −1 | −2 | −3 | −4 | −5 |
|---|---|---|---|---|---|
| 1 | 2 | 5 | 8 | 11 | 14 |
| 2 | 1 | $2^1/_2$ | 4 | $5^1/_2$ | 7 |
| 3 | $^2/_3$ | $1^2/_3$ | $2^2/_3$ | $3^2/_3$ | $4^2/_3$ |
| 4 | $^1/_2$ | $1^1/_4$ | 2 | $2^3/_4$ | $3^1/_2$ |
| 5 | $^2/_5$ | 1 | $1^4/_5$ | $2^1/_5$ | $2^4/_5$ |

When a sub-synchronous speed occurs it takes place at a speed

$$\frac{n}{S} = -\frac{p}{KN}$$

Thus in Tables II and III, all those values of $\frac{N}{P}$ in Table II give synchronous motor effects at positive speeds and those values in Table III give synchronous motor effects at negative speeds.

Corresponding tables of $\frac{N}{P}$ for two-phase motors are obtained from a formula similar to G. For two-phase the $3L$ in that formula is changed to $2L$

$$\frac{N}{P} = -\frac{2L+1}{K}$$

The tables of $\frac{N}{P}$ are Tables IV and V:

TABLE IV

| $K$ \ $L$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| −1 | 3 | 5 | 7 | 9 | 11 |
| −2 | $1^1/_2$ | $2^1/_2$ | $3^1/_2$ | $4^1/_2$ | $5^1/_2$ |
| −3 | 1 | $1^2/_3$ | $2^1/_3$ | 3 | $3^2/_3$ |
| −4 | $^3/_4$ | $1^1/_4$ | $1^3/_4$ | $2^1/_4$ | $2^3/_4$ |
| −5 | $^3/_5$ | 1 | $1^2/_5$ | $1^4/_5$ | $2^1/_5$ |

TABLE V

| $K$ \ $L$ | −1 | −2 | −3 | −4 | −5 |
|---|---|---|---|---|---|
| 1 | 1 | 3 | 5 | 7 | 9 |
| 2 | $^1/_2$ | $1^1/_2$ | $2^1/_2$ | $3^1/_2$ | $4^1/_2$ |
| 3 | $^1/_3$ | 1 | $1^2/_3$ | $2^1/_3$ | 3 |
| 4 | $^1/_4$ | $^3/_4$ | $1^1/_4$ | $1^3/_4$ | $2^1/_4$ |
| 5 | $^1/_5$ | $^2/_5$ | 1 | $1^3/_5$ | $1^4/_5$ |

It is seen that in the case of the two-phase motor most synchronous motor effects occur at the same positive and negative speeds.

## ACKNOWLEDGMENT

The author wishes to acknowledge the great help given by Mr. Gabriel Kron in checking the mathematics on the existence of infinite superimposed synchronous motor effects.

Since the preparation of this paper Mr. Kron has done considerable work on the causes of "hooks" and discontinuities in induction motor speed-torque characteristics. This material is in preparation for publication and should appear at an early date.

## Discussion

**W. V. Lyons:** We are indebted to Professor Dreese for calling our attention to this interesting and little known point in the theory of induction motors. I agree entirely with his explanation of the results he observed experimentally. When we apply harmonic analysis to an induction motor we find that there is a multiplicity of flux distributions flitting to and fro in the air-gap due both to the stator and to the rotor currents. When the conditions are such that any two of these flux distributions of the same number of poles, one due to the stator and the other due to the rotor currents, are traveling at the same speed and in the same direction, these distributions will develop either forward or backward torque depending upon their relative position in the air-gap but *not* upon their direction of motion. This torque may be classed either as induction torque or as synchronous torque depending upon how the rotor component of flux is produced. Remember that only stator and rotor fluxes having the same number of poles can react to give a steady torque. If the rotor flux is produced by a rotor current that is induced by a stator flux of the same number of poles the torque is classed as induction. If, however, the rotor flux is produced by a rotor current that is induced by a stator flux of a different number of poles the torque is classed as synchronous. In the former case the two component fields always travel at the same speed regardless of the speed of the rotor. This is the characteristic of the torque developed by an induction motor. In the latter case, however, the two component fields travel at the same speed and thus develop a steady torque only at some particular rotor speed. This is the characteristic of the torque developed by a synchronous machine. For example if a seventh harmonic in the stator flux induces a current in the rotor which produces a corresponding seventh harmonic rotor flux, these two component fluxes will react to give an induction torque as shown in Fig. 4. On the other hand if, for example, the fundamental stator flux induces a current in the rotor which produces a thirteenth harmonic in the rotor flux this will react with the thirteenth harmonic in the stator flux distribution at one particular speed, *viz.*, one-seventh of synchronism, and produce synchronous torque.

It seems to me that the impression has been created that the seventh harmonic induction torque is much smaller than it really is. The value of 0.01 for the seventh harmonic does not show the true condition. Let us assume that this seventh harmonic is 1 per cent of the fundamental when there is no reaction due to the rotor, *viz.*, at no load. Now at one-seventh of synchronous speed the reaction of the rotor currents is to reduce the fundamental flux to about one-half of its no-load value but to reduce the seventh harmonic not at all. The stator current at this time is about 15 times its no load value so that the seventh harmonic flux is about 15 per cent of the *no* load fundamental flux or about 30 per cent of the fundamental flux at one-seventh of synchronous speed. It should also be noted that the seventh harmonic speed-torque curve is not like that of a motor having a constant applied primary potential. In the neighborhood of one-seventh of synchronous speed this torque is like that developed by an induction motor in which the stator current is maintained constant.

**P. H. Trickey and C. R. Boothby:** This paper has been of special interest to us as we have been studying the effect of the field form on the speed-torque curve of induction motors for some time. The induction motor effect has taken most of the first part of the study as the number of rotor slots does not have so much effect and the rotors which were available could be used for the tests on all the harmonics.

The special case of the 24 slot stator and the 28 slot rotor happened to occur in some experimental work and the synchronous effect was present exactly as Mr. Dreese has shown. In the unfortunate motor which we built the inner end of the cusp was negative and the outer end was 125 per cent of maximum torque. After determining that the effect was actually synchronous our first conclusions were that the 28 teeth of the rotor looked in with the 28 poles of the seventh harmonic in the same manner that an unexcited synchronous motor locks in. As Mr. Dreese has shown, the magnitude of the seventh harmonic in the three phase, two slots per pole, full pitch winding, such as we had, is only 3.82 per cent. It seemed impossible that this small value of flux could cause such a great value of torque. We then wound the primary with 5/6 chording which has only a 1.03 per cent seventh harmonic. Still the same synchronous action occurred. The tests were not accurate enough to determine whether or not the magnitude was less, at least, there was not any great difference.

The motor which we used was skewed one rotor slot. We then built a rotor which was skewed about one and three-quarters rotor slots. This reduced the length of the cusp only about 25 per cent.

We believe that Mr. Dreese has made a very valuable contribution in discovering and so clearly explaining this synchronous motor effect.

**C. J. Koch:** In the paper a phenomenon is described which to my knowledge has never appeared in Institute publications. It is therefore not out of place to make a few comments at this time in regard to a convenient terminology for this phenomenon. When an induction motor has a dip in its speed torque curve at some particular speed it may be said to have a tendency to crawl at that speed. If the dip reduces the torque to a sufficiently low value the motor will fail to attain full speed and therefore actually does crawl at a subsynchronous speed. If the tendency to crawl is due to the induction motor action of the rotor bars acted upon by either the stator tooth harmonics or phase belt harmonics the motor may be said to have a tendency to crawl asynchronously. If however the crawling tendency is due to the locking together of harmonic fields, the motor has a tendency to crawl synchronously. We therefore distinguish between "asynchronous crawling" and "synchronous crawling." These terms are offered simply because they have been used for some time by my associates and have proved adequate in speaking of these phenomena.

The question has been asked in the past whether some commercial use cannot be made of this phenomenon. Thus by exaggerating the synchronous crawling tendency motors could be made to run synchronously at low speeds with comparatively few poles and few slots. Very often the trouble is to get the motor synchronized. Slightly above or slightly below the crawling speed the motor torque is pulsating but the average torque is still positive due to the fundamental induction motor torque which is trying to accelerate the motor to full speed. Whether or not it synchronizes and crawls is partly a matter of chance and depends on the actual angular position of the locking fields at the instant the motor passes through the crawling speed. The inertia to be accelerated has of course an important influence. Very small single-phase motors have been made on this principle, however. Thus a shaded pole single-phase motor having two salient poles and six bars in the rotor is made to actually run synchronously at 1200 rev. per min. rather than asynchronously at 3600 rev. per min. as might be expected.

I should like to ask one question. Some years ago Mr. Alger studied this phenomenon from the point of view of permeance waves and concluded that whenever the difference between the numbers of stator slots and rotor slots was a multiple of the number of poles harmonic fields would be produced which would lock at some particular speed of the rotor. This speed would be equal to $\frac{\text{Poles}}{\text{Rotor Slots}}$ times synchronous speed and would be at either a forward or a backward speed depending on whether the motor was three phase or two phase and had more or less slots in the rotor than in the stator. These results agree with the present paper with the following exception. If the difference in

slots equaled the number of poles times the number of phases the revolving harmonic fields locked when the rotor was at standstill. The commonly known tendency of some motors to tend to lock at standstill appeared to be one and the same phenomenon with synchronous crawling occurring only at a different speed. I should like to ask Mr. Dreese if in his studies he has been led to believe that the tendency to lock at standstill is the same sort of phenomenon as the synchronous crawling tendency.

**L. V. Bewley:** I should like to ask if it is not true that the English engineer, Chapman, many years ago wrote a very complete series of papers on the induction motor?

**R. E. Hellmund:** The fact which Mr. Dreese has established rather definitely, that we may meet with some synchronous motor effects in induction motors in addition to the various induction motor effects, makes an already difficult problem even more complex. Like most induction motor designers, I have previously met with the troublesome problem of cusps in speed-torque curves and as a result have given the subject a good deal of study. I have found that whenever the cusps are likely to be caused by induction motors effects, a great many possibilities exist for avoiding them. This is because an induction motor effect is impossible without a secondary current flowing in one of the members regardless of whether the superimposed fields are caused by the stator or by the rotor. This fact offers possibilities of various kinds, such as proper chording, various connections in the stator, proper pitch of rotor bars, etc., for making the flowing of any secondary currents, and therefore induction motor torques, impossible. With the synchronous locking effects described in this paper, some of these methods of attack are, however, impossible because synchronous locking is quite possible without the flowing of any secondary currents.

It is therefore evident that with the great many possible causes of both induction and synchronous torques, the number of different synchronous speeds, the necessity for designing motors for quiet operation, and the economical urge for covering various motor designs with as few slot combinations as possible, the designer's task is not a particularly easy one. However, there is a possibility of making a virtue out of a difficulty by purposely designing for subsynchronous speeds in certain small motor applications. This offers a means for designing slow-speed motors for such applications as synchronous clocks with a small number of poles and therefore a corresponding reduction in costs.

**E. E. Dreese:** I am glad to say that it is a great source of satisfaction to have the paper received with so much interest and comment.

The first part of Professor Lyons' remarks, as I gathered it, simply says in different language, the things that I tried to say in the paper although perhaps he says them better. The latter part of it has to do with the magnitude of the seventh harmonic that occurs in this motor. I show that the magnitude of the seventh harmonic of stator m. m. f. is about one per cent of the fundamental. He challenges that by saying that the magnitude of the torque coming from that seventh harmonic is more than one per cent and I agree but, if you will read the paper carefully, I think you will see that I simply used that one per cent to base my judgment on the fact that the seventh harmonic was not at fault. One per cent of magnetomotive force is correct. Twenty per cent of flux at that particular speed is also correct. The question of synchronous crawling at zero speed was brought up by Mr. Koch. He asks the question whether my study of this has revealed anything on synchronous crawling or locking at zero speed. In answer to that I can say that synchronous crawling at zero speed is not due to the synchronous motor effect described in this paper.

A considerable amount of water has flowed under the bridge since this paper was written a year ago. There are effects additional to those described in this paper such as the effect of revolving harmonic permeances. This effect acts much like the synchronous motor effect in its influence on the speed-torque curve and it might be called "reaction motor effect" due to the actual slotted structure of the iron, in which the revolving permeance features are brought out. There is every indication that it can explain the crawling at zero speed.

There is one important difference, I believe, between the synchronous motor effect and the reaction motor effect. The synchronous motor effect *cannot* be skewed out. I believe the reaction motor effect due revolving permeances can be skewed out.

I shouldn't close the discussion on this point without acknowledging the work of Mr. Gabriel Kron on this subject. He has gone considerably into this question and I think he has a paper now pending before the Institute which covers other causes for these cusps and hooks in induction motor curves and covers it more generally and more comprehensively than does the present paper.

The question has been asked as to whether or not some work done by Mr. Chapman in England a number of years ago did not predict this same thing. The work done by him had to do with the analysis of the harmonic waves due to the stator which is old to all of us. He went further, however, and analyzed the harmonics originating in the rotor. I discovered the paper after I had finished my analysis of rotor harmonics and I was glad to see that my results agreed with his. Mr. Chapman's work, however, did not at any time predict the thing we have described in the paper today. I have searched in vain to see any hint of it. Mr. Chapman does say there is such a thing as crawling due to harmonics but I do not believe the actual mechanism has been explained.

In this connection, you may be familiar with some experimental work done by Mr. Stiehl a few years ago, showing some very erratic speed-torque curves for induction motors. One of Stiehl's motors was a 24-slot stator, 28-slot rotor combination such as used in this paper. His curves did not show the synchronous motor effect but an induction motor effect instead, and it worried me for some time until I went into detail and found out he had got his curves on an inertia transient dynamometer and if the motor should go through the subsynchronous speed *continuously* his device would not have shown the synchronous locking. So, if any of you ever have recourse to that article of Stiehl's in which he describes these phenomena, you should bear in mind, that he was using a transient dynamometer which does not show the synchronous motor effect because of its limitations.

# Transformer Ratio and Differential Leakage of Distributed Windings

BY R. E. HELLMUND* and C. G. VEINOTT†
Fellow, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—This paper develops in as simple a manner as possible the necessity for the concept of "differential leakage" where transformer action takes place between two unequally distributed windings and explains the character of differential leakage. The value to be used for the transformer ratio in the case of such unequally distributed windings is also given. All considerations are based on the conventional stepped-wave field forms, and the mathematics used involve only the simplest linear equations. While the paper is mainly intended to be expository in nature, a general indication is given at the end as to how differential leakage and transformer ratios can be calculated for both single-phase and polyphase arrangements.*

## Introduction

In many a-c. motors in which transformer actions take place between two windings, certain problems arise in determining the proper transformer ratio for the two windings due to the fact that, for various reasons, the two windings are not distributed or arranged alike over the circumference. Furthermore, it is found expedient in such cases to introduce the concept of "differential leakage" in order to make the motors and their transformer actions subject to the ordinary analysis and calculating methods used for transformers.

Although Adams[3] called attention to the existence of differential leakage under the name of "belt leakage" as early as 1904, the nature of this phenomenon seems to be very little understood even today. This may be partly attributed to the fact that very little has been published on this subject in the technical press of this country. In Europe the subject matter has received a good deal of attention, as can be seen from the accompanying bibliography. However, many of the papers given there are difficult to follow, requiring considerable mathematical skill involving harmonic analysis and manipulation of Fourier's Series. Other methods as given by one of the authors of this paper show graphical solutions of the problem and are well adapted for deriving practical results for work with polyphase motors, but they are less suitable for demonstrating and explaining the fundamental nature of the phenomena involved.

Considerable confusion has also been caused by the fact that quite a variety of names has been applied to the same phenomenon. Adams calls it "belt leakage;" Hellmund and Krondl, "differential leakage;" Rogowski and Simons, "doubly-interlinked leakage;" Sumec, "unequally-interlinked leakage;" and Baffrey, "voltage of the higher harmonics." Further complication has arisen because, with some methods, it is more convenient to derive the combination of differential leakage and what is known as "zigzag" or "tooth-top leakage," and as a result differential leakage has sometimes been referred to as part of the zigzag or the tooth-top leakage, and the like. In view of this situation, this paper is offered principally as a contribution to clarify certain points regarding the transformer ratios for distributed windings, to set forth and explain the concept of differential leakage, to demonstrate the need for this concept in certain cases, and to show how it is comparable to other forms of leakage. The considerations used are based on the conventional stepped-wave, representing field forms with which every electrical student is familiar, and although it has not been found possible to avoid mathematics entirely, that used is of the simplest kind, involving nothing but a few simple equations with one or two unknown quantities. No attempt has been made to deduce complete new calculating methods or to add another long set of formulas to an already long set of existing ones. Incidentally, the outline given shows how the transformer ratio and differential leakage of a single-phase motor can be computed, but the paper is intended mainly to be expository in nature.

## Concentrated and Equally Distributed Windings

Leading up to the case of unequally distributed windings, brief reference may first be made to concentrated and equally distributed windings. The simplest example of concentrated windings magnetically coupled is that found in transformers. In this case there is always some flux which links only one winding in addition to the flux common to both windings. The former flux is called "leakage flux" and it is very easy to obtain a correct physical concept of it. Moreover, in such a case, the transformer ratio is simply the ratio of turns. The various relations are generally well known. By using the leakage coefficient, as described and defined in Appendix I, and the ordinary conception of transformer ratio, it is possible to calculate the voltages or currents in either winding regardless of which of the windings is used as the primary, and it is also easy to determine the various relations between currents and

*Chief Electrical Engineer, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

†Electrical Engineer, Westinghouse Elec. & Mfg. Co., East Springfield, Mass.

3. For references see Bibliography.

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30-66

voltages when the secondary is open or when it is short-circuited.

The relations are equally simple if the two windings are distributed either evenly or unevenly over the circumference of a motor, as long as the distribution and general arrangement is the same in both windings, as shown, for example, in Fig. 1. Here again, the transformer ratio is simply the ratio of the number of turns. It will be seen that in this figure there is always a wound secondary slot opposite a wound primary slot, and the ratio of turns is the same in all pairs of opposite slots,

FIG. 1—EQUALLY DISTRIBUTED WINDINGS

that is, 2 to 1 in this particular case. It is also evident that the field set up will have the form shown in Fig. 2 regardless of whether it is built up by the primary or by the secondary winding. Furthermore, let us neglect slot and coil-end leakages and the following relations will apply:

*Open-circuit Condition.* (a) Ratio of currents producing the same total flux. Since the winding $S$ has half as many turns as the winding $P$, and since the field form set up by both windings is the same, it is evident that it requires twice as much current in winding $S$ as it does in winding $P$ to set up the same total flux. For any value of such flux, we have

$$\frac{I_1}{I_2} = \frac{1}{2} \tag{1}$$

where $I_1$ = current in winding $P$
$I_2$ = current in winding $S$

(b) Ratio of open-circuit voltages—winding $P$ excited. The voltage induced in the two windings is evidently proportional to the number of turns. Therefore, with winding $P$ excited, we have

$$\frac{E_1}{E_2'} = 2 \tag{2}$$

where $E_1$ = voltage impressed on winding $P$
$E_2'$ = voltage induced in winding $S$

(c) Ratio of open-circuit voltages,—winding $S$ excited. It is equally evident that, with winding $S$ excited, we have

$$\frac{E_1'}{E_2} = 2 \tag{3}$$

where $E_2$ = voltage impressed on winding $S$
$E_1'$ = voltage induced in winding $P$

It is thus seen that, neglecting slot and coil-end leakages, the voltage ratio of the two windings, if either of the windings is excited, is the same as the ratio of the turns, and the current ratio is the reciprocal of this ratio.

*Short-circuit Condition.* Furthermore, if we assume the secondary winding as short-circuited and having zero resistance and zero leakage reactance, the voltage induced in it must be zero. The currents in the two windings flow in opposite directions, and so the resultant field as a whole, as well as at all parts of the gap surface, is zero. The voltage induced in the primary winding, if the latter is without resistance or leakage reactance, is zero as well. (If the well-known slot leakages and coil-end leakages are not neglected, the usual relations, as set forth more in detail in Appendix I, obtain.)

The above-mentioned obvious conditions existing in equally distributed windings have been recited principally for the sake of comparison with conditions to be found later for unequally distributed windings, and also to show that, with concentrated or equally distributed windings, the ordinary ratio of turns is sufficient for all ordinary calculations, and that the concept of differential leakage in such cases is not needed since the phenomena coming under this name do not exist.

## UNEQUALLY DISTRIBUTED WINDINGS

For the purpose of studying how these conditions change in the case of two unequally distributed windings, a very simple arrangement of this kind, as shown in Fig. 3, will be considered. To bring out more clearly the points to be made, it is assumed that the primary and secondary have the same number of slots and that such slots are opposite each other. This eliminates the possibility of any so-called zigzag or tooth-top leakage and thus avoids any complication which would be introduced by its existence. The ratio of turns is again assumed to be 2 to 1, but the distribution of the turns is different in the two windings, as shown in the figure.

*Open-circuit Conditions.* With these assumptions for the unequally distributed windings, some of the

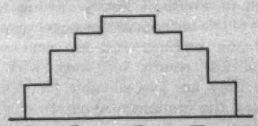

FIG. 2—FIELD FORM OF EITHER WINDING OF FIG. 1

same relations which were previously determined for the equally distributed windings will now be studied.

(a) Ratio of currents producing the same total flux. In order to determine the ratio of the respective currents which, when flowing in the two windings will produce the same total flux across the air-gap, a current ($I$), flowing in winding $P$ only, may first be assumed. It will set up a field as represented by the area ($a\ b\ c\ d\ e\ f\ g\ h$) in Fig. 4, and the total flux will be proportional to this area. The magnetization factor $K\ m$, defined as the ratio of the actual flux produced by the distributed winding to that which would be produced by the same total turns concentrated in the outermost slots, is 0.75 for this particular case (see Appendix II).

If we assume the same current flowing in winding $S$, a field proportional to the area $(m\,n\,o\,p\,q\,r\,s\,t)$ in Fig. 5 will be set up. The magnetization factor for this case is found to be 0.625 (see Appendix II).

Fig. 3—Unequally Distributed Windings

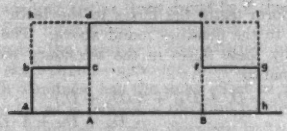

Fig. 4—Field Form of Winding $P$, Fig. 3

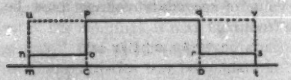

Fig. 5—Field Form of Winding $S$, Fig. 3

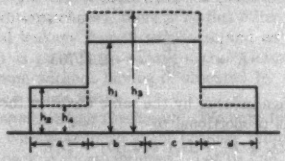

Fig. 6

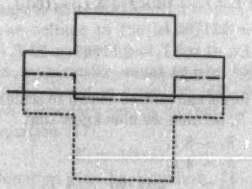

Fig. 7—Field Forms, $P$ Excited, $S$ Short-Circuited

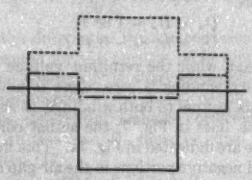

Fig. 8—Field Forms, $S$ Excited, $P$ Short-Circuited

From the above definition of the magnetization factor, it follows that the total flux produced by a distributed winding is equal to the flux which would be produced if all the turns in the distributed winding were concentrated in the outermost slot, multiplied by the magnetization factor. The fluxes which would be produced if the windings were concentrated are proportional to the areas $(a\,k\,l\,h)$ and $(m\,u\,v\,t)$ respectively. If the fluxes set up by the two windings are to be equal, the following obtains:

$$k_{m1} \times \text{area}\,(a\,k\,l\,h) = k_{m2} \times \text{area}\,(m\,u\,v\,t) \qquad (4)$$

It is further evident that the area $(a\,k\,l\,h)$ is proportional to the total ampere-turns in winding $P$, and the area $(m\,u\,v\,t)$ to the total ampere-turns in winding $S$. Therefore, from Equation (4),

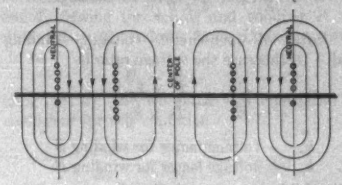

Fig. 7A—Lines of Force for Conditions of Fig. 7

$$k_{m1} \times I_1 \times T_1 = k_{m2} \times I_2 \times T_2$$

or

$$\frac{I_1}{I_2} = \frac{k_{m2}\,T_2}{k_{m1}\,T_1} \qquad (5)$$

if $T_1$ and $T_2$ are the numbers of turns in winding $P$ and $S$ respectively.

In our particular case, we find

$$\frac{I_1}{I_2} = \frac{0.625 \times 4}{0.750 \times 8} = 0.417 = \frac{1}{2.4} \qquad (6)$$

In other words, the ratio of the currents producing the same total air-gap flux is 1 : 2.4, while the ratio of the actual turns is 2 : 1.

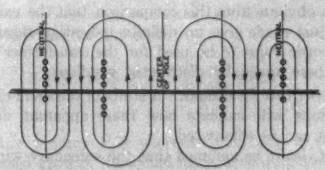

Fig. 8A—Lines of Force for Conditions of Fig. 8

(b) Ratio of open-circuit voltages,—winding $P$ excited. The voltage induced in either winding is proportional to the total number of turns multiplied by the voltage factor $k_p$, a factor which takes into account both the distribution of the air-gap flux and the distribution of the turns in the winding. The ratio of voltages is, therefore,

$$\frac{E_1}{E_2'} = \frac{T_1 \times k_{p1}}{T_2 \times k_{p2}'} \qquad (7)$$

where $k_{p1}$ = voltage factor for winding $P$
$k_{p2}'$ = voltage factor for winding $S$
with the field set up by winding $P$.

As shown in Equations (65) and (66) of Appendix II, $k_{p1}$ and $k_{p2}'$ are equal to 0.8333 and 0.75 respectively for this particular arrangement of coils, and so the ratio of voltages becomes

$$\frac{E_1}{E_2'} = \frac{8 \times 0.8333}{4 \times 0.75} = 2.222 \qquad (8)$$

(c) Ratio of open-circuit voltages,—winding $S$ excited. In this case the voltage ratio is

$$\frac{E_1'}{E_2} = \frac{T_1 \times k_{p1}'}{T_2 \times k_{p2}} \qquad (9)$$

where $k_{p2}$ = voltage factor for winding $S$
$k_{p1}'$ = voltage factor for winding $P$
with the field set up by winding $S$.

Using the voltage factors found in Equations (67) and (68) of Appendix II, this ratio becomes

$$\frac{E_1'}{E_2} = \frac{8 \times 0.90}{4 \times 0.85} = 2.11765 \qquad (10)$$

Thus far, the following has been established:

1. Ratio of total turns = 2.000
2. Ratio of currents producing the same total field = $0.417 = \frac{1}{2.4}$
3. Ratio of voltages if the field is built up by currents in winding $P$ only = 2.222
4. Ratio of voltages is the field is built up by currents in winding $S$ only = 2.11765

It is obvious from this comparison that the calculations just made give no definite indication regarding the proper value to be used for the transformer ratio with these unequally distributed windings.

*Short-circuit Conditions.* A study of the short-circuit conditions will indicate how these apparent discrepancies can be eliminated.

First, let it be assumed that the secondary winding $S$ is short-circuited and that, as before, its resistance and leakage reactance caused by slot and coil-end leakage can be neglected. Under these assumptions, the net voltage induced in this winding must be zero. The currents in the two windings will, therefore, assume such values as to satisfy this condition. Fig. 6 shows again the field of Fig. 4 as produced by a current in the primary winding in full lines, and also the field of Fig. 5 as produced by a current in the secondary windings in dotted lines, increased so as to have about the same value as the field shown in full lines. The currents $I_1$ and $I_2$ under the assumed short-circuit conditions, and therefore the height of the two field forms, are at present unknown, but we do know that

$$\left.\begin{aligned} h_1 &\sim {}^{*}8\, I_1 \\ h_2 &\sim 4\, I_1 \\ h_3 &\sim 4\, I_2 \\ h_4 &\sim 1\, I_2 \end{aligned}\right\} \qquad (11)$$

The resultant flux densities in the teeth $a$ and $d$ are proportional to

$$D_a = D_d \sim (h_2 + h_4) \sim (4\, I_1 + I_2) \qquad (12)$$

and those in teeth $b$ and $c$ to

$$D_b = D_c \sim (h_1 + h_3) \sim (8\, I_1 + 4\, I_2) \qquad (13)$$

With uniform teeth, the fluxes in the teeth are proportional to the densities found above. The voltage induced by these fluxes in the secondary winding is proportional to

$$1\,(D_a + D_b + D_c + D_d) + 3\,(D_b + D_c)$$
$$= D_a + D_d + 4\,(D_b + D_c)$$

or $$E_{2s} \sim 2\,(4\, I_1 + I_2) + 8\,(8\, I_1 + 4\, I_2) \qquad (14)$$

but the value of secondary voltage must be zero, so therefore from (14)

$$72\, I_1 + 34\, I_2 = 0 \qquad (15)$$

Calling $K$ the current ratio, that is, $\frac{I_2}{I_1}$, it follows from (15) that

$$K = -\frac{72}{34} = -2.11765 \qquad (16)$$

The voltage induced by the same fluxes in the primary winding is proportional to

$$4\,(D_a + D_b + D_c + D_d) + 4\,(D_b + D_c)$$
$$= 4\,(D_a + D_d) + 8\,(D_b + D_c)$$

or $E_{1s} \sim 8(4\, I_1 + I_2) + 16(8\, I_1 + 4\, I_2) = 160\, I_1 + 72\, I_2$ (17)

Since $I_2 = -2.11765\, I_1$

$$E_{1s} \sim 160\, I_1 - 2.11765 \times 72\, I_1$$
$$\therefore E_{1s} \sim 7.53\, I_1 \qquad (18)$$

The field forms can now be shown to scale as has been done in Fig. 7, because we now know that

$$\left.\begin{aligned} h_1 &\sim 8\, I_1 \\ h_2 &\sim 4\, I_1 \\ h_3 &\sim -\,2.11765 \times 4\, I_1 \\ h_4 &\sim -\,2.11765 \times I_1 \end{aligned}\right\} \qquad (19)$$

and therefore

$$\left.\begin{aligned} D_a &= D_d \sim 1.88\, I_1 \\ D_b &= D_c \sim -\,0.47\, I_1 \end{aligned}\right\} \qquad (20)$$

We see that, while the resultant voltage induced in the secondary winding is zero, there is nevertheless a resultant flux mutual to both windings, as shown by the dot-and-dash lines in Fig. 7; the actual corresponding lines of force are indicated in Fig. 7A. This flux has both positive and negative portions in the air-gap of the same pole face, but the positive portions predominate and so the total resultant flux is positive. The reason why this flux induces no resultant voltage in the secondary winding is simply that the smaller negative portions

*$\sim$ Proportionality sign.

interlink with three turns, while the total resultant flux, which is larger and positive, interlinks with but one turn; the negative voltage induced in the three inner turns is exactly equal and opposite to the positive voltage induced in the outer turn. With a primary winding ($P$) distributed in a different manner, the negative voltage induced in the four inner turns only partly neutralizes the positive voltage of the four outer turns, and so there is a definite positive voltage induced in the primary winding just as there would be if there were a leakage flux interlinking the primary winding. In other words, the resultant flux existing under the assumed short-circuit conditions, although interlinking with both windings, has the same effect as a leakage flux in so far as it induces a resultant voltage in only one of the windings; it may therefore be treated the same as a true leakage flux for all practical purposes. Since it is caused by the difference in distribution or arrangement of the windings, it may be called "differential leakage flux." As will be seen, the study of this flux and its characteristics has been materially facilitated by the investigation of the short-circuit condition. The reason for this is that, with this condition and the other conditions chosen, there is no flux other than the differential leakage flux in existence, and as a consequence, it is possible to obtain a true picture of the phenomenon, without having it obscured by the presence of any other fluxes.

*Differential Leakage Coefficient.* We have found that there is a voltage induced in the primary winding when the secondary is short-circuited. Let us find the voltage induced in the primary when the same current is passed through it with the secondary open. The ratio of the former voltage to the latter, we will call the "differential leakage coefficient," for in a transformer this ratio is numerically equal to the total leakage coefficient, as is shown in Equation (**62**), Appendix I.

With open secondary and a current $I_1$, $I_2$ is zero. So, from Equation (**17**),

$$E_1 \sim 160\, I_1 \tag{21}$$

Dividing Equation (**18**) by Equation (**21**),

$$\frac{E_{1s}}{E_1} = \frac{7.53\, I_1}{160\, I_1} = 0.047 = \sigma \tag{22}$$

where $\sigma$ is the differential leakage coefficient.

Let us assume for the purpose of further investigation that the winding $P$ is short circuited, while the winding $S$ is connected to the supply circuit, and let us calculate the differential leakage coefficient for this condition. In this case, $E_{1s}$ must be equal to zero, so from Equation (**17**),

$$160\, I_1 + 72\, I_2 = 0$$

Letting $K = \dfrac{I_2}{I_1}$ as before,

$$K = -\frac{160}{72} = -2.222 \tag{23}$$

The voltage induced in winding $S$ follows from Equations (**14**) and (**23**)

$$E_{2s} \sim \frac{72}{-2.222}\, I_2 + 34\, I_2 = 1.596\, I_2 \tag{24}$$

The fields for this last case are shown in Figs. 8 and 8A, and it will be seen that they differ from the fields in Figs. 7 and 7A.

The voltage induced in the winding $S$, with the same current $I_2$ flowing through it and winding $P$ open-circuited, ($I_1 = 0$), follows from Equation (**14**) or (**15**) to be

$$E_2 \sim 34\, I_2 \tag{25}$$

Dividing (**24**) by (**25**), we obtain the differential leakage coefficient for this condition

$$\sigma = \frac{E_{2s}}{E_2} = \frac{1.596\, I_2}{34\, I_2} = 0.047 \tag{26}$$

which is the same as previously found, although the fields are different.

*Transformer Ratio.* Using this value of differential leakage coefficient just found, let us calculate the transformer ratio, using the formulas derived in Appendix I for a transformer with leakage. (In making use of the formulas in this appendix, $\sigma_1$ or $\sigma_2$ will be replaced by $\dfrac{\sigma}{2}$.) With $S$ shorted and $P$ open, we obtain from Equation (**52**)

$$I_2' = -I_1 \times R \times \left(1 - \frac{\sigma}{2}\right)$$

or

$$R = -\frac{I_2'}{I_1}\,\frac{1}{1 - \dfrac{\sigma}{2}} \tag{27}$$

which becomes for our case

$$R = 2.11765 \times \frac{1}{1 - \dfrac{0.047}{2}} = 2.17 \tag{28}$$

If the winding $P$ is short-circuited and a voltage impressed upon $S$, we should have, according to Equation (**53**) in Appendix I,

$$I_1' = \frac{-I_2}{R}\left(1 - \frac{\sigma}{2}\right)$$

or

$$R = \frac{-I_2}{I_1'}\left(1 - \frac{\sigma}{2}\right) \tag{29}$$

which, using our values, becomes

$$R = 2.222\left(1 - \frac{0.047}{2}\right) = 2.17, \text{ as before.}$$

We have now found a transformer ratio which, when used in connection with the differential leakage coefficient, applies for the calculation of primary and secondary

current ratios in either direction, as should be the case.

Let us see if the same transformer ratio holds for the voltage ratio in either direction, as it should. With the secondary open and the primary connected to the line, we should have, according to Equation (41), Appendix I,

$$R = \frac{E_1}{E_2'}\left(1 - \frac{\sigma}{2}\right) \tag{30}$$

We previously found $\frac{E_1}{E_2'} = 2.222$ in Equation (8), so, therefore, with winding $P$ excited and $S$ open,

$$R = 2.222\left(1 - \frac{0.047}{2}\right) = 2.17, \text{ as before.}$$

Finally, if we excite $S$ and leave $P$ open, we should have, according to Equation (42),

$$R = \frac{E_1'}{E_2}\left(\frac{1}{1 - \frac{\sigma}{2}}\right) \tag{31}$$

but, from Equation (10), $\frac{E_1'}{E_2} = 2.11765$

$$\text{therefore } R = \frac{2.11765}{1 - \frac{0.047}{2}} = 2.17, \text{ as before.}$$

## Conclusions and General Discussion

Thus we see that by introducing the concept of differential leakage and by determining a differential leakage coefficient as shown, it is possible to derive a transformer ratio for distributed windings which applies to open-circuit and short-circuit conditions in either direction. The method previously shown for determining the differential leakage coefficient by finding the ratio of short circuit and open circuit voltage for the same primary current, Equation (22), may be used for single-phase motors in general; also, the transformer ratio may be determined as indicated, Equations (27) and (29).

However, after the concept of differential leakage coefficient has been established and the nature of the differential leakage demonstrated, it is possible, and frequently easier, to compute the differential leakage coefficient from the no-load voltages. In Appendix II it is shown how the no-load voltages, with either winding excited, can be determined. After this has been done, the differential leakage coefficient can be found from Equation (43), Appendix I, and the transformer ratio follows from Equation (44). In our example this gives the following results:

$$\frac{\sigma}{2} = 1 - \sqrt{\frac{E_1' \times E_2'}{E_2 E_1}} = 1 - \sqrt{\frac{2.11765}{2.222}} = 0.0235$$

or $\sigma = 0.047$

$$R = \sqrt{\frac{E_1' \times E_1}{E_2 \times E_2'}} = \sqrt{2.11765 \times 2.222} = 2.17$$

which agree with those previously obtained.

In using Equation (43) it is necessary to evaluate the quantity under the radical with great accuracy since this quantity is nearly 1.0 and is subtracted from 1.0, the difference being small. A simpler formula based on the well-known approximation that $\sqrt{1 - A} = 1 - \frac{A}{2}$, if $A$ is small, can be derived from Equation (43), giving

$$\sigma = 1 - \frac{E_1' \times E_2'}{E_2 E_1} \tag{43a}$$

For polyphase motors the same general principles apply and the same general methods of calculation may be used. However, there is one condition existing in polyphase motors which does not occur in the ordinary single-phase case. In polyphase motors, differential leakage may occur even though the slots and turns may be equally distributed in the two members. This is due to the fact that in a wound-secondary polyphase motor, for instance, the rotor can assume positions

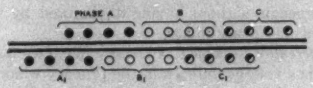


Fig. 9—Displacement of Phase Belts in a Three-Phase Machine

where its phase belts do not coincide with those of the stator, as indicated in Fig. 9 for a three-phase motor. With the phase belts thus displaced, the conditions in the two members are not equal; as a result the fields set up by the two windings are different for any given axis, which in turn is the cause of differential leakage. It was this type of leakage caused by the difference in the phase belts that Adams[3] first pointed out under the name of "belt leakage."

The conditions in connection with polyphase motors are further complicated by the fact that the field form of each of the members changes while the field rotates, which, with the methods indicated above for single-phase motors, makes it necessary to study the field forms for the various time and space relations, as has been done by a number of authors. As an alternative, the no-load conditions can be more readily studied graphically by the vector analysis given by one of the authors[5] of this paper in a previous article.

Up to this point, and particularly in the example given above for single-phase motors, the slots for the two windings have been assumed to coincide, which was done in order to eliminate the existence of zigzag or tooth-top leakage. With this assumption, all of the fluxes across the gap interlink with both windings, a

fact which apparently has led to the name "doubly-interlinked leakage" used by some authors. If the slots are assumed no longer to coincide, there will be certain fluxes flowing across the gap from one member to the other which interlink with only one winding. These fluxes are usually referred to as "zigzag" or "tooth-top leakage fluxes." However, the methods indicated in this paper for determining the leakage coefficient will give the sum of the zigzag and the differential or doubly-interlinked leakage, and in many cases the separation of the two types of leakages is difficult. This is the reason why some authors have given the two leakages combined and have referred to the combination under any of the various designations given above. In the previously-mentioned article by one of the authors of this paper is derived the combination of the two for polyphase motors having an equal number of slots in both members, and Fig. 10 reproduced here is from such previous work. In this case it is readily seen that the area under the curve $B$ represents the differential or doubly-interlinked leakage varying with the relative positions of the phase belts, while the areas between curves $A$ and $B$ represent

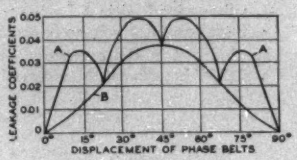


Fig. 10

zigzag leakage varying with the relative positions of the slots. For cases with an unequal number of slots, the separation cannot be accomplished in so simple a manner, and whenever for some reason or other the separation of the two seems desirable, it will be found expedient to determine the combination by the methods outlined in this paper, to calculate the zigzag leakage by any of the existing methods for its determination, and then subtract it from the sum of the two in order to obtain the differential or doubly-interlinked leakage.

The practical importance of the differential leakage varies considerably with the case under consideration. We have pointed out that it is present with any arrangement where the two windings are unequally arranged either on account of the distribution of the turns or the position of the phase belts, or on account of both. It may further be pointed out that differential leakage may even exist in a single winding with primary and secondary taps. A practical example of this kind is the armature of a frequency-changer of the commutator type where certain taps are connected to slip-rings and the other end of the winding to the commutator. For any position of the armature where the commutator brushes do not happen to be in the same location as the taps to the slip-rings, there will be differential leakage.

Generally speaking, the more the field forms of the two windings, or of the same winding with different taps, differ from each other, the larger the differential leakage will be. An appreciable difference will be found in single-phase commutator motors, for instance, where the armature has a single set of brushes with a full-pitch winding resulting in a triangular field form, while the stator is wound to give it a trapezoidal field form or is arranged so as to approach a sinusoidal field form rather closely. Another case where differential leakage can be very appreciable in single-phase motors is where there is transformer action between an armature coil short-circuited by a brush and a distributed stator winding. The short-circuited armature coil gives a rectangular field form which differs considerably from the field forms set up by distributed stator windings.

In three-phase induction motors with the most favorable chording, differential leakage can be made almost negligible, while with full-pitch three-phase windings, it is often of practical importance. In two-phase motors it is generally larger than in three-phase motors, and with full-pitch two-phase windings, it may be of great practical importance. Another instance in which differential leakage can be quite large is that of two-phase motors operated with a three-phase secondary. In most cases, the relative importance of differential leakage is, of course, governed by its magnitude relative to that of the other types of leakage fluxes. Thus, in small, slow-speed induction motors where the other types of leakage are very appreciable, the differential leakage will very often be of negligible quantity. On the other hand, in large high-speed motors where the other leakages are relatively small, the differential leakage may be, and frequently is, of practical importance.

The general statements just preceding regarding the relative importance of differential leakage, while not covering all possible cases, may be of assistance in so far as they may indicate where the detailed calculation of the leakage coefficient is desirable. While the methods indicated in this paper for determining the leakage coefficient are very simple in principle, they become quite cumbersome and time-consuming where the number of slots per pole is larger than in our example, as is usually the case in practise. If, wherever such procedure is possible, the two windings involved are designed to have field forms which are very similar to each other, the detailed calculation of the differential leakage may often be eliminated merely by making a small allowance for the differential leakage to be added to the other leakages. On the other hand, where for some reason or other the field forms materially differ from each other, an exact predetermination of the performance of the apparatus will necessitate the determination of the differential leakage by one of the

methods indicated, unless the desired or similar data are available from previous investigations.*

## Appendix I

### General Conventions About Leakage

Although various fundamental relations between leakage fluxes and transformer ratio have been derived in literature, a number of different factors has been called the "leakage coefficient." This has led to some confusion, and, moreover, since most of these relations were left in the form most suited to the particular method of analysis employed by the one deriving them, it may be well to define the leakage coefficient as used in this paper. Incidentally, a number of other relations used in the paper or convenient for other purposes is developed.

A two-winding transformer, as shown in Figs. 11 to

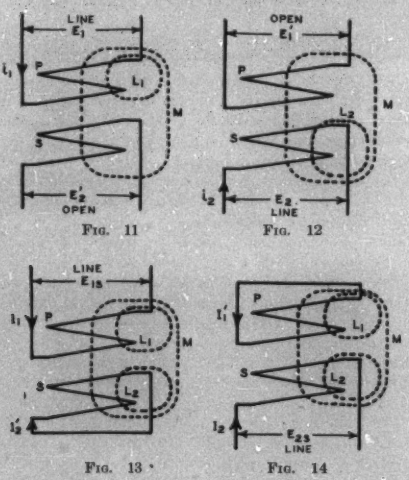


Fig. 11 Fig. 12

Fig. 13 Fig. 14

Figs. 11, 12, 13, 14—Fluxes in a Two-Winding Transformer under Various Conditions

14, is assumed for deriving these relations. Although all the leakage fluxes and mutual fluxes may in practise not link all the turns, the actual fluxes are replaced by the equivalent fluxes which would induce the same voltage if they linked the full number of turns. The reluctances, of course, are fictitious, but serve well for the purpose for which they are intended.

### Open-Circuit Conditions

If the coil $P$ in Fig. 11 carries a current $i_1$, while the coil $S$ is open-circuited, this current will set up a mutual flux $M$ interlinking with both coils and a leakage flux $L_1$ interlinking with coil $P$ only. Both of these fluxes induce in coil $P$ voltages proportional to their magnitude, and the primary leakage coefficient $\sigma_1$ is defined by

$$\sigma_1 = \frac{E_{1l}}{E_{1m} + E_{1l}} = \frac{E_{1l}}{E_1} \tag{32}$$

where $E_{1l}$ = leakage reactance voltage in coil $P$
$E_{1m}$ = voltage induced in $P$ by mutual flux
$E_1$ = total reactance voltage in coil $P$.

The leakage coefficient may also be given by

$$\sigma_1 = \frac{L_1}{M + L_1} = \frac{\mathcal{R}_m}{\mathcal{R}_m + \mathcal{R}_1} \tag{33}$$

where
$\mathcal{R}_m$ = reluctance of path of mutual flux
$\mathcal{R}_1$ = reluctance of path of primary leakage flux.

Similarly, if we assume coil $P$ open and a current passed through $S$ as shown in Fig. 12, the secondary leakage coefficient $\sigma_2$ is defined as

$$\sigma_2 = \frac{E_{2l}}{E_{2m} + E_{2l}} = \frac{E_{2l}}{E_2} \tag{34}$$

where $E_{2l}$ = voltage induced in coil $S$ by the leakage flux
$E_{2m}$ = voltage induced in $S$ by the mutual flux
$E_2$ = total reactance voltage in coil $S$

The voltage induced in the open-circuited winding can now be expressed in terms of the voltage induced in the winding connected to the line. In Fig. 11, the mutual flux induces in the open-circuited winding $S$ a voltage

$$E_2' = \frac{E_{1m}}{R} \tag{35}$$

where
$E_2'$ = voltage induced in coil $S$ when coil $P$ is excited
$R$ = ratio of turns in coil $P$ to turns in coil $S$.

The total voltage $E_1$ induced in coil $P$ is $E_{1m} + E_{1l}$, and since, from Equation (32),

$$E_{1l} = \sigma_1 E_1 \tag{36}$$

we have

$$E_{1m} = E_1 (1 - \sigma_1) \tag{37}$$

Substituting this value of $E_{1m}$ in Equation (35) gives

$$E_2' = E_1 \frac{(1 - \sigma_1)}{R} \tag{38}$$

In a similar manner it can be shown that the voltage induced in coil $P$ when coil $S$ is excited, the former being open, is

$$E_1' = E_2 R (1 - \sigma_2) \tag{39}$$

where
$E_1'$ = voltage induced in coil $P$ when $S$ is excited

If the voltages in Equations (38) and (39) are known from tests, and the turns ratio $R$ is given, the primary and secondary leakage coefficients can be calculated directly from these equations. If the ratio $R$ is unknown, as it often is in motors with distributed wind-

*See Bibliography.

ings, Equations (38) and (39) contain three variables, so neither the two leakage coefficients nor the transformer ratio can be found. Usually, however, $\sigma_1$ and $\sigma_2$ are nearly equal, and so we have

$$\sigma_1 = \sigma_2 = \frac{\sigma}{2} \tag{40}$$

where $\sigma$ = total leakage coefficient = $\sigma_1 + \sigma_2$

Making this substitution in Equations (38) and (39), we get

from (38) $$R = \frac{E_1}{E_2'}\left(1 - \frac{\sigma}{2}\right) \tag{41}$$

from (39) $$R = \frac{E_1'}{E_2}\left(\frac{1}{1 - \frac{\sigma}{2}}\right) \tag{42}$$

Now we have two equations with two unknowns, both of which can be found by ordinary algebraic processes to be, for the leakage coefficient

$$\frac{\sigma}{2} = 1 - \sqrt{\frac{E_1' \times E_2'}{E_2 \times E_1}} \tag{43}$$

and for the transformer ratio

$$R = \sqrt{\frac{E_1' \times E_1}{E_2 \times E_2'}} \tag{44}$$

It is interesting to note that, if the primary and secondary leakage coefficients are equal, the transformer ratio is the geometric mean of the two voltage ratios obtained by first exciting one winding, then the other.

## Short-Circuit Conditions

Many useful relations dependent upon the leakage coefficients can be derived from a consideration of short-circuit phenomena. In Fig. 13, coil $S$ is short-circuited, and it is assumed that a current $I_1$ is passed through the primary. (It is assumed that the resistance of both windings can be neglected.) In this case, the mutual flux $M$ will induce a voltage in $S$, causing a current $I_2'$ to flow. The mutual flux $M$ will be proportional to the net ampere-turns acting on the magnetic circuit divided by the reluctance of the latter,

or $$M \sim \frac{I_1 + \frac{I_2'}{R}}{\mathcal{R}_m} \tag{45}$$

Leakage fluxes are set up in each winding as follows:

$$L_1 \sim \frac{I_1}{\mathcal{R}_1} \tag{46}$$

$$L_2 \sim \frac{I_2}{\mathcal{R}_2 R} \tag{47}$$

where $\mathcal{R}_2$ = reluctance of path of $L_2$

(Dividing by $R$ in the last equation puts $L_2$ on the same basis as $M$).

Since the secondary was assumed to have no resistance, the total voltage induced in it must be zero. This can be true only if

$$L_2 = -M \tag{48}$$

Substituting the values of $L_2$ and $M$ from Equations (45) and (47) in Equation (48) and solving for $I_2'$, gives

$$I_2' = -I_1 R \frac{\mathcal{R}_2}{\mathcal{R}_m + \mathcal{R}_2} \tag{49}$$

It would, however, be more convenient to have $I_2'$ in terms of the leakage coefficient rather than in terms of the reluctances. By analogy to Equation (33)

$$\sigma_2 = \frac{\mathcal{R}_m}{\mathcal{R}_m + \mathcal{R}_2} \tag{50}$$

and $$1 - \sigma_2 = \frac{\mathcal{R}_2}{\mathcal{R}_m + \mathcal{R}_2} \tag{51}$$

Therefore, substituting Equation (51) in Equation (49) gives

$$I_2' = -I_1 R (1 - \sigma_2) \tag{52}$$

By a similar analysis based on short circuiting coil $P$ and sending a current through coil $S$ as shown in Fig. 14, it can be shown that

$$I_1' = -\frac{I_2}{R}(1 - \sigma_1)^* \tag{53}$$

A comparison of short-circuit conditions with those obtaining on open circuit leads to interesting relations. The voltage induced in the winding $P$ in Fig. 13 where the secondary is shorted, is given by

$$E_{1s} \sim M + L_1 \tag{54}$$

in which $M$ and $L_1$ can be taken from Equations (45) and (46), giving

$$E_{1s} \sim \frac{I_1 + \frac{I_2'}{R}}{\mathcal{R}_m} + \frac{I_1}{\mathcal{R}_1} \tag{55}$$

Introducing the value of $I_2'$ from Equation (52) and simplifying, gives

$$E_{1s} \sim I_1 \frac{\mathcal{R}_1 \sigma_2 + \mathcal{R}_m}{\mathcal{R}_m \times \mathcal{R}_1} \tag{56}$$

This still leaves $E_{1s}$ expressed in terms of the

*Two more relations, interesting but not essential to this paper, can be derived by again assuming that primary and secondary leakage coefficients are equal and solving for the unknowns in Equations (52) and (53), obtaining

$$\frac{\sigma}{2} = 1 - \sqrt{\frac{I_1' \times I_2'}{I_2 \times I_1}} \tag{a}$$

$$R = \sqrt{\frac{I_2 I_2'}{I_1' I_1}} \tag{b}$$

Note the similarity to Equations (43) and (44)

reluctances, which is undesirable. If we solve for $\mathfrak{R}_1$ in Equation (33), we obtain

$$\mathfrak{R}_1 = \frac{\mathfrak{R}_m}{\sigma_1}(1 - \sigma_1) \tag{57}$$

Introducing this value of $\mathfrak{R}_1$ into Equation (56) gives us

$$E_{1s} \sim \frac{I_1}{\mathfrak{R}_m} \; \frac{\sigma_1 + \sigma_2 - \sigma_1 \sigma_2}{1 - \sigma_1} \tag{58}$$

When $S$ is open-circuited as in Fig. 9, the voltage induced in $P$ is

$$E_1 \sim M + L_1 \sim \frac{i_1}{\mathfrak{R}_m} + \frac{i_1}{\mathfrak{R}_1} \tag{59}$$

and, by again utilizing Equation (57) and simplifying,

$$E_1 \sim \frac{i_1}{\mathfrak{R}_m}\left(\frac{1}{1 - \sigma_1}\right) \tag{60}$$

Now, if it be assumed that the same current is passed through $P$ when $S$ is shorted as when open, *i. e.*, that $i_1 = I_1$, division of Equation (58) by Equation (60) gives

$$\frac{E_{1s}}{E_1} = \sigma_1 + \sigma_2 - \sigma_1 \sigma_2 \tag{61}$$

Usually the product $\sigma_1 \sigma_2$ is small, and therefore if $\sigma_1 + \sigma_2 = \sigma$ as previously assumed, we may write

$$\sigma = \frac{E_{1s}}{E_1} \tag{62}$$

This, of course, is a well-known and familiar relation used in many theories of transformers and motors with transformer actions.

## Appendix II

### Magnetization and Voltage Factors of a Distributed Winding

*Magnetization Factor.* The magnetization factor of a distributed winding is the ratio of the actual flux set up to the flux which would be set up if all the turns in the winding were concentrated in a coil having a spread of a full pole-pitch.

For the windings shown in Fig. 3,

$$k_{m1} = \frac{\text{area } (a\,b\,c\,d\,e\,f\,g\,h)}{\text{area } (a\,k\,l\,h)} = 0.75 \tag{63}$$

$$k_{m2} = \frac{\text{area } (m\,n\,o\,p\,q\,r\,s\,t)}{\text{area } (m\,u\,v\,t)} = 0.625 \tag{64}$$

*Voltage Factor.* The voltage factor of a distributed winding is the ratio of the voltage actually induced in the winding to that which would be induced if all the flux linked all the turns.

It is evident from this definition that the voltage factor is dependent not only upon the distribution of the winding itself, but also upon the distribution of the air-gap flux. Thus, there will be two voltage factors for the primary winding, one for the condition where the air-gap flux is set up by the winding $P$ itself, and the other for the condition where the air-gap flux is set up by the winding $S$. The former will be denoted by $k_{p1}$ and the latter by $k_{p1}'$, while the corresponding factors are denoted by $k_{p2}$ and $k_{p2}'$.

When the air-gap flux is set up by winding $P$ in Fig. 3,

$$k_{p1} = \frac{4 \times \text{area } (a\,b\,c\,d\,e\,f\,g\,h) + 4 \times \text{area } (A\,d\,e\,B)}{8 \times \text{area } (a\,b\,c\,d\,e\,f\,g\,h)}$$

$$\text{(see Fig. 4)} = \frac{(4 \times 120) + (4 \times 80)}{8 \times 120} = 0.8333 \tag{65}$$

$$k_{p2}' = \frac{1 \times \text{area } (a\,b\,c\,d\,e\,f\,g\,h) + 3 \times \text{area } (A\,d\,e\,B)}{4 \times \text{area } (a\,b\,c\,d\,e\,f\,g\,h)}$$

$$\text{(see Fig. 4)} = \frac{(1 \times 120) + (3 \times 80)}{4 \times 120} = 0.75 \tag{66}$$

When the air-gap flux is set up by winding $S$ in Fig. 3

$$k_{p1}' = \frac{4 \times \text{area } (m\,n\,o\,p\,q\,r\,s\,t) + 4 \times \text{area } (C\,p\,q\,D)}{8 \times \text{area } (m\,n\,o\,p\,q\,r\,s\,t)}$$

$$\text{(see Fig. 5)} = \frac{(4 \times 50) + (4 \times 40)}{8 \times 50} = 0.90 \tag{67}$$

$$k_{p2} = \frac{1 \times \text{area } (m\,n\,o\,p\,q\,r\,s\,t) + 3 \times \text{area } (C\,p\,q\,d)}{4 \times \text{area } (m\,n\,o\,p\,q\,r\,s\,t)}$$

$$\text{(see Fig. 5)} = \frac{(1 \times 50) + (3 \times 40)}{4 \times 50} = 0.85 \tag{68}$$

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## Discussion

**H. C. Specht:** The authors of this paper have illustrated the transformer action of distributed winding in a way which gives a very clear physical concept of this phenomenon.

There is one item that may be not so easily understood—that dealing with the short circuit condition of two equally distributed windings, as in Fig. 1, where it is assumed that the resistance and leakage reactance are zero. The voltage and flux and, consequently, the current must be zero. Nevertheless the authors figure a current in the primary and secondary in order to determine the current transformer ratio. There is nothing wrong with the method although in reality such currents do not exist and cannot be obtained by actual test. The conditions are of an imaginary nature and represent only means to arrive at the results given in the paper. The conditions obtaining in Fig. 3 are, however, not so fictitious. This imaginary condition is certainly of great help in obtaining the conception of differential leakage.

The authors have chosen in their analysis the same number of slots and coils in both members, primary and secondary, and directly opposite to each other in space. This is done, of course, for simplicity. However, it might have been well to give a simple illustration of a few cases in which the number of slots is not the same and in which one member rotates as is the case in induction motors. This would make the paper more complete and more useful for practical design work.

**R. E. Hellmund:** The purpose of the present paper was, as indicated, to attack the same problem, which is somewhat involved, from a different point of view and to present as simple an analysis as possible. We have purposely refrained from

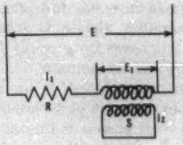


Fig. 1

including in the paper a great deal of additional available material and have excluded everything except what appeared to be essential to a simple explanation of the phenomena and a few general remarks relating to the practical importance of the differential leakage and transformer ratio. The previous remarks may also serve as a reply to a part of Mr. Specht's discussion.

In further answer to the latter, reference may be made to Fig. 10 of our paper. It is reproduced from one of my previous articles, and it will be seen that the leakage coefficient is given for all rotor positions of a three-phase motor. The average of the curves given represents the leakage for the rotating motor condition. This figure was derived for an equal number of slots in the stator and rotor. The method by which it was derived can also be utilized for an unequal number of slots, but in such cases the zigzag and differential leakage cannot be as readily separated as in Fig. 10. It will be necessary to figure the zigzag leakage by one of the existing methods and subtract it from the total in order to obtain the differential leakage.

Mr. Specht has further drawn attention to the fact that, on account of certain hypothetical assumptions made in our paper, it is concluded that in the case of Fig. 1 there is a current flowing although the voltage impressed is zero. This difficulty can be readily overcome by assuming the circuits as indicated in Fig. 1 herewith, including a resistance $R$ in series with the primary motor winding $P$. The secondary winding $S$ is short-circuited. We can now impress a total voltage $E$ and regulate $R$ until any desired current ($I_1$) is flowing. It will then be found that in the case of Fig. 1 in the paper, where there is no differential leakage, the voltage $E_1$ across the primary winding is zero, while in the case of Fig. 3 where there is differential leakage, there will be a definite value $E_1$ across the primary winding. In other words, in the circuit of Fig. 1 herewith it is no longer necessary to assume that a current is flowing with a voltage of zero impressed on the circuits.

When I was originally working on differential leakage, my principal interest was, of course, the performance calculation of motors and the influence which differential leakage had upon such values as power factor, pull-out torque, starting torque, etc. During more recent years my interest in the phenomenon was

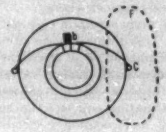


Fig. 2

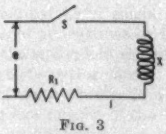


Fig. 3

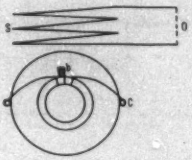


Fig. 4

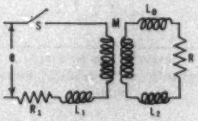


Fig. 5

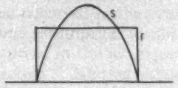


Fig. 6

revived because it entered rather prominantly into certain difficult commutating problems. As is well known, the commutation of certain a-c. motors is not perfect because there may be a definite voltage induced in the short-circuited armature coil which is not compensated for. In such cases there is, of course, a short-circuit current flowing in the coil which has to be interrupted when the circuit is opened.

Such a case is illustrated in Fig. 2 herewith. The circuit of the short-circuited coil of Fig. 2 can be represented as shown in

Fig. 3 herewith, with a definite voltage ($e$) induced in the circuit which contains an inductance $X$ and a resistance $R_1$. The opening of the circuit at the brush is represented by a switch $S$. If we thus look at the commutation problem as a switch problem, we know that the sparking at the switch is not governed merely by the induced voltage ($e$) and the current $I$ flowing in the circuit, but to a very great extent by the magnetic energy stored in the inductance $X$. If we assume now a case as shown in Fig. 2, without a stator winding or any other damping circuit, the inductance of the short-circuited coil will be very large because it is formed by the entire main flux path $F$. In other words, with a given voltage $e$ of possibly three or four volts, very bad commutating conditions may be encountered with such a large amount of stored magnetic energy.

Assuming now the more common case with a stator winding $S$ as shown in Fig. 4, of this discussion the circuit of which is closed, either through the armature, as is often the case, or through an external circuit, we have an equivalent switching circuit as shown in Fig. 5 herewith. It shows the mutual inductance $M$ between the short-circuited armature coil and the secondary stator circuit. Both primary and secondary circuits have resistances, $R_1$ and $R_2$, and leakage reactances $L_1$ and $L_2$, and the secondary circuits may have in addition an external reactance $L_0$, the effect of which is the same as that of the leakage reactance $L_2$. If with such a circuit the leakage reactances are small, the sparking conditions will be materially improved over those in Figs. 2 and 3 because a large part of the stored magnetic energy can be dissipated in the resistance $R_2$ of the secondary circuit. However, in the same measure as the leakage reactances increase, the sparking conditions grow worse, and it is for this reason that the leakages between the short-circuited armature coil and the stator winding, and among them the differential leakage, become of practical importance. If the stator coil $S$ in Fig. 4 herewith is a single coil located in stator slots opposite the armature slots containing the short-circuited coil, the leakage is likely to be small and the commutating conditions fairly good. On the other hand, if the stator winding is distributed, as is often the case, to approach a sinusoidal field form (as shown by $s$ in Fig. 6), rather large differential leakage will be encountered because the short-circuited coil has a rectangular field form $r$. With such widely different field forms, I have found that the differential leakage effect can be as high as nine to ten per cent of the reactance of the main flux path, which in turn can result in very bad commutating conditions.

# Induction Motor Performance Calculations

BY P. L. ALGER*

Fellow, A. I. E. E.

***Synopsis.***—*By means of solutions of the induction motor exact equivalent circuit in the form of infinite power series, approximate formulas for the important motor characteristics are derived. These formulas enable the effects of magnetizing current, core loss, and primary resistance on maximum torque, starting current, and so forth, to be readily taken into account with engineering accuracy. A new form of power factor chart is presented, which enables the power factor–load curve of any motor to be conveniently determined from no load test data. Exact values of power factor can be obtained from the chart by applying differential corrections, formulas for which are given.*

*The methods outlined were developed to secure an optimum combination of speed, accuracy, and consistency in design calculations, and have been in regular use for the past seven years.*

## I. Available Methods of Calculation

THE art of calculating the load characteristics of an induction motor may be said to have begun with the invention of the circle diagram by Behrend and Heyland. Later, the theory of the transformer was developed, and thence Steinmetz derived the equivalent circuit of the induction motor. These two methods have since been used with various modifications, but no entirely new methods have been devised.

In the author's experience, the equivalent circuit method of calculation has proved best suited for all purposes, except that of ready visualization. The circle diagram is useful, especially to the novice, for visualizing the motor's performance over its entire range of operation; but the equivalent circuit enables the characteristics of widely different motors to be determined with the greatest speed and accuracy. The calculations in the solution of the equivalent circuit must be carried out in logical sequence, and preferably with a power factor slide rule,[2] to obtain both speed and accuracy, but other means than straight-forward calculations can be employed with advantage.

In design work, many questions require only approximate, while others require accurate answers. A single method which will yield approximate results quickly, and will also give accurate results with a greater expenditure of time is, therefore, very desirable. Such a method can be developed for most design problems by deriving fundamental equations that take into account only the major phenomena, and also deriving correction formulas which take into account deviations caused by secondary phenomena. The induction motor is particularly suited to this method of design, since many of its characteristics differ only slightly from those of an ideal motor without core loss, primary resistance, or magnetizing current.

It is the purpose of this paper, therefore, to show how the general solution of the equivalent circuit of the polyphase induction motor can be expressed in infinite power series, of which the first order terms are identical with the usual text book formulas, and the higher order terms represent differential corrections to those ideal formulas. Approximate correction factors to apply to the simple ideal formulas are thence derived, which give results to engineering accuracy, and which are very convenient for many design purposes.

The method proposed is an alternative to that recently presented by Mr. W. J. Branson,[1] algebraic formulas supplemented by a single chart being used instead of a series of approximately 100 charts. Both methods assume the equivalent circuit (Fig. 1) to truly represent the motor's performance. The only difference in the basis of the two methods is that Mr. Branson assumed the core loss branch of the equivalent circuit

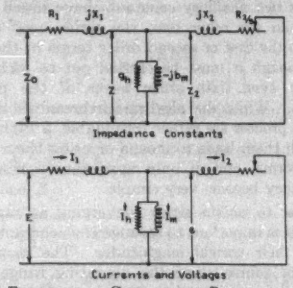


Fig. 1—Equivalent Circuit of Polyphase Induction Motor

to be connected directly across the line terminals, instead of inside the primary impedance, as in Fig. 1. If all the core loss occurred in the primary core back of the teeth, the first assumption would be nearly exact, while if it all occurred in the air-gap surfaces the latter would be satisfactory. Neither connection is exactly correct, and both require separate allowances for stray load losses, so that these differences are unimportant.

## II. Basis of the New Method

The "exact equivalent circuit" of a polyphase induction motor is shown in Fig. 1. In using this circuit, several assumptions are involved, which will be explained in the next section, but these do not lead to any marked departures from experimental results.

*General Electric Company, Schenectady, New York.

2. For references see Bibliography.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*



30-55

There are six independent constants of the circuit, which can be reduced to two principal and two subsidiary constants, by assuming the leakage reactance to be equally divided between primary and secondary ($X_1 = X_2$), and by recognizing that the secondary resistance, $R_2$, and the slip only occur together as the ratio $\frac{R_2}{s}$, so that $\frac{R_2}{s}$ can be used as the independent variable. The principal constants are then the magnetizing and leakage reactances, $X_m$ and $X$, and the subsidiary constants are the primary resistance, $R_1$, and the core loss conductance, $G_h$. There is, in fact, one other constant, the friction and windage, which must be specified to determine the motor efficiency, but this can easily be taken care of by subtracting it from the output indicated by the circuit, without affecting in any way the circuit calculations.

The problem now is to derive simple means of determining any particular characteristic of the motor by use of the equivalent circuit, for any set of values of the four motor constants. To solve this problem, the four constants will be expressed as voltage or current ratios, and the circuit will be solved for the general case by developing it in the form of an infinite power series. Since the two auxiliary constants have much smaller values than the other two, the series need only be carried to the first or second order terms in these constants, though it must be carried out to include the fourth or even sixth order terms of the principal constants. While the algebraic expressions resulting from this process are rather formidable, a little familiarity with them leads to means of using them in convenient forms, and, if only approximate results are desired, they become very simple.

In order to obtain series converging as rapidly as possible, it is important to arrange the constants in the order of their normal magnitudes. The magnitudes depend, of course, upon the operating range of the motor under consideration; the magnetizing current being a very small part of the total under starting conditions, for example, although it is a very large proportion of the whole at light loads. For this reason, it is convenient to carry out the solution separately for the three different ranges of operation which are of interest, corresponding to normal operation under load, the region of maximum torque, and the region of starting. In the following sections of the paper, the process indicated is carried through for these three conditions in turn.

## III. Assumptions and Nomenclature

In conformity with the usual practise, the following assumptions will be made:

(1) $X_1 = X_2$, or primary reactance equals secondary reactance. This assumption is made for the reason that the departures from it met with in practise can cause only small errors; that it is difficult to determine $X_1$ and $X_2$ separately by test; and that to keep $X_1$ and $X_2$ separate in either design or approximate equivalent circuit calculations involves a great deal of extra labor.

(2) $I_m = I_1$ at no load, or the running light power factor is very low. This assumption is made for the reasons that it is closely true for motors above 5 hp. rating; that the departure from fact is greatest in high power factor motors, where the value of $I_m$ is of least importance; and that the approximation greatly simplifies the work.

(3) $I_m$ is proportional to $e$, or the magnetizing current is proportional to $e$. This is true except for the effect of saturation, which cannot be analytically expressed.

(4) The core loss is proportional to $e^3$. This has been shown by many tests to be nearly true at magnetic densities usual in induction motors. At high voltages, the exponent is usually greater than 2, while at low voltages it may be a little less than 2.

(5) All impressed current and voltage harmonics are neglected, or sinusoidal wave forms are assumed throughout.

(6) Stray load losses are neglected, although these can readily be taken into account by increasing the effective primary and secondary resistances by appropriate amounts.

A list of the symbols employed follows:

### Nomenclature

$a = \frac{I_m}{I}$ = ratio of no load magnetizing current to current at assumed load

$b = \frac{I X}{E}$ = ratio of total reactance drop to impressed voltage

$c = \frac{I R_1}{E}$ = ratio of primary resistance drop to impressed voltage

$d = \frac{I R_2}{E}$ = ratio of secondary resistance drop, based on primary current, to impressed voltage

$e$ = induced voltage per phase due to air-gap flux

$E$ = impressed voltage per phase

$F = \frac{\text{friction loss}}{\text{output}}$ = ratio of friction and windage losses to output

$f$ = frequency in cycles per second

$g_h$ = core loss conductance in mhos per phase

$G$ = conductance in mhos per phase

$h = \frac{\text{core loss}}{\text{volt amperes input}}$ = ratio of core loss watts per phase to volt amperes input per phase

$I_m$ = no load current, or magnetizing current, in amperes per phase

$I$ = current in amperes per phase
$j$ = symbol for $\sqrt{-1}$
$k = \dfrac{R_2}{s\,Z_0} = \dfrac{d}{s}$ = ratio of per cent secondary resistance drop to per cent slip
$R$ = resistance in ohms per phase
$s$ = ratio of slip to synchronous speed
$X$ = reactance in ohms per phase
$Y$ = admittance in mhos per phase
$Z$ = impedance in ohms per phase

In general, subscripts 1, 2, $m$, and 0 refer to the primary, secondary, magnetizing, and total or line constants. When no subscript is used, the combined characteristics of the magnetizing and secondary circuits in parallel are indicated. The arrangement of the equivalent circuit is illustrated by Fig. 1.

The quantities $b$, $c$, and $d$, which vary directly as the line current, and $a$ and $h$, which vary inversely, are the essential variables that determine a motor's performance, both as affected by load changes and by variations in the design constants.

## IV. Solution in the Neighborhood of Full Load

At full load as a motor, $s$ is quite small, and $R_2/s$ is the largest part of the total motor impedance, $Z_0$. Hence, we may most conveniently calculate all the impedances of the circuit as products of $R_2/s$ by a power series. Having done this, we may find an expression for $k = \dfrac{R_2}{s\,Z_0}$ by successive approximations, and, by substituting its value in the other expressions, obtain the ratios of all the impedances to $R_2/s$. These ratios and quantities derived from them will give the power factor, torque, and other quantities it is desired to know.

As a prelude to the calculations, it is desirable to note the following equalities:

$$X_1 = X_2 = \frac{b\,R_2}{2\,k\,s} \tag{1}$$

$$e_m = E\left(1 - \frac{a\,b}{2}\right) \tag{2}$$

$$b_m = \frac{s}{R_2}\left(\frac{2\,a\,k}{2 - a\,b}\right) = \frac{s}{R_2}\,a\,k\left(1 + \frac{a\,b}{2} + \frac{a^2\,b^2}{4}\right) \tag{3}$$

$$g_h = \frac{k\,h_s}{R_2}\left(1 + a\,b + \frac{3\,a^2\,b^2}{4}\right) \tag{4}$$

The first step is to express the secondary circuit admittance, $Y_2$, as an infinite series, derived by taking the reciprocal of $Z_2$.

$$Z_2 = \frac{R_2}{s}\left(1 + \frac{j\,b}{2\,k}\right) \tag{5}$$

$$Y_2 = \frac{s}{R_2}\left[\left(1 - \frac{b^2}{4\,k^2} + \frac{b^4}{16\,k^4} - \frac{b^6}{64\,k^6}\right) - j\left(\frac{b}{2\,k} - \frac{b^3}{8\,k^3} + \frac{b^5}{32\,k^5}\right)\right] \tag{6}$$

Adding the magnetizing admittance, $Y_m$, to $Y_2$, and taking the reciprocal, we have their combined impedance, $Z$:

$$Z = \frac{R_2}{s}\Bigg[\Bigg[1 - \left(a^2\,k^2 + a\,b + k\,h\right) + \Bigg(a^4\,k^4 + a^3\,k^2\,b + 3\,a^2\,k^3\,h + \frac{a^2\,b^2}{4} + 2\,a\,b\,k\,h + k^2\,h^2 + \frac{b^2\,h}{4\,k}\Bigg) - \Bigg(a^6\,k^6 + a^5\,k^4\,b + 5\,a^4\,k^5\,h + \frac{a^4\,b^2\,k^2}{4} + \frac{a^3\,b^3}{2} + 2\,a^3\,k^3\,b\,h + \frac{3\,a^2\,b^2\,k\,h}{4} + 6\,a^2\,k^4\,h^2 + 4\,a\,b\,k^2\,h^2 + k^3\,h^3 + \frac{3\,b^2\,h^2}{4}\Bigg)\Bigg] + j\Bigg[\left(a\,k + \frac{b}{2k}\right) - \left(a^2\,k^3 + a^2\,b\,k + \frac{a\,b^2}{4\,k} + 2\,a\,k^2\,h + b\,h\right) + \Bigg(a^5\,k^5 + a^4\,k^3\,b + \frac{a^3\,b^2\,k}{4} + 4\,a^3\,k^4\,h + 3\,a^2\,k^2\,b\,h + \frac{a\,b^2\,h}{2} + 3\,a\,k^3\,h^2 - \frac{b^3\,h}{4\,k^2} + \frac{3\,b\,k\,h^2}{2}\Bigg)\Bigg]\Bigg] \tag{7}$$

The addition of the primary impedance, $R_2/s\left(\dfrac{c}{k} + j\,\dfrac{b}{2\,k}\right)$, to $Z$, gives the total motor impedance, $Z_0$:

$$Z_0 = \frac{R_2}{s}\Bigg[\Bigg[1 - \left(a^2\,k^2 + a\,b + k\,h - \frac{c}{k}\right) + \Bigg(a^4\,k^4 + a^3\,k^2\,b + 3\,a^2\,k^3\,h + \frac{a^2\,b^2}{4} + 2\,a\,b\,k\,h + k^2\,h^2 + \frac{b^2\,h}{4\,k}\Bigg) - \Bigg(a^6\,k^6 + a^5\,k^4\,b + 5\,a^4\,k^5\,h + \frac{a^4\,b^2\,k^2}{4} + \frac{a^3\,b^3}{2} + 2\,a^3\,k^3\,b\,h + \frac{3\,a^2\,b^2\,k\,h}{4} + 6\,a^2\,k^4\,h^2 + 4\,a\,b\,k^2\,h^2 + k^3\,h^3 + \frac{3\,b^2\,h^2}{4}\Bigg)\Bigg] + j\Bigg[\left(a\,k + \frac{b}{k}\right) - \left(a^2\,k^3 + a^2\,b\,k + \frac{a\,b^2}{4\,k} + 2\,a\,k^2\,h + b\,h\right) + \Bigg(a^5\,k^5 + a^4\,k^3\,b + \frac{a^3\,b^2\,k}{4} + 4\,a^3\,k^4\,h + 3\,a^2\,k^2\,b\,h$$

$$+\frac{a\,b^2\,h}{2}+3\,a\,k^3\,h^3-\frac{b^2\,h}{4\,k^2}+\frac{3\,b\,k\,h^2}{2}\Big)\Big)\Big] \quad (8)$$

The absolute value of $Z_0$, found by extracting the square root of the sum of the squares of the resistance and reactance components, is:

$$|Z_0|=\left(\frac{R_2}{s}\right)\Big[1+\Big(-\frac{a^2\,k^2}{2}+\frac{b^2}{2\,k^2}+\frac{c}{k}-k\,h\Big)+\Big(\frac{3\,a^4\,k^4}{8}$$

$$+\frac{3\,a^2\,k^3\,h}{2}-\frac{a^2\,k\,c}{2}-\frac{a^2\,b^2}{4}-\frac{a\,b\,c}{k}-\frac{a\,b^2}{4\,k^2}$$

$$+k^2h^2-\frac{b^2\,h}{4\,k}-\frac{b^2\,c}{2\,k^2}-\frac{b^4}{8\,k^4}\Big)+\Big(-\frac{5}{16}a^6k^6-\frac{17}{8}a^4k^4h$$

$$+\frac{3}{16}a^4k^2b^2+\frac{3}{8}a^4k^2c-\frac{3\,a^3\,b^2}{8}+2a^3k^3bh+\frac{a^2\,k\,b\,c}{2}$$

$$+\frac{5\,a^2\,b^2\,k\,h}{8}-\frac{9\,a^2\,k^4\,h^2}{4}+a^2k^2hc+\frac{a^2\,b^2\,c}{2\,k}+\frac{3\,a^2\,b^4}{32\,k^2}$$

$$+\frac{a^2\,c^2}{2}-\frac{a\,b\,k^2\,h^2}{2}+a\,b\,h\,c+\frac{3\,a\,b^2\,c}{4\,k^2}+\frac{a\,b^3}{8\,k^4}$$

$$+\frac{a\,b\,c^2}{k^2}-k^3\,h^3+\frac{b^2\,h^2}{4}-\frac{b^4\,h}{4\,k^2}+\frac{3\,b^4\,c}{8\,k^3}$$

$$+\frac{b^6}{16\,k^6}+\frac{b^2\,c^2}{2\,k^4}\Big)\Big)\Big] \quad (9)$$

The complete solution of the equivalent circuit has now been formally obtained, and it remains to reduce the expressions to useful forms. The first objective we will set is the calculation of the slip, $s$, for a given primary current, from known values of the circuit constants. Taking the reciprocal of (9), and multiplying through by $R_2/s$, we find:

$$k=\frac{R_2}{s\,Z_0}=1+\Big(\frac{a^2\,k^2}{2}-\frac{b^2}{2\,k^2}-\frac{c}{k}+k\,h\Big)$$

$$+\Big(-\frac{a^4\,k^4}{8}-\frac{a^2\,k^3\,h}{2}-\frac{a^2\,k\,c}{2}-\frac{a^2\,b^2}{4}+\frac{a\,b\,c}{k}$$

$$+\frac{a\,b^2}{4\,k^2}-\frac{3\,b^2\,h}{4\,k}+\frac{3\,b^2\,c}{2\,k^3}+\frac{3\,b^4}{8\,k^4}$$

$$+\frac{c^2}{k^2}-2\,c\,h\Big)+\Big(\frac{a^6\,k^6}{16}+\frac{5\,a^4\,k^4\,h}{8}+\frac{a^4\,k^3\,c}{8}$$

$$+\frac{a^4\,k^2\,b^2}{16}+\frac{5\,a^2\,b^3}{8}-2\,a^3\,k^3\,b\,h+\frac{a^2\,k\,b\,c}{2}$$

$$+\frac{a^2\,b^2\,k\,h}{8}-\frac{a^2\,k^4\,h^2}{4}+\frac{a^2\,b^2\,c}{2\,k}+\frac{a^2\,b^4}{32\,k^2}$$

$$+\frac{a\,b\,k^2\,h^2}{2}-\frac{9\,a\,b^3\,c}{4\,k^2}-\frac{3\,a\,b^5}{8\,k^4}-\frac{3\,a\,b\,c^2}{k^3}-\frac{b^3\,h^2}{4}$$

$$+\frac{b^4\,h}{k^3}-\frac{15\,b^4\,c}{8\,k^5}-\frac{5\,b^6}{16\,k^6}-\frac{3\,b^2\,c^2}{k^4}-c\,k\,h^2$$

$$+\frac{a\,b^2\,h}{2\,k}+\frac{7\,b^2\,c\,h}{2\,k^2}+a\,b\,c\,h-\frac{c^2}{k^3}+\frac{3\,c^3\,h}{k}\Big) \quad (10)$$

As the value of $k$ in the neighborhood of full load is not far from unity, we may readily solve (10) by successive approximations, obtaining:

$$k=1+\Big(\frac{a^2}{2}-\frac{b^2}{2}+h-c\Big)+\Big(\frac{3\,a^4}{8}-\frac{a^2\,b^2}{4}$$

$$+\frac{a\,b^2}{4}-\frac{b^4}{8}+a\,c\,(b-a)+h\Big(a^2-\frac{b^2}{4}\Big)$$

$$+h(h-2c)\Big)+\Big(\frac{5\,a^6}{16}+\frac{5\,a^3\,b^3}{8}-\frac{3\,a^4\,b^2}{16}-\frac{7\,a^2\,b^4}{32}$$

$$+\frac{a\,b^5}{8}-\frac{b^6}{2}-c\Big(a^4+\frac{a^2\,b^2}{4}-a^2\,b+a\,b\,c-a\,b\,h$$

$$+\frac{5\,b^2\,c}{2}\Big)+h\Big(\frac{5\,a^4}{4}-2\,a^3\,b-\frac{a^2\,b^2}{4}$$

$$+\frac{3\,a^2\,h}{4}-3\,a^2\,c+\frac{a\,b\,h}{2}-\frac{b^2\,h}{4}+\frac{a\,b^2}{4}$$

$$+\frac{9\,b^4}{8}-2\,c\,h+h^2\Big)-c^2\Big) \quad (11)$$

For practical purposes, the second and higher order terms in (11) may be replaced by the single term $2\,a^2\,b^2$, which is closely equal to them for normal motors, so that we finally obtain:

$$k\simeq 1+\frac{a^2-b^2}{2}+h-c+2\,a^2\,b^2 \quad (12)$$

Equation (12) has been tested in comparison with the results of complete circuit calculations over a wide range of motor constants, and it has been found to be accurate within 1 per cent for usual values of $k$ (1 to 1.2), and to 5 per cent for abnormal values of $k$ (up to 1.4).

This equation is extremely useful in making performance calculations from test results. For there is no suitable means of directly measuring $R_2$, and a knowledge of this is essential for the start of the equivalent circuit calculations for a definite value of slip. Measurement of $R_2$ by standstill impedance tests involves large errors due to iron losses and eddy currents, and, on slip ring motors, its measurement with direct current applied across the rings involves transformer ratio calculations which may lead to errors.

The normal procedure in testing is, therefore, to operate the motor under load, and take simultaneous readings of line current and slip, establishing a slip-current curve. This test does not require any torque or wattmeter measurements, and so is conveniently and accurately performed. The usual primary

resistance, running light, and blocked rotor tests determine the values of $c$, $a$, $h$, and $b$ for any assumed value of primary current, $I_1$. Substituting these values in (12) gives the value of $k$, which in conjunction with the test $s - I_1$ curve gives $R_2$ from the identity $R_2 = k\,s\,Z_0$. A check may be obtained by repeating the calculations for several values of current, since the same value of $R_2$ should be found in all cases. Thus, a single pair of test values of $s$ and $I_1$ is sufficient, instead of the whole curve. Without using Equation (12), the same answer can be found by guessing the value of $k$, thence finding $R_2$, carrying through an equivalent circuit calculation for the known slip, and comparing the value of $I_1$ thus found with the measured value. By repeating the process with successively closer values of $k$ until agreement is reached, the correct answer can finally be obtained, and this was the method formerly used.

Other useful expressions are those for the secondary current, secondary induced voltage, and power factor. The secondary current is readily determined from the identity $I_2 = I_1 \mid Y_2 Z \mid$. $\mid Y_2 \mid$ is the reciprocal of the absolute value of (5) and $\mid Z \mid$ is the absolute value of (7). Evaluating these quantities with the aid of (11), and multiplying them together gives:

$$\frac{I_2}{I_1} = 1 - \left(\frac{a^2}{2} + \frac{a\,b}{2} + h\right) + \left(-\frac{a^4}{8} + \frac{a^3\,b}{4} + \frac{a^2\,b^2}{2} + a^2\,c + \frac{a\,b\,h}{2} + \frac{b^2\,h}{2} + c\,h\right) \tag{13}$$

which is approximately equal to:

$$\frac{I_2}{I_1} \simeq .98 - \frac{a^2}{2} - \frac{a\,b}{2} \tag{14}$$

This equation is convenient for determining the actual secondary copper loss, and hence the torque and rotor heating, for any slip when the usual no load test data are available.

Similarly, the induced secondary voltage, referred to primary, is given by evaluating the identity $e = E\,Y_0\,Z$ with the aid of Equations (9), (7), and (11), whence:

$$\frac{e}{E} = 1 - \left(\frac{a\,b}{2} + \frac{3\,b^2}{8} + c\right) + \left(\frac{3\,a^2\,b^2}{8} + \frac{a^2\,c}{2} + \frac{7\,a\,b^3}{16} + \frac{b^2\,h}{2} + \frac{5\,b^2\,c}{8} - \frac{9\,b^4}{128} + 2\,c\,h\right) \tag{15}$$

which is approximately equal to:

$$\frac{e}{E} \simeq 1 - \left(\frac{a\,b}{2} + \frac{3\,b^2}{8} + c\right) + a^2\,b^2 \tag{16}$$

Equation (16) is convenient for determining the actual secondary flux densities and the air-gap flux under load conditions. At no load, the per unit primary reactance drop is $\frac{a\,b}{2}$, so that, assuming the core loss to vary as $e^2$, the ratio of actual core loss under load to that at no load is:

$$\frac{e^2}{E^2\left(1 - \frac{a\,b}{2}\right)^2} = (1 + a\,b)\left(\frac{e^2}{E^2}\right)$$

$$= 1 - \frac{3\,b^2}{4} - 2\,c, \text{ approx.} \tag{17}$$

This equation does not make any allowance for stray load losses, which are due to the leakage fluxes produced by the load currents, but it does give the same value for core loss as found by the formal solution of the equivalent circuit of Fig. 1.

All the equations given can be applied to induction generators by simply changing the signs of the $h$ and $c$ terms in the equations, wherever they appear.

## V. Determination of the Power Factor

The power factor may be calculated from the identity, power factor $= R_0 \mid Y_0 \mid$, $R_0$ being given by the resistance component of (8), and $\mid Y_0 \mid$ by the reciprocal of (9). Carrying out the operations indicated, and substituting (11) in the result to eliminate $k$, we find:

$$\text{Power factor} = 1 - \frac{(a+b)^2}{2} + \left(\left(-\frac{a^4}{8} + \frac{a^3\,b}{2} + \frac{3\,a^2\,b^2}{2} + \frac{3\,a\,b^3}{4} - \frac{b^4}{8}\right) + b\,h\,(a+b) + 2\,a\,c\,(a+b)\right) + \left(\left(-\frac{a^6}{16} + \frac{a^5\,b}{8} - \frac{9\,a^4\,b^2}{16} - \frac{15\,a^3\,b^3}{8} - \frac{39\,a^2\,b^4}{32} + \frac{a\,b^5}{4} - \frac{b^6}{2}\right) - c\left(4\,a^2\,b + \frac{9\,a^2\,b^2}{2} + a\,b\,c + 3\,a^2\,c + \frac{5\,b^2\,c}{2} + c^2\right) - c\,h\,(3\,a\,b + b^2 + c - h) + h\left(\frac{a^4}{4} - 2\,a^2\,b^2 - 2\,a\,b^3 + \frac{9\,b^4}{8}\right) - h^2\left(\frac{3\,a^2}{4} + \frac{a\,b}{2} + b^2\right)\right) \tag{18}$$

The complete form of Equation (18) is much too long for practical use, and unfortunately no way has been found for reducing it to an approximate expression of accuracy better than 2 or 3 per cent. It can be expressed in a variety of approximate forms, however, which are useful in rough calculations, such as:

$$\text{Power factor} \simeq 1 - \frac{(a+b)^2}{2} + 3\,a^2\,b^2 \tag{19}$$

This equation indicates clearly the symmetrical way in which $a$ and $b$ determine the power factor, but it is not accurate enough for performance calculations.

It is important to have a ready method of finding the

power factor for any load, when no load test data only are available, so that we must resort to a new expedient. By assuming definite values of the variables $c$ and $h$, we can reduce the variables determining the power factor to three: $a$, $b$, and $R_2/s$. This enables a power factor chart to be plotted, the power factor being given as a function of $R_2/s$ for various values of $a$ and $b$. Such a chart, shown in Fig. 2, can readily be drawn with sufficient accuracy to enable the power factor to be read off to about 0.2 per cent for any conditions. The values read directly will, of course, be in error due to the differences between the actual and assumed

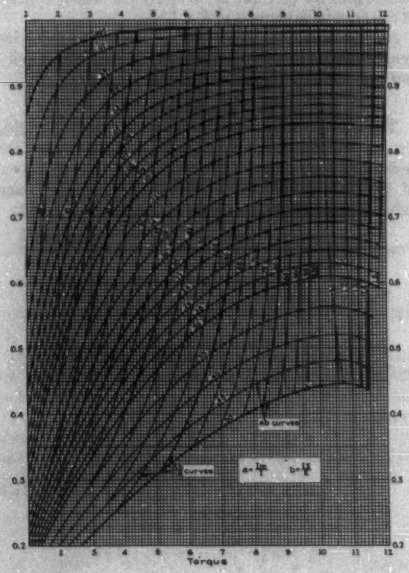


FIG. 2—POWER-FACTOR CHART FOR MEDIUM SIZED MOTORS

values of $c$ and $h$, but these errors can be corrected for by means of the proper terms of Equation (**18**). By constructing two or three such charts for particular values of $c$ and $h$ with definite increments between, the true power factor can be determined with sufficient accuracy for most purposes by a single chart reading, and can be found to within about 2 per cent either by interpolating between two chart readings or by adding a small correction to the reading from a single chart.

The power factor chart shown in Fig. 2 has proved extremely useful in design work, as it enables rapid and consistent predictions of performance to be made with good accuracy. For establishing results from guarantee tests, however, the complete equivalent circuit calculations (Fig. 1) are generally preferable, as they are more basic, and the extra time required is justified in such cases.

Somewhat similar power factor charts have been disclosed by others,[2] but no adequate methods for locating power factor load curves and for correcting the chart results to exact values have heretofore been given. The chart here described was first devised by Mr. H. Maxwell about 1910, and was successively modified by Mr. C. Macmillan and others of the author's associates before it was put into its present exact form in 1923.

The detailed procedure in making the chart is substantially as follows, the numerical values given being those used in making Fig. 2:

1. Arbitrary numerical values for the impressed voltage, $E$, and the leakage reactance, $X$, of the circuit in Fig. 1 are assumed, that will be convenient in calculation.

2. A series of values of the product $a\,b$, covering the range from 0 to 0.50, is assumed.

3. The primary resistance for any value of $a\,b$ is determined by arbitrarily assuming a definite value for $c$, as 0.04, at a load current corresponding to a definite ratio of $a$ to $b$, as 2. These values fix $R_1$ for any value of $a\,b$, the numbers cited giving $R_1 = 0.04\,X\sqrt{\dfrac{2}{a\,b}}$.

4. The magnetizing reactance for any value of $a\,b$ is

$$X_m = \frac{X}{2}\left(\frac{2}{a\,b} - 1\right).$$

5. An arbitrary value, as 0.02, is assumed for core loss current ratio, $h$, at a load current corresponding to a definite ratio of $a$ to $b$, as 2. These values fix $g_h$ for any value of $a\,b$, the numbers cited giving

$$\frac{0.01\sqrt{2\,a\,b}}{X\,(1 - a\,b)}$$

6. For each value of $a\,b$, a circuit is set up with the constants given above, as shown in Fig. 3, and calculations of the circuit impedance are made over a range of values of $R_2/s$ from approximately $X$ to $\infty$.

7. A curve of circuit power factor *versus* secondary input is plotted for each value of $a\,b$, the curves for different values of $a\,b$ being put on a common scale by taking the secondary power input at the load where $b = a$, or where $Z_0 = \dfrac{X}{\sqrt{a\,b}}$, as 10 for each curve.

8. On each curve, points corresponding to definite ratios of $b$ to $a$, as 0.1, 0.2, 0.3, . . . . are marked, and points for each value of $b/a$ are connected by other curves.

9. If desired, a correction for normal friction and windage loss may be made by an appropriate shift of the horizontal scale.

The use of the chart may best be illustrated by an example. Suppose no load tests on a motor have shown

that its running light current is 10 amperes, and that its leakage reactance, determined from standstill tests, divided into normal voltage, gives a current of 200 amperes; and it is desired to find its power factor at a load current of 30 amperes, and its maximum power factor. The value of $a\,b$ is evidently 10 divided by 200, or 0.05, and the value of $b/a$ at 30 amperes input is 0.15 divided by 0.333, or 0.45. The intersection of the two corresponding curves on Fig. 2 gives a power factor of 0.902, and following the $a\,b = 0.05$ curve to its summit gives the maximum power factor as 0.917. The ratio of abscissas at the two points, 6.63 to 10.03, indicates that the torque at maximum power factor is 1.53 times the torque at 30 amperes, and this ratio divided by the power factor ratio indicates that the current at maximum power factor is approximately 45.3 amperes. At half the load torque corresponding to 30 amperes input, the abscissa is half of 6.63, and the power factor is, therefore, 0.792.

If it is desired to obtain exact power factor values, it is necessary to correct the chart values for the errors due to discrepancies between the actual and the chart values of $c$ and $h$, as indicated above. By referring to Equation (18), and taking out all the terms that involve $c$, we find that the coefficient of $c$, or the per cent change in power factor due to 1 per cent change in $c$, is:

$$\left(\frac{\Delta\,\text{P. F.}}{\Delta c}\right) = 2\,a\,(a+b) - \left(4\,a^3\,b + \frac{9\,a^2\,b^2}{2} + 2\,a\,b\,c + 6\,a^2\,c + 5\,b^2\,c + 3\,c^2 + 3\,a\,b\,h + b^2\,h + 2\,c\,h - h^2\right) \quad (20)$$

This may be approximately represented by:

$$\left(\frac{\Delta\,\text{P. F.}}{\Delta c}\right) = 2\,a\,(a+b) - 8\,a^3\,b \quad (20)$$

and this equation gives the correction accurately enough for all practical purposes.

Similarly, the coefficient of $h$ in Equation (18) is:

$$\left(\frac{\Delta\,\text{P. F.}}{\Delta h}\right) = b\,(a+b) + \left(\frac{a^4}{4} - 2\,a^2\,b^2 - 2\,a\,b^3 + \frac{9\,b^4}{8} - \frac{3\,a^2\,h}{2} - a\,b\,h - 2\,b^2\,h - 3\,a\,b\,c - b^2\,c - c^2 - 2\,c\,h\right) \quad (21)$$

which reduces to the following approximate form:

$$\left(\frac{\Delta\text{P. F.}}{\Delta h}\right) = b\,(a+b) - a^2\,b^2 \quad (21)$$

Thus, if the motor used in the example given above had a per unit primary resistance drop at 30 amperes of 0.06, and a no load core loss current of 0.9 amperes per phase, the values of $c$ and of $h$ at this load, 0.06 and 0.03, respectively, would be in excess of the chart values, and so the true power factor would be higher than that indicated. The chart value of $c$ is 0.04 when $a = 2\,b$, or $0.04\sqrt[3]{\frac{2\,b}{a}}$ at any other load, hence is 0.038 at 30 amperes input, where $b/a = 0.45$. Hence, by second (20), the discrepancy in $c$ makes the true power factor greater than the chart value by:

$$(0.060 - 0.038)\,(2\,(0.333)\,(0.333 + 0.15) - 8\,(0.333)^2\,(0.15)\,) = 0.0061$$

Similarly, the chart value of $h$ at 30 amperes input is $0.02\sqrt{\frac{a}{2\,b}}$, or 0.021, and the increase in power factor due to the discrepancy between the motor's and the chart constants is, by second (21):

$$(0.030 - 0.021)\,(0.15\,(333 + 15) - (0.05)^2) = 0.0006.$$

The true motor power factor at 30 amperes input is, therefore, 0.0067 greater than the chart indicates, or is 0.909.

Equation (18) can also be used to find the location of maximum power factor. By differentiating (18) with respect to current, and recognizing that the numerical per cent variations of $a$, $b$, $c$, and $h$ for 1 per cent change in current are all the same, but that $a$ and $h$ decrease while $b$ and $c$ increase with increase in current, the per cent change in power factor due to 1 per cent change in primary current is found to be:

$$\frac{\Delta\,(\text{P. F.})}{\frac{\Delta\,I_1}{I_1}} = (a^2 - b^2) + \frac{1}{2}\,(a^4 - 2\,a^3\,b + 3\,a\,b^3 - b^4) - 2\,a\,c\,(a-b) - b\,h\,(a-b) \quad (22)$$

Equating this to 0, the point of maximum power factor is found to occur when $b/a = 1 + \frac{a\,b}{4}$ very nearly. The corresponding locus is indicated by the dashed line on Fig. 2.

Other relations obtainable from (18) show that the effect on power factor of an increase in frequency at constant line current and voltage is practically the same as the effect of an equal per cent increase in line current at constant voltage and frequency. Also, an increase in voltage with fixed frequency and current has exactly the same effect on power factor as an equal per cent decrease in current with voltage and frequency constant, neglecting saturation.

All the results given apply equally well to induction generators and motors, if the signs of the $c$ and $h$ terms are changed wherever they appear. However, the power factor chart of Fig. 2 is drawn for positive values of $c$ and $h$, so that the corrections to it for the negative values corresponding to generator operation will be relatively large. The power factor so obtained for an induction generator is, of course, leading with respect to the delivered power.

## VI. Efficiency Determination

The readiest exact method of calculating efficiency from test data is by summation of losses. First, the core loss plus friction and windage are determined from no load tests, and then the motor power factor is found with the aid of the chart, for an assumed primary current. The primary copper loss is calculated from this known current, and the measured primary resistance. The secondary resistance is determined from the measured values of slip and current, by (**12**), and the secondary current is found by (**14**), whence the secondary copper loss is known. The sum of these, plus the stray load loss allowance, if any, give the total losses. The input being known from the assumed current and the calculated power factor, the efficiency is at once known. Repetition for different currents establishes a curve of efficiency against output, from which values at the desired loads may be taken.

Instead of using the power factor chart, and calculating the efficiency for an assumed primary current, it may be preferable to use the equivalent circuit directly, and calculate the efficiency for a given slip. When $R_2$ is found from the test-slip-current curve and Equation (**12**), and the rest of the circuit constants are found from no load tests, the equivalent circuit can be solved by ordinary complex number calculations for successive assumed values of slip, and the efficiency and power factor will both then be found at once. In this method stray load losses are usually allowed for by an appropriate increase in the primary resistance.

In making all these calculations by whatever method, it must be remembered that the reactive component of the standstill impedance of the motor does not represent the leakage reactance to be used in the equivalent circuit, but must be corrected for three distinct reasons:

(a) When saturation of the leakage paths occurs, the reactance decreases with increasing current, so that the test value of standstill reactance measured at the current corresponding to the particular load under consideration must be used in each case.

(b) When the secondary current distribution varies with the frequency, as in multiple squirrel cage and deep bar windings, the standstill reactance must be increased in proportion to the increase in the inductance corresponding to the reduction in frequency.[4]

(c) In all cases, the shunting of the secondary leakage by the magnetizing reactances must be allowed for, so that the true total leakage reactance for use in the equivalent circuit is approximately $\left(1+\frac{a\,b}{4}\right)$ times its apparent value found by standstill test (see Equation (**44**)).

## VII. Solution in the Neighborhood of Maximum Torque

At maximum torque, $R_2/s$ is nearly equal to $X$, and the line current is usually about 4 times full load current. Hence, the normal values of the circuit variables are quite different in this region from their values near full load. $b$ is now large (about 0.7), $a$ is quite small, $c$ is of the same order as $a$, and $h$ is so small as to be almost negligible. By repeating the previous equivalent circuit calculations, but with the terms rearranged to allow for their new orders of magnitude, we can obtain useful formulas for the motor characteristics in this region. As less accuracy is needed here, the calculations need not be carried out to as many terms as before. In developing the final equations for characteristics in this region, it is important to use only expressions whose values are functions of the motor design constants and not variables that depend on the load. The products $a\,b$, $b\,h$, $c/b$, $a\,c$, and so forth, fulfil these requirements, and, therefore, the results are all expressed in terms of these quantities. Thus, although the equations involve $a$, $b$, $c$, and $h$, which vary with load, these variables only appear in relations which make them invariant, and, therefore, the equations hold no matter what value of current is assumed in calculating the particular values of $a$, $b$, and so forth.

Equations (**1**) to (**5**) inclusive are valid here, as at full load, but Equation (**6**) is no longer satisfactory, as the large value of $b$ makes it converge too slowly. In place of (**6**), we can write:

$$Y_2 = \frac{s}{R_2}\left[\frac{(4\,k^2 - j\,2\,b\,k)}{4\,k^2 + b^2}\right] \tag{23}$$

Adding $Y_m$ to (**23**), and taking the reciprocal, we find the apparent secondary impedance to be:

$$Z = \frac{R_2}{s}\left[\left[1 - a\,b + \left(\frac{a^2\,b^2}{4} + \frac{b^2\,h}{4\,k} - k\,h - a^3\,k^2\right) + \left(a^3\,k^2\,b + \frac{a^2\,b^2}{4} + 2\,a\,b\,k\,h\right)\right] + j\left[\frac{b}{2\,k} + \left(a\,k - \frac{a\,b^2}{4\,k}\right) - (b\,h + a^2\,b\,k) - \left(a^3\,k^3 + 2\,a\,k^2\,h - \frac{a\,b^2\,h}{2} - \frac{a^3\,b^4}{16\,k}\right)\right]\right] \tag{24}$$

Adding the primary impedance to $Z$ gives the total motor impedance:

$$Z_0 = (R+R_1) + j(X+X_1) = \frac{R_2}{s}\left[\left[1 + \left(\frac{c}{k} - a\,b\right) + \left(\frac{a^2\,b^2}{4} + \frac{b^2\,h}{4\,k} - k\,h - a^2\,k^2\right) + \left(a^3\,k^2\,b + \frac{a^3\,b^3}{4} + 2\,a\,b\,k\,h\right)\right] + j\left[\frac{b}{k} + a\,k - \frac{a\,b^2}{4\,k}\right) - (b\,h + a^2\,b\,k) - \left(a^3\,k^3 + 2\,a\,k^2\,h - \frac{a\,b^2\,h}{2} - \frac{a^3\,b^4}{16\,k}\right)\right]\right] \tag{25}$$

The square of the absolute value of $Z_0$ is found by adding the squares of the real and $j$ components of (25):

$$|Z_0|^2 = \frac{R_1}{s^2}^2 \Bigg[ \left(1 + \frac{b^2}{k^2}\right) + \left(\frac{2c}{k} - \frac{a b^2}{2 k^2}\right)$$

$$+ \left(\frac{c^2}{k^2} - \frac{2 a b c}{k} - a^2 b^2 - 2 k h - a^2 k^2 - \frac{3 b^2 h}{2 k} + \frac{a^2 b^4}{16 k^2}\right)$$

$$+ \left(\frac{a b^3 h}{k} + \frac{a^2 b^2}{2} + \frac{a^2 b^5}{8 k^2} - 2 a^2 k c\right.$$

$$\left. + \frac{a^2 b^2 c}{2 k} + \frac{b^2 c h}{2 k^2} - 2 c h\right) \Bigg] \tag{26}$$

From (26) and the indentity $R_2 = s k |Z_0|$, we find:

$$(k + c)^2 = 1 - b^2 + \frac{a b^3}{2} + \left(2 a b c k + a^2 b^2 k^2\right.$$

$$\left. + 2 k^3 h + a^2 k^4 + \frac{3 b^2 k h}{2} - \frac{a^2 b^4}{16}\right) - \left(a b^3 k h\right.$$

$$\left. + \frac{a^2 b^3 k^2}{2} + \frac{a^2 b^5}{8} - 2 a^2 k^3 c + \frac{a^2 b^2 c k}{2} + \frac{b^2 c h}{2} - 2 k^2 c h\right) \tag{27}$$

which, when solved by successive approximations, reduces to:

$$k = \sqrt{1 - b^2} - c + \left(\frac{a b^3}{4} + \frac{a^2}{2} + h + a b c - \frac{a^2 b^2}{4}\right)$$

$$+ \left(\frac{a b^5}{8} + \frac{3 a b^7}{32} - \frac{3 a^3 b^4}{32} - \frac{5 a^2 b^6}{64} - a^2 c - \frac{b^2 h}{4}\right)$$

$$+ \left(\frac{a^2 b^3}{8} - 2 c h - a b c^2 - \frac{a^2 b^2 c}{4} + \frac{5 a b^9}{64}\right) \tag{28}$$

or, very approximately, to:

$$k \simeq \sqrt{1 - b^2} - c + \left(\frac{a b^3}{4} + \frac{a^2}{2} + h\right) \tag{29}$$

which corresponds to Equation (12). The torque developed is equal to:

$$T = e^2 G_2 = \frac{e^2 R_2}{s Z_2^2} = \frac{I_1^2 R_2}{S} \left(\frac{Z}{Z_2}\right)^2$$

$$= \frac{s E^2}{R_2} \left(\frac{k^2 Z^2}{Z_2^2}\right) = \frac{E^2}{X} \frac{(b k Z^2)}{Z_2^2} \tag{30}$$

which reduces to:

$$T = \frac{b E^2}{X} \Bigg( \sqrt{1 - b^2} - (a b + c) + \left(\frac{3 a b^3}{4} + \frac{a b^5}{4} + 2 a b c\right)$$

$$+ \left(\frac{3 a^3 b^2}{2} - \frac{a^2}{2} - h + a b h + \frac{7 b^2 h}{4} - \frac{27 a^3 b^4}{32}\right)$$

$$+ \left(2 c h + 2 a^2 c + \frac{5 a b^7}{32} + \frac{a^3 b}{2} - \frac{19 a^2 b^6}{64} - \frac{13 a^2 b^2}{8}\right.$$

$$\left. - 2 b^2 c h - a b c^2 - \frac{9 a^3 b^3 c}{2} + \frac{a b^9}{8} + \frac{25 a^3 b^5}{32} - \frac{11 a b^3 h}{4}\right) \Bigg) \tag{31}$$

This equation is not useful for calculating the torque at any particular point, but is extremely useful for the information it conveys in regard to the maximum torque. By differentiating (31) with respect to current (remembering that the rates of per cent change of $b$ and $c$ are equal to the rate of per cent change in current and the rates of per cent change of $a$ and $h$ are numerically the same but are negative), equating to zero, and solving by successive approximations, we find the approximate expression for $b$ at maximum torque:

$$\sqrt{1 - b^2} = 0.707 \left(1 - \frac{a b}{4} - \frac{11 a^2 b^2}{16}\right) - \frac{5 b h}{8}$$

$$+ \frac{3 c}{8 b} - \frac{c^2}{16 b^2} + \frac{a c}{16} \tag{32}$$

Substituting (32) in (31), the value of the maximum torque itself is found to be:

$$T_{max} = \frac{E^2}{2 (R_1 + X)} \left[1 - \frac{3 a b}{4} + \frac{a^2 b^2}{4} - \frac{c^2}{2 b^2} - \frac{b h}{4} + a c\right] \tag{33}$$

This expression agrees perfectly with those found in standard textbooks, if $a b$ is made equal to zero. The usual formulas simply neglect the influence of the magnetizing current on the maximum torque, but (33) shows that this influence, expressed by the reduction factor

$$1 - \frac{3 a b}{4} + \frac{a^2 b^2}{4},$$

is by no means negligible. By reference to the power factor chart of Fig. 2, it will be seen that normal motors with full load power factors of 0.90, 0.80, and 0.70 (full load generally occurs when $b = 0.5\,a$, approximately) have $a b$ values of 0.053, 0.11, and 0.17, respectively, and consequently have maximum torques respectively 4, 8, and 14 per cent below the values indicated by the standard text book formulas. Low-speed motors, which have particularly low power factors, have to be especially liberally designed to secure normal overload torque margins on this account.

From (28) and (32) the value of $k$ at maximum torque is found to be:

$$k = 0.707 - \frac{a b}{200} + \frac{a^2 b^2}{2} + \frac{5 b h}{8} - \frac{c}{3 b}$$

$$+ \frac{5 c^2}{16 b^2} + \frac{3 a c}{8} \tag{34}$$

and from this the slip at maximum torque is:

$$s = \frac{I\,R_2}{k\,E} = \frac{b\,R_2}{k\,X} = \frac{R_2}{X}$$

$$\left(1 + \frac{a\,b}{4} - \frac{c}{16\,b} - \frac{a^2\,b^2}{4} - \frac{c^2}{8\,b^2} - \frac{a\,c}{4}\right) \quad (35)$$

or, approximately:

$$S = \frac{R_2}{X}\left(1 + \frac{a\,b}{4}\right) \quad (36)$$

The power factor at maximum torque is:

$$\text{P. F.} = \frac{k\,s\,R_0}{R_2} = k\left[1 + \left(\frac{c}{k} - a\,b\right) + \left(\frac{a^2\,b^2}{4} + \frac{b^2\,h}{4\,k} - k\,h - a^2\,k^2\right) + \left(a^3\,k^2\,b + \frac{a^3\,b^3}{4} + 2\,a\,b\,k\,h\right)\right]$$

$$= 0.707 - \frac{7\,a\,b}{10} - \frac{a^2\,b^2}{40} + \frac{b\,h}{10} + \frac{3\,c}{8\,b} - \frac{c^2}{16\,b^2} + \frac{7\,a\,c}{8} \quad (37)$$

approximately, or is normally a little below 70 per cent. By a similar procedure, the maximum output is found to be:

$$\text{Maximum output} = \frac{E^2}{2\,(R_1 + R_2 + X)}\left[1 - \frac{3\,a\,b}{4} + \frac{a^2\,b^2}{4} - \frac{(c + d)^2}{2\,b^2} - \frac{b\,h}{4} + a\,c\right] \quad (38)$$

and it occurs at a slip equal to:

$$s = \frac{R_2}{X}\left[1 + \frac{a\,b}{4} - \frac{(c + d)}{16\,b} - \frac{a^2\,b^2}{4} - \frac{(c + d)^2}{8\,b^2} - \frac{a\,c}{4} - \frac{5\,a\,d}{16}\right] \quad (39)$$

and at a power factor equal to:

$$\text{P. F.} = 0.707\left(1 - a\,b + \frac{c + d}{2\,b}\right) \quad (40)$$

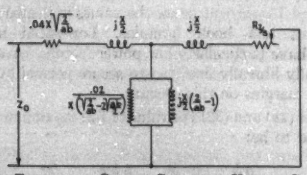


Fig. 3—Equivalent Circuit Constants Used in Calculating Power-factor Chart

## VIII. Solution in the Neighborhood of Standstill

Near standstill, and in reversed rotation, the secondary reactance is larger than $R_2/s$, so that the circuit should be developed in powers of $d$ instead of powers of $b$. Here, also, the core loss can be neglected, and $a$ is much smaller than before.

The apparent secondary impedance on this basis is:

$$Z = X_1\left[\left(\frac{2\,d}{b\,s} - \frac{2\,a\,d}{s}\right) + j\left(1 - \frac{a\,b}{2} + \frac{2\,a\,d^2}{b\,s^2}\right)\right] \quad (41)$$

and the total impedance is:

$$Z_0 = X_1\left[\left(\frac{2\,d}{s\,b} + \frac{2\,c}{b} - \frac{2\,a\,d}{s}\right) + j\left(2 - \frac{a\,b}{2} + \frac{2\,a\,d^2}{b\,s^2}\right)\right] \quad (42)$$

the absolute value of which is:

$$|Z_0| = X_1\left[2 - \left(\frac{a\,b}{2} - \frac{d^2}{b^2\,s^2} - \frac{2\,c\,d}{b^2\,s} - \frac{c^2}{b^2}\right) - \left(\frac{d^4}{b^4\,s^4} + \frac{4\,c\,d^2}{b^4\,s^3} + \frac{6\,c^2\,d^2}{b^4\,s^2} - \frac{a\,d^3}{b\,s^2} + \frac{4\,c^3\,d}{b^4\,s} - \frac{a\,c^2}{b} + \frac{c^4}{b^4}\right)\right] \quad (43)$$

or, very approximately:

$$Z_0 \simeq R_1 + R_2\,(1 - a\,b) + j\,X\left(1 - \frac{a\,b}{4}\right) \quad (44)$$

and:

$$|Z_0| \simeq X\left(1 - \frac{a\,b}{4}\right) + \frac{(R_1 + R_2)^2}{2\,X^2} \quad (45)$$

The torque is, approximately:

$$\text{Starting Torque} = \frac{2\,E^2\,R_2}{X^2 + (R_1 + R_2)^2}\left(1 - \frac{a\,b}{2}\right) \quad (46)$$

Thus, the torque at low speeds is reduced by the factor $1 - \frac{a\,b}{2}$ as a result of the presence of the magnetizing current, or by about two-thirds as much as the maximum torque is reduced. This reduction factor is very important in low-speed motors, and in the induction starting of synchronous motors.

It is important to note that Equation (44) shows that the true leakage reactance for use in the equivalent circuit, $X$, is greater than the apparent reactance by the factor $1 + \frac{a\,b}{4}$, approximately. Some writers use the apparent value of $X$ directly in all their calculations; in an analogous way to that in which the actual magnetizing current, $I_m$, is used here in place of the magnetizing current which would flow if full voltage were

impressed at the air-gap. These variations in usage are likely to cause confusion in comparing results if they are not observed.

## IX. Numerical Results

It is difficult to define the accuracy with which the foregoing formulas determine the motor characteristics, since the errors depend on the relative values of all the variables. The formulas have been used with satisfaction in regular design work for the past six years, however, and the errors have been found well within allowable tolerances for most purposes. To illustrate their use, and to indicate the magnitude of error to be expected in ordinary practise, the numerical results obtained in the cases of five motors of widely different characteristics are presented in comparison with the values obtained by regular circuit calculations.

The selected motors had the following ratings, all for 60 cycles:

| Motor No. | Poles | Horsepower | Rev. per min. | Voltage |
|---|---|---|---|---|
| 1 | 4 | 500 | 1800 | 2200 |
| 2 | 8 | 10 | 900 | 440 |
| 3 | 10 | 125 | 720 | 2200 |
| 4 | 14 | 15 | 514 | 440 |
| 5 | 20 | 500 | 360 | 440 |

In each case, the usual no load test data and one point on a test slip-current curve are given. Thence the equivalent circuit constants are determined, and the characteristics at a point near full load are calculated, first by the approximate formulas, and then by the exact equivalent circuit. In all cases, the reactance, $X$, was determined from standstill tests, with the corrections described at the end of section VI. Many comparisons of actual load tests with equivalent circuit calculations, using reactances so determined and proper load loss allowances, have shown that agreement well within the accuracy of measurement is secured. Thus, the variations between the parallel columns are true indications of the errors of the new formulas.

| Motor No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Measured Values | | | | |
| $E$ | 2200 | 254 | 1270 | 254 | 254 |
| $I_m$ | 16.9 | 5.75 | 9.62 | 16.0 | 267 |
| $W_h$ | 2170 | 83 | 847 | 233 | 3900 |
| $R_1$ | 0.349 | 0.85 | 1.16 | 0.380 | 0.0048 |
| $X$ | 5.71 | 3.50 | 7.40 | 2.03 | 0.070 |
| $s$ | 0.0130 | 0.0320 | 0.0343 | 0.0320 | 0.0132 |
| $I_1$ | 65.6 | 13.2 | 29.2 | 24.0 | 620 |

$W_h$ is the no load core loss in watts per phase; $s$ and $I_1$ are corresponding points on the test slip-current curves.

CALCULATED CIRCUIT DATA

| | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact |
|---|---|---|---|---|---|---|---|---|---|---|
| $I_1$ | 65.6 | 65.6 | 13.2 | 13.2 | 29.2 | 29.2 | 24.6 | 24.6 | 620 | 620 |
| $a$ | 0.258 | | 0.435 | | 0.329 | | 0.650 | | 0.431 | |
| $b$ | 0.170 | | 0.182 | | 0.170 | | 0.197 | | 0.171 | |
| $c$ | 0.0104 | | 0.0442 | | 0.0267 | | 0.0368 | | 0.0117 | |
| $h$ | 0.0150 | | 0.0247 | | 0.0228 | | 0.0373 | | 0.0247 | |
| $k$ | 1.028 | 1.029 | 1.070 | 1.072 | 1.039 | 1.039 | 1.22 | 1.30 | 1.101 | 1.106 |
| $R_2$ | 0.449 | 0.449 | 0.658 | 0.659 | 1.55 | 1.55 | 0.404 | 0.430 | 0.00596 | 0.00599 |

$I_1$ is an assumed primary current at which the characteristics are desired. $k$ is determined by Equation (12) and $R_2$ by the formula $\frac{s\,k\,E}{I_1}$. The exact values of $k$ and $R_2$ were found by repeated trials with the equivalent circuit.

CALCULATED VALUES AT THE ASSUMED CURRENTS

| | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact |
|---|---|---|---|---|---|---|---|---|---|---|
| P. F. | 0.924 | 0.916 | 0.842 | 0.843 | 0.896 | 0.891 | 0.698 | 0.700 | 0.846 | 0.837 |
| Corr. P. F. | 0.917 | 0.916 | 0.845 | 0.843 | 0.892 | 0.891 | 0.704 | 0.700 | 0.836 | 0.837 |
| $I_2$ | 60.6 | 61.0 | 11.2 | 11.2 | 26.2 | 26.3 | 17.2 | 17.1 | 526 | 528 |
| $e$ | 2108 | 2108 | 231 | 233 | 1188 | 1192 | 229 | 230 | 240 | 240 |

The power factor values are from Fig. 2, and the corrected values are from Equations (20) and (21). $I_2$ and $e$ are from Equations (14) and (16).

| Motor No. | 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| CALCULATED MAXIMUM VALUES | | | | | | | | | | |
| | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact |
| Max. P. F. | 0.927 | 0.920 | 0.872 | 0.875 | 0.908 | 0.904 | 0.804 | 0.809 | 0.881 | 0.871 |
| Max. torque | 380 | 385 | 6.92 | 6.86 | 89.8 | 89.4 | 122 | 120.4 | 409 | 408 |

The maximum power factor is from Fig. 2, and the maximum torque, in synchronous kilowatts per phase, is from Equation (33).

CALCULATED STANDSTILL VALUES

| | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact | Approx. | Exact |
|---|---|---|---|---|---|---|---|---|---|---|
| Starting current | 386 | 386 | 68.2 | 68.0 | 164 | 164 | 121.5 | 120.2 | 3660 | 3710 |
| Starting torque | 63.6 | 63.8 | 2.81 | 2.84 | 39.2 | 39.2 | 52.0 | 54.3 | 74.4 | 73.0 |

The current and torque are both determined by Equation (**44**). The torque is given in synchronous kilowatts per phase.

## X. Conclusions

A method of solving the polyphase induction motor equivalent circuit has been developed, which enables simple algebraic formulas to be used for the calculation of all the useful motor characteristics except power factor, with satisfactory accuracy. Heretofore complete circuit calculations, circle diagram constructions, or multiple chart references have been required to secure the same results, the formulas ordinarily presented in text books being too inaccurate for regular design use. Also, a comprehensive and accurate power factor chart has been shown, which is extremely useful in design work.

The "differential correction method," as it may be called, is believed to possess unique advantages in combining speed with accuracy, and in facilitating determination of the effects of independent changes in particular motor constants on any motor characteristic.

The most useful formulas developed are believed to be (**12**), (**14**), (**16**), (**20**), (**33**), (**36**), (**38**), (**40**), (**44**), and (**46**), each of which involves the product of the simple formula for an ideal motor by a correction factor based on the per unit reactance and loss constants of the motor.

A prime object of presenting this paper has been to lay a groundwork for ultimate agreement on standards for the determination of motor performance from test results. The A. I. E. E. Standards do not now give precise instructions for doing this, and it is therefore important that more complete methods should be agreed upon. While no exact procedure for this purpose is recommended here, it is believed that Equations (**12**), (**14**), (**33**), and (**44**) may be useful in this connection.

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## Discussion

**H. C. Specht:** In the paper by Mr. Alger the assumption is made that the measured total leakage reactance can be divided equally for the primary and secondary. This has been the practise for many years. This is fairly correct for wound rotor motors with slip rings; however, for most squirrel-cage motors this is seldom accurate enough. It may be well to split up the measured leakage reactance in the ratio of the primary and secondary leakage as has been obtained by calculation.

Further Mr. Alger assumes that the core loss is proportional to the square of the induced voltage and that at high voltages the exponent is usually greater. I take for granted hereby is meant the core losses at high saturation.

Strictly sinusoidal wave forms are assumed. Although this has been a common practise for many years it does not represent the real case and often the results are badly affected by the high harmonics which more or less exist in all motors.

For the ohmic resistance, the resistance obtained by direct current method is generally used. In fact the effective a-c. resistance is somewhat higher and it seems that Mr. Alger is considering this fact but does not give a method to determine the accurate increase. By some authors on induction motors an empirical percentage of 15 to 25 per cent is assumed. It seems to me it would be worth while to do some research work on this subject.

The various equations developed by Mr. Alger with a few exceptions seem to me too long for practical use and by shortening these, simply by neglecting some members of the equations the accuracy may not be sufficient for all cases. In particular the determination of the power factor does not seem to me practical, the equation itself is much too long for practical use as stated in the paper, and even the assistance of a chart as given by Mr. Alger does not represent a quick method.

In my opinion I do not see any advantage in using an entirely algebraic method of calculating the performance. I am in favor of figuring only some values that can easily be obtained and obtaining the others by the circle diagram. In all my experience I have obtained in this way quick and sufficiently accurate results.

I do not believe that complicated calculations for the determination of motor performance from test results will lead to an agreement on standards. I agree with Mr. Alger that Equations **12**, **14**, **33**, and **44** may be acceptable.

The fact remains that the customer will judge motors by the results obtained on test rather than by theoretical performance calculations.

**R. E. Hellmund:** Mr. Alger's paper and Mr. Specht's discussion thereof merely confirm in my mind the usual experience that every engineer likes his own calculating and design methods best. While a standardization of calculating methods may have certain advantages, I am not at all convinced that such advantages would be worth while in view of the disadvantages which such standardization would bring with it. Any calculating method for everyday use must of necessity make certain approximations to be practical. Whatever such approximations may be, they are usually quite satisfactory for the average case, but there are always extreme cases where the same

approximations would lead to unsatisfactory results. This in itself makes standardization dangerous, especially in the hands of the younger and inexperienced engineer. Furthermore, engineers are differently constituted mentally, and therefore methods giving one engineer the most satisfactory conception and understanding of his work will not prove nearly as useful to another engineer as some other available methods. Finally, the standardization of working, or, as you might call them, "thinking methods" would be likely to stifle the individuality and originality of the engineer.

Having thus granted that various methods should preferably be used by different engineers, I do not hesitate to state that my preference is in the same direction as that of Mr. Specht's with regard to the use of the circle diagram. The use of this method has become so common in the working up of performance from test results that it should certainly be retained as one of the generally recognized methods. I have even made it a practise to use the circle diagram almost exclusively for design purposes, because after the calculations required for any method are made the diagram can be constructed in a few minutes and is then available for deriving a complete motor performance. By using the ratio $\frac{A\,B}{A\,C}$ as the leakage coefficient and figuring the angle ($E$) of the circle displacement, the circle $B\,D\,C$ can be drawn. This gives for any arbitrarily assumed point $D$ a primary current $A\,D$ and a secondary current $B\,D$. It is then possible to figure the primary copper losses $D\,E$ and draw the line $E\,F$. Its

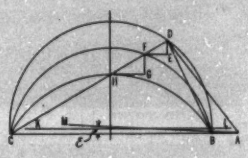


Fig. 1

intersection with $C\,D$ locates the torque circle $B\,F\,C$. By figuring the secondary losses $F\,G$, the output circle $B\,H\,C$ can be found. The constant losses give the distance of the line $L\,K$ from $A\,C$, and we are now ready to find currents and power factor for any desired load. The efficiency also can be taken from the diagram, but may have greater accuracy if calculated in the usual way after the currents have been determined.

I prefer the circle diagram method not only because it gives a better visual picture of the motor performance and the possibilities for changes in design, but also because it represents a method which can be easily remembered. Although I have not designed any induction motors for about fifteen years, I could readily calculate the motor performance from the diagram as shown without referring to any notes. This obviously would be impossible with a set of formulas and curves as given in Mr. Alger's paper.

**C. J. Koch:** Mr. Specht has raised the question as to whether the measured total leakage reactance can be divided equally for the primary and secondary. Of course, the probability is that in a very few cases that is true, primary and secondary reactances are exactly equal and in all motors of the double type it is quite far from being true. However, the error induced by moving the magnetizing current to the right or left in that figure so as to make $X\,1$ greater than $X\,2$ is true and as a matter of fact, except in low speed motors the result would hardly be modified. If the magnetizing current was assumed to be low, the assumption is that the core loss variation is not as much as it might appear. What we do, is take the value of core loss with the dynamometer when the motor is running light and it draws so many watts from the line. The air-gap goes down slowly and it is assumed that it is involved and that the actual L. U. T. voltage varies only perhaps ten per cent. So the assumption which we are making does not involve any very great error.

In regard to measuring the resistance by direct current I presume Mr. Specht had reference to the primary resistance. We know in large motors it may be higher than the resistance to direct current. However, the means for calculating this current are so well known to everyone that it has been more or less taken for granted in this paper. In small motors it is entirely absent and there is no need for increasing the primary resistance when it is carrying alternating current. I don't think it was Mr. Alger's intention to recommend these design methods to be used by everyone. As Mr. Hellmund says, everyone has his own preference in his every day work.

However, Mr. Alger's idea was rather this: at the present time various manufacturers give guarantees on efficiency of motors which are not based on full load tests of the motors but are based on so-called running light tests and block rotor tests and the manufacturers then deduce from these tests what the motor will actually do under load. In the organization I represent we use equivalent circles, others use the circle diagram, but the recommendations of the Institute are not very clear as to just what should be done or how it is being done. I think Mr. Alger's offering in the conclusion was the intention of improving the A. I. E. E. Standards, by giving a more definite method for going from the running light load tests to the actual power tests under full load.

**P. L. Alger:** I believe the equivalent circuit of Fig. 1, with the branch impedances properly determined, represents the motor performance with great accuracy, and that the straight algebraic solution of the circuit for a single load is both quicker and more accurate than a circle diagram solution. The circuit impedances are not truly constant, however, as all the reactances decrease with increasing current, and in double squirrel cage motors especially, the secondary resistance increases and the secondary reactance decreases markedly with decreasing speed. Hence, different values of the impedances must be used for different operating ranges, which is another way of saying that the imperfections of the circuit can be conveniently allowed for by varying the "constants."

The circle diagram shown by Mr. Hellmund assumes the primary copper loss to be the secondary current squared times the primary resistance, plus the no load copper loss. This gives rise to relatively large errors. In addition, the diagram is no more a true circle than the equivalent circuit is correct, when the branch impedances vary from saturation or other causes. Thus, for most accurate calculations, a different set of values for the circuit constants and a different circle diagram should be drawn for each region of motor operation.

I have found the formulas given in the paper, and especially the power factor chart, to be very convenient for regular use.

I have recently had the pleasure of meeting Mr. D. B. Hoseason, who has developed a very similar method of calculation, and who informed me that he is using it for regular design work.

# Voltage Irregularities in D-C. Generators

BY J. T. FETSCH*

Associate, A. I. E. E.

***Synopsis.***—*This paper enumerates the voltage irregularities which may occur in d-c. generators. It gives a description of these irregularities, the cause of their occurrence, the magnitude of their values, their effect on radio circuits, and states the problem encountered in their measurement.*

*A method is described for the measurement of these voltage irregularities, by the use of an oscillograph, a blocking condenser, and a current transformer.*

*A number of oscillograph records, illustrative of the voltage irregularities existent in various d-c. generators, is shown, and an analysis of the wave form made for each component of slow and fast ripple. These records were taken under various electrical and mechanical conditions of the generators. Comparisons between these records are made.*

*Conclusions are drawn as to features desirable in d-c. generators.*

* * * * *

## General Introduction

THE general idea is held that the voltage from a d-c. generator consists of a continuous smooth produced electromotive force with practically no fluctuations. This opinion is decidedly a misapprehension, since in some cases the voltage irregularity may be as large as 5 to 10 per cent, although in the majority of cases the range is around 1 to 2 per cent. The value of this irregularity encountered, depends almost wholly on design, and is governed principally by the type of winding, shape and size of poles, the type and number of slots, to a degree upon the size of the machine, the air-gap, the electric and magnetic loading, the occasional lack of the interpole feature, and the method of fabrication. This last item is important, as will subsequently be brought out in this article.

For ordinary commercial power work where machines of comparatively low voltage are used, a ripple voltage of one per cent is usually not harmful, but where the d-c. generator is of the high-voltage type and is used for a special purpose such as the source of supply for plate power and bias of vacuum tubes, the following harmful effects may ensue: First, there may be modulation of the radio frequency output of the vacuum tube, causing sidebands and an accompanying broadness of the signal transmitted. This may be especially objectionable where telephone is being used. Second, generator hum in nearby receivers may be experienced by the setting up and the radiating of highly damped radio frequency oscillations in the power supply leads of the high-voltage source. Third, unduly high peak voltages on radio equipment being supplied with such a source.

The problem at hand is to measure this ripple voltage by some method, and whatever method is used, must be sufficiently sensitive and owe its successful operation to the utilization of the very small currents available for measurements. Several methods were tried, but failed on account of inadequacy or the lack of sufficient degree of sensitivity. The reason for this is because the ripple voltages present in high-voltage machines are only of the order of 10 to 20 volts, and the ripple current which flows through the circuit impedances only of the order of one or two milliamperes. Now, if a current transformer is used for stepping up this minute current to about 100 milliamperes, then the standard element of an oscillograph can be actuated to a degree sufficient to give a very good record of the voltage irregularity. By utilizing this method of transformer and oscillograph, it was possible to measure ripple voltages of the order of ¼ of one per cent and sometimes better. In addition, the oscillograph record of the wave form is very valuable, as it is the basis for the analysis of the causes of these voltage irregularities.

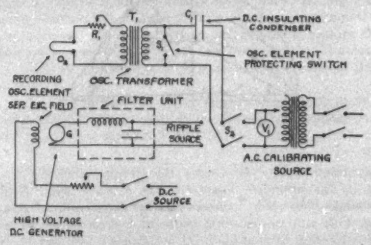


Fig. 1—Diagram of Connections for Measurement of Voltage Irregularities

$V_1$ = 0-15 volts a-c. 25-2000 cycles
$S_2$ = D. P. D. T. transfer switch
$C_1$ = 2-3 microfarads, insulated to withstand d-c. generator voltage
$S_1$ = S. P. S. T. protecting switch
$T_1$ = oscillograph current transformer ratio approx. 95 to 1
$R_1$ = 2 ohm variable resistance
$O_2$ = standard oscillograph element 1 cm./50 ma.
$G$ = high-voltage d-c. generator under test

## 2. Description of Method for Measuring Voltage Irregularities

This method gives a photographic method of the voltage irregularity under investigation by the combined use of an oscillograph, a current transformer, and a condenser. Referring to Fig. 1, the oscillograph element $O_2$ is that used in the standard type of oscillograph, and has a sensitivity of one cm. deflection on the screen per 50 milliamperes. In

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30-56

conjunction with this oscillograph element $O_2$ is used a current transformer $T_1$, so that the minute value of primary current composing the ripple may be stepped up to a useful value to operate the element $O_2$. A condenser $C_1$ of 2 to 3 microfarads is inserted in series with the primary of the transformer to prevent direct current from flowing, yet allowing the ripple current to pass through. This condenser must have negligible leakage, else sufficient direct current might pass through the transformer primary, thus causing the iron core to saturate and thereby prevent the faithful reproduction of the voltage irregularities being studied. The switch $S_1$ is for protecting the element $O_2$ and the transformer $T_1$, and is always kept closed except during observations and photographic recording of the ripple wave form, and while the element is being calibrated. The variable resistance $R_1$ is about two ohms and is used to regulate the amplitude of vibration of element $O_2$. The switch $S_2$ is used as a transfer from the unknown ripple source to the a-c. calibrating source. $G$ is a generator, with separately excited field, whose ripple voltage is under investigation. A filter unit is shown connected into the high-voltage circuit, but may be removed from the circuit if desirable. The calibrating circuit shown comprises a sinusoidal source of known frequency with the possibility of variation, and a transformer for reducing the voltage to a desirable value. This voltage is indicated by meter $V_1$, and is then fed to the oscillograph circuit.

The procedure in obtaining records is first to calibrate the element $O_2$, second to take an oscillographic record of the ripple, and third to recalibrate the element $O_2$. These calibrations are then averaged, and applied to the trace of the film taken during calibrations. This must be done for each film record to ensure accuracy, as there are physical factors which disturb the permanent calibration of the oscillograph element. For calibration, voltages of the proper amplitude and frequency corresponding to those inherent in the ripple source are used. These can be determined by observations on the screen and by simple calculations.

In manipulation of the apparatus, the frequency of the a-c. source is first adjusted to that belonging to a certain component of the ripple voltage. The voltage $V_1$ as read on the meter is then adjusted by varying the supply source until observations show proper amplitude of vibration as seen on the scanning screen.

The amplitude of vibration may be recorded photographically or measured on the oscillograph screen. Examples of those taken by the former method are shown in Film No. 1, where a 25-cycle source was used for calibration and of Film No. 15, where a 1000-cycle source was used. These calibrations at different frequencies are applied to their respective ripple components found in the oscillographic trace. It is necessary to apply a different calibration constant for each frequency, because the calibration varies somewhat with the frequency.

In preparation for taking an oscillographic record of a voltage irregularity, after the calibration has been obtained, Switch $S_2$ is placed to the left, and the apparatus placed in operation for taking a record of the generator ripple. The field of the d-c. generator $G$ is gradually increased until normal generated voltage is indicated. After conditions are steady $S_1$ may be opened, and the voltage irregularity observed on the oscillograph screen. If this is judged satisfactory for photographing, a record may be made, care being taken to omit no part in the operating procedure of the oscillograph instrument, lest negative results follow. From here on the calibration procedure is once again gone through as explained previously under calibration.

In the interpretation of the film records, for obtaining the per cent ripple voltage, the question arises as to what shall be designated as the per cent ripple. This is to be designated as the voltage variation from the highest positive peak to the lowest negative peak on a trace divided by the average d-c. potential of the generator as read on a D'Arsonval instrument.

As a definition for the components of the ripple voltage, the slow speed components will be all of those due to grain direction, speed variation, and other armature reluctance variations of any kind, while high-speed ripple will be termed that caused by the slots and that due to commutation.

In finding the per cent ripple, the low-speed and the high-speed components of the ripple voltage have their individual calibrations applied, and then, either the per cent ripple can be given for each component, or added together to give the total.

## 3. Voltage Irregularities which Occur and an Explanation of Origin of Each

An analysis of this problem by means of oscillographic records proves that the following voltage irregularities exist collectively or in part in high-voltage d-c. generators.

(a) Slot ripple.

(b) Commutator ripple.

(c) Armature reluctance variation ripple due to grain direction in steel.

(d) Armature reluctance variation ripple due to improper physical alinement.

(e) Speed variation due to improper shaft alinement of motor and generator.

(*A*) *Slot Ripple.* Slot ripple is due to resultant pulsations in magnetic flux which surge through the armature windings of the generator, thereby causing periodic voltages to appear at its terminals. These pulsations arise by virtue of the fact that the slots on the armature periphery are moving by the leading, and trailing pole tips, thus effecting changes in magnetic reluctance and field distribution in the air-gap as they do so. It can easily be seen that the periodicity of this pulsating electromotive force will be the product of the total number of slots times the rev. per sec. of the armature.

An explanation of the resultant flux pulsation and its accompanying induced electromotive force in the armature winding can be seen by studying the diagram shown in Fig. 2. Here is a developed simplex, singly re-entrant drum winding for a two-pole machine. There are eight slots on the armature of this machine on which all even conductors are located at the bottom of the slots, and all odd conductors located at the top of slots, or vice versa.

Considering the direction of rotation of the generator to be to the right (as shown in Fig. 2), the leading pole tips will be the left hand edges of the $N$ and $S$ poles and the trailing pole tips the right hand edges of the $N$ and $S$ poles.

Now, whenever an armature tooth passes by a leading pole tip into the magnetic field there will be a decrease in reluctance of the magnetic circuit at this point. Correspondingly, when a slot passes by a leading pole tip into the magnetic field, there will be an increase in the reluctance of the magnetic circuit at this point.

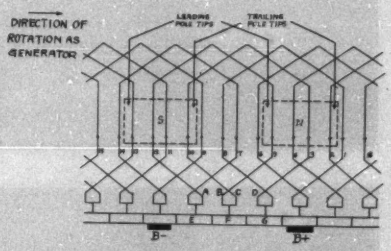



Fig. 2—Developed Two-Pole Simplex Single Re-entrant Drum Winding

Also, when the above armature teeth or slots pass out of the magnetic field from under the trailing pole tips the reluctance of the magnetic circuit is changed similarly to those cases explained above.

Referring to Fig. 2, and especially with regard to conductors $A\ B$ and $C\ D$, let us imagine that a tooth is passing by the trailing tip of the $S$ pole and at the same time imagine that a tooth is passing by the leading tips of the $N$ pole. This means a decrease in reluctance in both cases. The effect of this change in reluctance will be to increase the magnetic flux through the armature coils $A\ B$ and $C\ D$. In turn, a pulsating electromotive force will be induced in the windings and will appear across commutator bars $E\ F$ and $F\ G$. As these coils are part of the total number included between the brushes $B\ B$, this pulsation will appear at the brushes of the machine.

Now, going back a bit, let us imagine that conditions were such as enumerated in the above case, except that instead of the tooth passing by the leading tip of the

*N* pole, a slot is passing by. Here, in one instance, the reluctance is increased and in the other instance, the reluctance is decreased. These will tend to offset each other. If they are equal in magnitude and oppositely directed, no pulsating voltage will be induced in the windings *A B*, and *C D*, hence no resultant slot ripple voltage will appear at the machine terminals.

The point to be made in the above explanation is that slot ripple can be entirely eliminated by proper design. This depends on the proper per cent of pole enclosure with respect to the armature slots. The distance from leading to trailing tips of adjacent poles should be proper so as to eliminate the magnetic pulsation enumerated above. Moreover, the pole coverage should be such as to include an integral number of slots or teeth. Of course, the fringing effect may change this stipulation somewhat, but the condition desired in attaining is that there be no resultant flux change through the generator windings for the complete obliteration of slot ripple.

A quick test can be made on generators to ascertain whether they will have slot ripple. If the conditions as set forth above are existent, there will be no resultant variable forces on the armature during rotation due to the slots. Keeping this in mind, if an armature is slowly rotated by hand, with full field applied, there will be no variation in torque. This means that here the generator will be devoid of slot ripple. On the other hand, if variations in torque occur as the armature is rotated, this means unequal changes in the magnetic forces at the leading and trailing tips, and hence ripple voltages will be inherent in the generator.

*B. Commutator Ripple.* Commutation ripple is that voltage irregularity arising from the reversal of current flow in the armature coils due to the brush passing from bar to bar of the commutator. When this current is changed in an armature coil, a reactance voltage is set up. This reactance voltage must be compensated for, else it will appear at the terminals of the generator.

In earlier types of d-c. machines, it was taken care of, at least partially, by brush advance, and in modern design by interpoles mainly, although even now many small machines are built with the omission of the interpole feature.

In order for a machine devoid of interpoles to commutate successfully, the coil undergoing commutation is moved into an adverse field. By so doing, a voltage is induced in the coil, large enough not only to overcome the reactance voltage set up in the coil, but of sufficient strength to make a current flow in the opposite direction in the coil equal in value to the load current. For this condition little or no sparking will occur at the brushes, and no voltage is left over to affect the terminal voltage of the machine. The disadvantage of this type of correction for commutation is that the adjustment holds only for a definite load current through the generator. Any other value of generator current produces some sparking at the brushes and some commutation voltage irregularity.

This drawback is overcome by the use of the interpole for commutation purpose. As the strength of the interpole is proportional to the load current, the induced voltage in the coil under the interpole will thus be proportional to the load current, as is also the reactance voltage in the coil. Thus, with proper adjustment, commutation irregularities practically do not exist. Experience so bears out the above statement with regard to the advantages of the interpole feature that all machines used as d-c. high-voltage sources should be equipped with interpoles.

*C. Armature Reluctance Variation Due to Grain Direction.* There is another voltage variation which is noted in d-c. high-voltage generators due to grain direction in the sheet steel used for the armature material. This grain direction is a property imparted to the sheet steel during manufacture and causes the steel to have somewhat better magnetic properties in the direction of sheet rolling, than in other directions. Thus, this permits pulsations in the magnetic circuit as the armature rotates, and therefore ultimately affects the terminal voltage of the generator.

In the use of sheet steel for armature laminations, certain methods of manufacture are employed in the stamping of the armature laminations and in the fabrication (construction) of the armature from these laminations. Usually, where small d-c. motors and generators are concerned, the armature generally consists of a single lamination stamped from a piece of sheet steel. Moreover, a place for a keyway is incorporated in this lamination by having the punching die so made as to cut out a rectangular place in the steel. At the factory where these laminations are punched, the sheet silicon steel is fed into a machine at one end, and the lamination stamped out of this material, the lamination being always stamped in the same relative direction with respect to the grain of the material. This direction is usually along the longest dimension of the sheet. Hence, all the laminations, when stamped, have the same relationship between the direction of the grain in the sheet steel and the slot made for the keyway.

Now, it can be seen that when these laminations are all assembled in the form of an armature, the magnetic properties of the armature are going to be somewhat better between those points which include the line coincident with the grain direction, than with any other direction. Thus, with an armature of this type (and up to this time all small armatures are built up of a stack of single disks with slots and keyway stamped therein) there will be a pulsation in the reluctance between the pole faces as the armature rotates. This pulsation will cause a variation in the flux threading the armature, the rate of pulsation being determined by the speed and number of poles of the machine. The period will be twice the rev. per sec. of the machine

because it must be noted that for every revolution of the armature the grain direction is coincident with the line of the poles twice, considering a two-pole machine. Thus the periodicity of this variation will be twice the product of the rev. per sec. times half the number of poles. Good examples of this are Films Nos. 16, 20, and 24. These all show this grain direction voltage irregularity, and are examples of four-pole generators. The periodicity of this voltage irregularity proves to be as stated above, *i. e.*, the rev. per sec. times half the number of poles. While these few films show in a very pronounced fashion the effect of grain on the terminal voltage of a generator, every film included herein shows this effect to a greater or less extent.

irregularity would be four times the product of the rev. per sec. times half the number of poles, instead of twice as in the preceding explanation. A striking example of this is afforded by Films Nos. 17 and 18, and all subsequent films taken with motor generator set No. 3. Here the pulsation, due to grain direction, is twice the frequency of what would be expected with a large diameter armature. Owing to the fact that the diameter of the shaft of this generator is nearly 30 per cent the armature diameter, this accounts for the doubled periodicity of the magnetic pulsation.

In connection with the effect of grain direction, the following may be pointed out. If the generator is of the interpole type, there will be an additional point of

While in general the magnetic path from pole to opposite pole through the armature is best when the grain direction in the armature laminations is coincident with a line through the centers of these poles, nevertheless a digression from this condition is sometimes existent. For machines with very small armatures it may happen that on account of the diameter of the shaft being comparable with that of the armature, the path of least reluctance of the armature and poles does not occur when the grain direction is coincident with a line through the centers of the main poles, but occurs both before and after this position is reached. In this case, the periodicity of this voltage

minimum reluctance besides that stated above and this will have some relationship with the grain direction of the armature and a line through the centers of the interpoles. This reluctance variation, unlike the one above, may or may not produce a voltage irregularity, depending on certain factors such as the design of the machine. What can happen is that the wave form of the voltage irregularity may change with load, as the magnetomotive forces acting, and the flux distribution at no load are different from those acting at various loads. These magnetomotive forces can disturb the flux distribution in the air-gap and in conjunction with the grain direction, bring about a change in wave form

of the ripple. The effect of these magnetomotive forces with an interpole machine is much more likely to disturb the flux configuration in the air-gap than with a machine devoid of interpoles.

A description of the effect of grain in a machine can be better elucidated, perhaps, by means of Figs. 3, 4, and 5. Fig. 3 shows a two-pole interpole machine with the grain direction indicated. When the grain direction is in line with the main poles, the reluctance of the magnetic circuit is minimum, and is somewhat greater in all other positions of the armature. Fig. 4 shows the

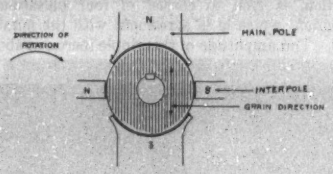



Fig. 3

field distribution under the main poles. As the machine rotates, and the grain direction comes under position *A*, Fig. 4, there is a sudden increase in magnetic flux. This flux surges through the generator winding and induces a voltage as shown in Fig. 5, at position *D*. When the grain direction reaches *B*, the flux increase no longer is taking place, hence there is no electromotive force induced in the generator winding. This is the

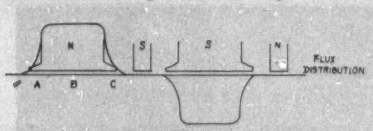



Fig. 4

point where the ripple voltage is zero, (position *E*, Fig. 5). Later on when the grain direction reaches *C*, Fig. 4, there is a diminution in the magnetic flux, and hence an electromotive force of opposite polarity is induced in the generator windings as is indicated by position *F*, Fig. 5. Throughout the remainder of the revolution an exact repetition of the above changes takes place. Examples can be seen by examination of any of the records presented herein. In particular Film No. 2 bears out this explanation.

*D. Armature Reluctance Variation Due to Improper Physical Alinement.* If an armature is not running true, so that the armature periphery and the field bore are both eccentric to the shaft, then the conditions represented may be such as to produce a reluctance variation, and so a voltage irregularity. Also, if the armature shifts to and fro longitudinally, so that the pole face does not always cover the ends of the armature, the effective flux acting through the armature windings may be reduced at certain instants, causing voltage irregularities. The periodicity of the former will be equal to the rev. per sec., whereas that of the latter may be some integral number times the rev. per sec.

*E. Speed Variation Due to Improper Shaft Alinement of Motor and Generator.* As the steadiness of the generated d-c. voltage depends on the constancy of the generator speed, any factor causing variation in speed will influence the terminal generated e. m. f. A few possibilities can be mentioned as first, a variation in motor speed, second, a variation in torque on the generator armature, and third, misalinement of the motor and generator shafts. It is this latter factor that sometimes may play an important part in causing a voltage irregularity, sometimes being the greatest in magnitude, compared to any other.

This may come about, if the shafts of the motor and generator are out of alinement, and a flexible coupling connects them. What takes place is that a to and fro oscillation is set up, due to the pliable material of the coupling flexing during certain parts of the shaft revolution. A little later, this flexure changes, and this pliable material between the two faces of the steel couplings takes on another configuration. The contact

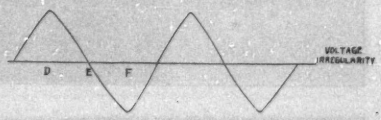



Fig. 5

points between the leather and the couplings are continually changing their effective radii, and fluctuations in speed arise thereby. Immediately upon alinement of the shafts of such a motor generator set, the voltage irregularity due to this cause disappears.

## 5. Oscillographic Records of Voltage Irregularities in High-Voltage D-C. Generators

Herewith are presented examples of oscillograph records of voltage irregularities taken by the method described in this article. The records were taken from generator sources used as d-c. high-voltage supplies for radio equipment. These films show quite a few unexpected phenomena, and each film will be described separately as almost every record brings out and substantiates some particular fact.

Concerning the film records, complete data such as calibration values of volts per inch, ripple percentage, and other facts have all been recorded directly on the oscillograph film.

*Film No. 27.* The first oscillographic record to be presented is that of the generator of set No. 1, taken on Film No. 27. This two-pole generator has 30 slots and 90 commutator segments. It is devoid of the interpole feature, and does not have the proper pole coverage with respect to the slots for eliminating slot ripple.

It is shunt wound, and has a single high-voltage commutator.

With a study of Film No. 27, it can be seen that slot ripple exists as is shown by the 30 pulsations occurring per revolution of the armature. This is a high-frequency ripple of 819 cycles per second, and is not extremely difficult to filter.

Some commutator ripple is also present due in part to the lack of the interpoles, and to the division of the winding. This too, like slot ripple, is of high frequency, but is not generally of very great amplitude as compared with other kinds of ripple.

The effect of grain direction in the armature can be observed and is seen to consist of four pulsations instead of two as is generally obtained. This is caused by the smallness of the generator armature, the machine being of only 0.5 kw. rating. This is a slow speed voltage irregularity and requires a very large filter to eliminate effectively.

No other irregularities are discernible in this machine, and hence indicate either the entire absence or the extreme smallness of their values.

A point to be noted is the variation in the amplitude of the ripple with load. In this particular generator, the ripple increased about 30 per cent from no load to full load.

*Film No. 16.* The four-pole generator used in obtaining this film record is that of motor generator set No. 9. It has 49 slots and 195 commutator segments. There are two high-voltage commutators connected in series; the machine has interpoles to take care of commutation, and has a compound field.

Slot ripple is non-existent in this machine as the design of the pole coverage with respect to the armature slots is such as to eliminate it.

Commutator ripple is also non-existent, principally on account of the interpole feature.

An armature reluctance variation e. m. f. due to grain direction, is seen to consist of four pulsations per revolution, which is in agreement with the number of poles. The amplitude of this ripple increases about 10 per cent from no load to full load, and a small amount of saturation effect can be noticed on the full load trace.

There is a slight indication that the speed of the machine varies with the revolution of the armature, as the peaks of the ripple wave form recorded on the trace are not all of the same height. This, of course, may be due to slight misalinement of the armature and poles rather than due to speed variation.

*Films No. 20 and No. 24.* These two records were taken from the four-pole generator of set No. 8. This machine, with the exception of a possible different shunt field winding and of more turns per armature coil, is exactly similar to the generator of motor generator set

No. 9 whose oscillographic record is shown in Film No. 16. It has 49 slots and 195 commutator segments. There are two high-voltage commutators connected in series; the machine has interpoles and has a compound field.

Both slot ripple and commutator ripple are nonexistent for the same reasons given in the above explanation for Film No. 16.

Similarly, as in the previous example, armature reluctance variation due to grain direction is seen to consist of four pulsations per revolution, which is also in agreement with the number of poles of this machine. Here, unlike the results shown on Film No. 16, the amplitude of this ripple decreases slightly (about 5 per cent) with load and a small amount of saturation effect can be noticed on the full load trace, but is not so pronounced as it is on the full load trace of Film No. 16.

In the comparison of generator No. 9 with generator No. 8, whereas these machines are so nearly identical, yet the former is a 4000-volt 7.5-kw. generator, and the latter a 2500-volt 5.0-kw. generator. For continuous full load operation, the 4000-volt machine has a 50 deg. cent. temperature rise, and the 2500-volt machine has a 40 deg. cent. temperature rise.

Obviously, this points to the fact that the electric and magnetic loading of the 4000-volt generator is much greater than that of the 2500-volt generator. If the full load traces of these two machines are compared, the above fact is substantiated by the greater amount of saturation indicated on the trace of the 4000-volt machine than is indicated on that of the 2500-volt machine.

*Films No. 25 and No. 26.* These two records, one of which is at no load and the other at full load, were obtained from the two-pole generator of motor generator set No. 5. The machine has 22 slots and the 89 commutator segments. There are two high-voltage commutators connected in series; the machine has interpoles, and has a compound field.

Slot ripple is present in this machine, and the number of pulsations per revolution of the armature is 22, corresponding to the number of slots. This is due to improper pole coverage with respect to the armature slots.

Referring back to machines No. 8 and No. 9, the idea might occur that the reason for the absence of slot ripple in these machines is on account of the presence of the two commutators in series. If the ripple voltage from each commutator were equivalent in wave form and 180 deg. out of phase, then the terminal voltage would contain no ripple, but as can be seen by

consideration of the directions of the generated voltages, these voltage irregularities, if present, are in phase, and add up directly.

Thus, in a two-commutator armature, whatever voltage irregularity appears across each of the commutators, should appear collectively across both when they are connected in series with the d-c. voltages additive, and such is the case with motor generator set No. 5.

An armature reluctance variation voltage due to grain direction appears in Films No. 25 and No. 26, consisting of two pulsations per revolution, which is in agreement with the number of poles. The amplitude of this ripple increases about 30 per cent with load.

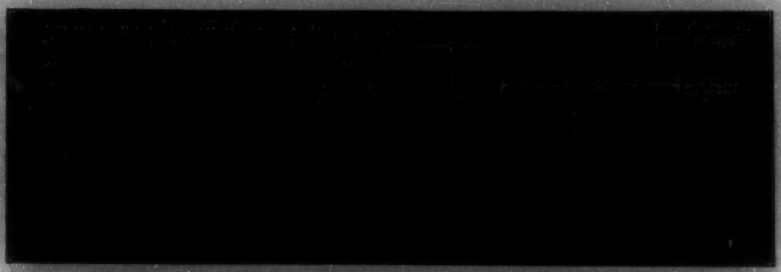
Here also is some indication that the speed of the machine varies with the revolution of the armature, as the successive peaks of the ripple wave form recorded on the trace are of different amplitude.

*Films No. 2 and No. 4, No. 8 and No. 14, No. 11 and No. 12.* These records all appertain to the same source, that is, motor generator set No. 11. This equipment consists of three units, one motor with two generators. These two-pole generators each have 40 slots and 320 commutator segments. Each generator unit has a single high-voltage commutator, interpoles, and a compound field. The 7500 volts is obtained by connecting these two 3750-volt units in series.

Films No. 11, No. 12, and No. 14 were taken with the armature grain direction of the two generator units at 90 deg. relative to each other, while with Films No. 2, No. 4, and No. 8, the armature grain direction of the two generator units was in like direction, relative to each other. For the former condition, the generator keyways were actually in a 180 deg. relationship, while for the latter condition the keyways were in a 90 deg. relationship.

Attention is called to the fact that when the grain direction in the armatures of the two generators are at 90 deg. relative to each other, the voltage irregularities due to grain do not add up directly, but geometrically at right angles. Hence the ripple should be of a smaller magnitude for this condition than when the grain of the armatures is in like direction. This is borne out by examination of Films No. 11, No. 12, and No. 14, all showing a smaller ripple percentage as compared with corresponding Films No. 4, No. 2, and No. 8, respectively.

Analysis of these films discloses the fact that slot ripple and armature grain ripple, with a minute amount of commutation ripple, are present. Moreover, the percentage of ripple and its wave form change with load. The wave form is also different for the generator keyway relationships of 90 deg. and 180 deg. respectively. The latter fact is by virtue of the way in which the ripple voltage wave forms of the two generators add when in series and undisplaced, and when displaced from each other by 90 deg. The reason for the change in wave form with load is due to the collective influence



of the interpoles, armature reaction, and grain direction, and the added possibility of speed variation due to some factor such as variable motor torque or the effect of the coupling.

*Films No. 19 and No. 23.* Both of these records are taken from aircraft generators, each two-pole machines. On Film No. 19, the wave form divulges the presence of slot ripple, that of grain direction, and a slight amount

of commutator ripple. On Film No. 23 is indicated slot ripple and that due to grain direction. The largeness in percentage or ripple present in these machines is due to the design and to the economy with which the materials are used, *i. e.*, the electric and magnetic loading are extremely high.

*Films No. 17 and No. 18.* These two film records were taken from the two-pole generator of set No. 3. This machine has a compound field and its armature has 38 slots and 133 commutator segments. It is devoid of interpoles, and so as to ensure reasonably good commutation, the brushes are advanced about 40 deg. in the direction of rotation.

Film No. 17 was recorded without a filter in the high-voltage generator supply. Here the slot ripple preponderates by far over the grain direction irregularity. Commutation ripple can be seen here and there on the trace, superimposed on the slot pulsations, but with regard to amplitude, it is of minor importance. Film No. 18 was recorded with the filter in the high-voltage generator supply circuit and here the slot ripple has been almost entirely eliminated, but the grain direction ripple still persists. It should be noted that the no load and full load traces on Film No. 18 are somewhat dissimilar. At no load the grain direction component can be noticed as four pulsations per revolution, instead of two as would be expected on an average machine. This difference is due to the smallness in armature diameter. These same four grain pulsations also appear on the full load trace in Film No. 18, but they are superimposed on another variation that does not occur in the no load trace. The explanation of this additional irregularity will be given in connection with the next four film records.

*Films No. 28, No. 29, No. 30, No. 31.* These four records were taken from the same generator as were the above Films No. 17 and No. 18. The object was to ascertain how the ripple wave form varied as load was applied to the generator. Loads of 115 milliamperes, 250 milliamperes, 480 milliamperes, and 667 milliamperes (full load) were applied and the ripple wave forms recorded for these conditions as shown in Films No. 29, No. 28, No. 30, and No. 31 respectively. The cause of the great change in wave form and amplitude from no load to full load is to be attributed to the misalinement of the motor and generator shafts.

The dissimilarity between Films No. 18 and No. 31 arises from the fact that the operating condition of motor generator set No. 3 was poorer for the latter film. This one was taken about a month later so that the maladjustment of the set had increased during that interval of time.

For comparison of the above four films, a shaft contact trace was included on each film. This was

done by having a contactor, attached to the shaft, close an oscillograph circuit for a very short interval once per revolution.

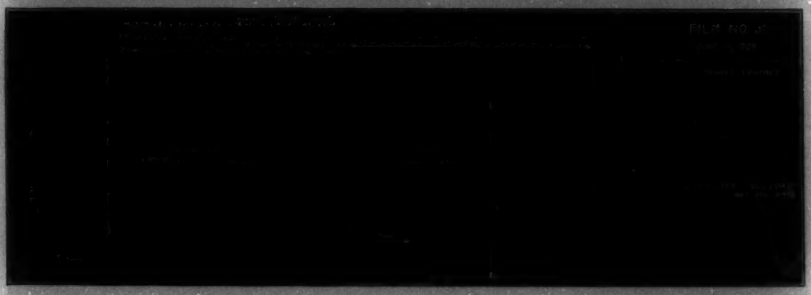
One additional fact that may be mentioned is that for light loads, the generator armature of motor generator set No. 3 apparently shifts longitudinally once every two revolutions, as is shown on Film No. 29.

*Films No. 43, No. 44, No. 45, and No. 46.* These four film records show the ripple wave form of the generator of set No. 3, taken with the coupling plates of the motor and generator out of alinement by approximately 1/16 in. Corresponding to Films No. 43, No. 44, No. 45, and No. 46 are four relationships of the motor coupling with the generator coupling, namely 0 deg., 90 deg., 180 deg., and 270 deg. respectively.

For each of these records, the ripple by inspection is seen to be of different wave form, but it must be noticed that the grain direction component appears in each film unchanged. The component which changes in wave form is caused by the pliable part of the coupling flexing, thus introducing variations in speed, and thereby voltage fluctuations.

In addition, at this point of the experiment, a one turn loop was placed around the armature, the ends of this loop being connected to a pair of slip rings. By means of brushes, the potential generated in the loop was carried to an oscillograph element for recording. The recorded wave form shows directly the flux distribution in the air-gap, and indicates how very ragged and irregular this can be. With such a distribution it is surprising that the terminal voltage of this generator is as smooth as shown in Film No. 17, this record having been taken without filter.

For purposes of comparison, it will be noticed that the shaft contact trace used as a reference appears to have been moved to the right in Film No. 44 by 90 deg. electrically over that of Film No. 43, and that of Film No. 45 moved 180 deg., and that of No. 46 moved 270 deg. Here the loop wave form should be used as reference, as this is kept intact and the various points on the ripple traces and the loop traces have the same relationship in each of the above four films.



*Films No. 33, No. 34, No. 35, and No. 36.* These four film records were taken from the same machine as above, that of motor generator set No. 3, but with the couplings on the shafts of the motor and generator placed in good alinement, and with the above four relationships of the motor coupling with the generator coupling, *i. e.*, 0 deg., 90 deg., 180 deg., and 270 deg. The voltage irregularity which appears on these four films is mainly that of grain direction variation, the other components of ripple present in the preceding four records having been eliminated by proper alinement. Moreover, the percentage ripple has decreased about

50 per cent as compared with the four previous films, This gives an idea of the importance of proper alinement of the motor generator set.

*Films No. 41 and No. 42.* Here the generator brushes were retarded the distance of 5 commutator bars from their normal advanced position, and two records taken, one at no load, and one at full load. The former shows a small amount of commutation ripple, which disappears when load is placed on the machine. In addition the loop indicates the voltage induced in individual armature coils, and shows the sudden small irregular changes in flux which are continually taking place.

*Films No. 38 and No. 39.* Film No. 38 was taken with normal brush advance, while Film No. 39 was taken with the brushes advanced a distance of 5 commutator segments beyond this position. Here a voltage irregularity appears with 19 pulsations per revolution, corresponding to half the number of slots. This gives some indication of the importance of having the brushes set for the proper condition of commutation, whether the generator is either of the non-interpole type or a machine with interpoles.

*Film No. 21.* This film was added by way of parenthesis, since it is a record of the wave form of a six-phase kenotron rectifier rather than that of a generator. There is one trace showing the no load ripple at 6200 volts direct current and the other trace at 5400 volts with 5.12-kw. load. Though the power supply frequency is 25 cycles per second, the frequency of the no load trace is 50 cycles per second. The light load trace shown is somewhat irregular, but is at a frequency of 25 cycles per second. With additional load the ripple becomes sinusoidal at a frequency of 25 cycles per second and its amplitude increases.

## Conclusions as to Desirable Features in D-C. Generators for Minimizing Voltage Irregularities

This investigation of voltage irregularities has shown that it is desirable to have the following features inherent in d-c. high-voltage generators:

1. The armature laminations should have their grain oriented in various directions normal to the shaft, so as to cause the armature reluctance to average to uniformity. In the case of circular punchings for small machines, this orientation of grain will permit cross flux from one plate to another, due to permeability difference, with the accompanying slight increase in eddy current losses, but this will not be of a serious nature. For segmental punchings as used on large generators, the grain direction should parallel the teeth, on account of the high teeth flux densities used.

2. Proper design as regards pole coverage and armature tooth and slot dimensions should be employed in the physical make-up of the generator so as to eliminate slot ripple.

3. All generators to be used as high-voltage d-c. supplies should have interpoles, as the characteristics of machines so equipped are much better than the non-interpole machines both from the standpoint of commutation and voltage irregularity.

4. Motor generator sets should have a coupling of such design and characteristics so as not to produce side shifting of the generator armature under fluctuating or continuous load. Moreover, the coupling should not affect the generator speed and cause periodic fluctuations therein.

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## Discussion

**L. V. Bewley:** On page 1070, Mr. Fetsch gives five causes of voltage irregularities:

1. Slot ripple,
2. Commutator ripple,
3. Armature reluctance variation ripple due to grain direction in steel,
4. Armature reluctance variation ripple due to improper physical alinement,
5. Speed variation due to improper shaft alinement.

To these may be added:

6. Ripple due to the oscillation about its mean position of the belt of conductors between brushes.

Mr. Fetsch's study is experimental. It is of interest to see if these ripples can be calculated, and to consider how they may be eliminated. In my paper, *Induced Voltage of Electrical Machines*, (A. I. E. E. Trans., Vol. 49, April 1930, p. 456), I gave a general equation for the induced voltage of electrical machines having

parallel coil sides and in which the flux distribution can be specified as Fourier series. It is

$$E = -2L \frac{\tau}{\pi} \frac{n N^1}{10^8} \sum_1^\infty C_{ck} C_{dk} C_{pk} C_{sk} \left[ \frac{1}{k} \frac{d\beta k}{d t} \sin k \left( \frac{x_0 \pi}{\tau} + \gamma_k + \psi_k + \psi_k^1 \right) + \left( \frac{d \gamma_k}{d t} + \frac{\pi}{\tau} \frac{d x_0}{d t} \right) \beta_k \cos k \left( \frac{x_0 \pi}{\tau} + \gamma_k + \psi_k^1 + \psi_k \right) \right]$$

in which the $C$'s are the harmonic reduction factors due to skew, pitch, belt distribution, and phase connection; $k$ is the order of the space harmonic, $\beta_k$ the $k$th harmonic of flux density, $\gamma_k$ its position, and $x_0$ the position of the phase belt. The other factors are defined in the paper, but are not pertinent to this discussion. There are thus three ways in which a voltage can be induced in the windings:

1. Pulsation of the flux harmonics as standing waves $d\beta_k/d t$
2. Rotation of the flux harmonics as traveling waves $d\gamma_k/d t$
3. Rotation of the armature conductors at speed $d x_0/d t$

The first four causes of ripples in d-c. generators are due to $d\beta_k/d t$ and the other two causes to speed variation $d x_0/d t$. Now it happens that the frequency of the commutator ripple $b$ and the belt oscillation ripple $f$ are the same, but since they are due to different causes, if the harmonic reduction factors are adjusted for the cancellation of the $k$th harmonic voltage when caused by $d\beta_k/d t$ it does not follow that this voltage will be cancelled when due to $d x_0/d t$.

A complete analysis of the ripples in d-c. generators involves flux plots of the field form for different relative positions of the slots with respect to the poles, the specification of the instantaneous distribution as Fourier series, and finally the numerical solution of the general equation at enough successive points so that the ripples can be plotted.

**J. T. Fetsch, Jr.:** The additional voltage irregularity that Mr. Bewley mentioned was not discernible on the records obtained in my tests. Perhaps the ripple obtained by the oscillation of the belt of conductors between brushes about its mean position would be more pronounced in machines of low voltage, with an armature of just a few slots, coils, and commutator bars.

It is of interest to note that some of the records of ripple show only that of grain direction effect. Since this can be eliminated by various degrees of orientation of the armature lamination, it should be possible to design d-c. generators devoid of ripple e. m. fs.

# Cooperative Courses—Their Development and Operating Principles

BY KARL L. WILDES[1]

Member, A. I. E. E.

***Synopsis.***—*The Cooperative Idea has been the motivating spirit in the various attempts to bring together the educational and industrial elements in engineering. The outstanding milestones of progress in this undertaking are the "Sandwich System" of Scotland, the establishment of shops in schools, the rise of educational opportunities in industrial concerns, the report of Sir William White's committee of practising engineers and educators in England, and finally, the conception and inception of the cooperative courses at the University of Cincinnati and at the Massachusetts Institute of Technology.*

*These courses are taken as examples of two types of cooperative course called respectively the "Cincinnati Plan" and the "M. I. T. Plan." Each of these possesses a structure and a set of operating principles determined by the purpose for which it was instituted and the conditions under which it is carried out. The operating principles of the M. I. T. Plan are discussed in detail in this paper. The graduates of both these plans are demonstrating that the results sought are being accomplished.*

* * * * *

"THEORY is the commander, practise the soldiers," said the far-sighted Da Vinci. The cooperative idea, or the principle of coordinating theory with practise, has struggled for expression down through the ages. As time goes on, it is bound to express itself with increasing forcefulness, and at the present time effective applications of the principle are in use in this country, especially in the field of engineering education. With the growing interest in the relative functions of the technical colleges and the electrical industries, it would seem to be timely that a review of the development and operating principles of this type of training be presented before the Institute.

## The Cooperative Idea—Development

*The Antagonism between Theory and Practise.* The engineering profession arose out of the crafts, and naturally enough the early engineering processes were the craftsman's rule-of-thumb methods. Such empirical information as was found practicable was handed down and augmented by later engineers, and thus was the fund of engineering knowledge built up. Practise, then, was the only means of entrance into this profession, and it became the custom for young men, usually with little scientific education, to serve several years as apprentices with their elders, after which they might be recognized as civil engineers. For many years the young man who had studied the then existing sciences was not too welcome in engineering circles, for he was bothersome; he had to be divested of his academic ideas before he could begin to learn anything practical. The cooperative idea was facing, in this situation, the apparently insurmountable task of reconciling the practising engineering profession with the technical college, an outgrowth of the schools of science in the universities.

*Conciliatory Moves.* The first gesture of the cooperative idea in technical education was probably seen in Germany. The notion that boys finishing at the "*gymnasium*" were too immature and lacking in educational appreciation to make the most of their studies in the "*polytechnikum*," led to the system of placing them in mechanical workshops for at least one year before entrance into the scientific school. A certain evaluation of materials and methods and an increased desire for scientific knowledge were thought to result from this practise; in fact, the results were so convincing that the plan spread into neighboring countries and still persists, notably in the higher technical colleges of Germany and Scandinavia, as a requirement for a degree.

The "Sandwich System" came into use nearly a century ago, not as an educational move, as some have supposed, but rather from financial expediency. According to a Scottish engineer,[2] Scotchmen of former generations could not afford attendance at the university for more than six months in the year, which explains the short six months' session of the Scottish universities. As Glasgow University was one of the first to teach engineering science, the short session and the large engineering community naturally evolved the sandwich system, which gives the student six months at the university and six months in the workshop. There was no attempt here to coordinate the school work with that of the shops, or vice versa, but it has been remarked by employers that this type of education produces "men who can make a good living." Here the cooperative idea almost came to light.

*The Move of the School toward Industry.* Inspection and instruction trips into industrial establishments have been featured by technical schools in this country from the very first[3] (1824). In the case of Worcester Polytechnic Institute (1868), a small manufacturing plant was established on the campus. Skilled journeymen

1. Asst. Professor of Elec. Engg., Massachusetts Institute of Technology, Cambridge, Mass.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

2. Captain J. M. Scott-Maxwell, *I. E. E. Jl.*, Vol. 57, 1919, p. 466.

3. "History of Rensselaer Polytechnic Institute," P. C. Ricketts, John Wiley & Sons, Inc., 1895, p. 43.



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were employed and articles of commercial value were produced by students and journeymen working together. About a decade later, instructional shops were established at the Massachusetts Institute of Technology, for the purpose of teaching the fundamental shop operations, without consideration of factory production. Both these types persist in their respective institutions and one or the other has been adopted by practically every engineering college in this country. These, and other moves on the part of the schools to develop the industrial side, were prompted by the cooperative spirit in them reaching out for the practical.

*The Move of Industry toward the School.* But the cooperative spirit also reached out from industry toward education. This is perhaps best evidenced by the establishment of courses of classroom instruction in the great manufactories, first for trades instruction and later for engineering instruction. The classroom instruction provided by the industries has in some cases risen to a high type of theoretical instruction, as exemplified by the "Out-of-Hour Courses" of the Bell Telephone Laboratories, the "Advanced Course in Engineering" of the General Electric Company, and the "Design School" of the Westinghouse Electric and Manufacturing Company. The establishment of scientific research laboratories in the large companies was also a decided advance toward recognition of the closer relationship between pure and applied science.

*Eminent Engineers and Educators Express Themselves.* In 1903, a committee of very eminent British engineers[4] and educators, under the chairmanship of Sir William H. White, was appointed "to consider and report . . . as to the best methods of training for all classes of engineers; it being an instruction to this committee that the principle shall be maintained that the education of an engineer must include both practical experience and scientific training." An exhaustive inquiry, similar in nature to the recent one made by our Society for the Promotion of Engineering Education,[5] asking opinions of practising engineers and professors, was used as a basis of this committee's 13 recommendations, which include the following: a year's experience in a mechanical engineering workshop, termed the "Introductory Workshop Course," one academic year common to all types of engineering students, in which mathematics and mechanics would be stressed, two academic years allowing some specialization, and three years of practise in a particular field (Civil Engineering, Mechanical Engineering, etc.). Finally, if post graduate work became desirable, it was to follow the practical experience. It was also mentioned that for mechanical engineers it might be advisable to place all the practical training before the college course, in which case it was very important to provide evening classes, for "otherwise boys would lose seriously during four or five years' suspension of systematic study." For those who take the Introductory Workshop Course only, "the Committee thinks it is most important that all boys should at least maintain their scholastic acquirements." It was also held feasible to cut down the total time by sandwiching the practise, as at Glasgow. The greatest of the British engineering minds were striving to accomplish a plan which was a shadow of the cooperative idea.

*The Idea Born.* None of the foregoing arrangements merits the cognomen of "cooperative education" as it is practised in its most effective forms in America at the present time. Finally, in 1906 the "idea" succeeded in breaking the shell and appearing as a reality. During the years occupied by Sir William White's investigation, Mr. Herman Schneider had conceived the scheme of coordinating engineering theory, best taught in the schools, with engineering practise, best taught in the industries, and he was having difficulty in putting his proposal into operation. Great credit is his due, however, for his persistent and energetic labors, for finally in Cincinnati he discovered an attractive situation in which he could launch his project. Thus came into being the world's first real cooperative course, recognized in America and in Europe alike as the birth of the cooperative idea.

## The Cooperative Idea—Operating Principles

*The Cincinnati Course—Aim.* The peculiar situation into which the cooperative idea was born had much to do with the structure and therefore with the operating principles of this first course. Cincinnati is a city of great industrial plants, like those of the present Cincinnati Grinders, the Union Gas and Electric Company, and the Cincinnati Traction Company. It is also a public-spirited city having at heart the progress of its public institutions, including its municipal university as well as its private business enterprises. It is at once evident that the local industries furnish not only exceptional opportunities for training young men and women, but for utilizing their services after they are trained. The demand upon the university is therefore chiefly for the production of engineers to occupy the responsible positions in these industries. To quote President Schneider,[6] "The aim of the course is not to make a so-called pure engineer; it is frankly intended to make an engineer for commercial production."

*The Cincinnati Plan—Original Structure.* Originally, the course was laid out to cover six years, alternating the student week by week between shop and college during the academic year of eight months, and placing him in the shops also during the four months of vacation. This arrangement gives a total of four years in the shops and 24 months in college, as compared with the 32 months of the regular four-year plan. President Schneider

4. *Inst. Civil Eng. Proc.*, Vol. CLXVI, Part IV, 1906, p. 159.

5. Bulletin No. 13 of the Investigation of Engineering Education, S. P. E. E., Dec. 1927.

6. "The Cooperative Course in Engineering at the University of Cincinnati," Herman Schneider, *Proc. S. P. E. E.*, Vol. XV, 1907, p. 391.

reports that more, rather than less, scholastic work was accomplished under the cooperative plan than under the regular one, due chiefly to the eagerness for study engendered by the contact with shops, and to the fact that the boys did some studying on their own initiative in the industrial periods. The story of the experimental period of this undertaking is most fascinating,[7] and in it some important changes took place, as will be seen; but with only a passing reference to this story, we will pass to the final set-up of the course as it exists today, and we

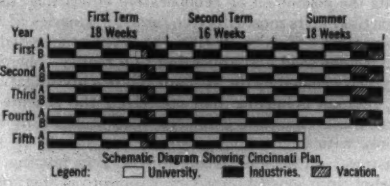


FIG. 1—SCHEMATIC DIAGRAM SHOWING CINCINNATI PLAN

will call this scheme the "Cincinnati Plan" of cooperative education. Several other prominent institutions, about 20 in number, such as the University of Akron, Georgia School of Technology, and Antioch College, have established courses after this plan.

*The Cincinnati Plan—Present Structure.* The present structure of the Cincinnati Plan is this: a summer practise period is advised previous to entrance to the course, and beginning with the fall term of the first year the student alternates in four-week periods between college and shops throughout the five-year course, with four weeks of vacation per year. The shop work is coordinated by a staff of coordinators in such a way that the jobs whose chief value lies in shop discipline and simple operations are given to the freshmen, and those requiring more judgment and training are given to the upper classmen. These coordinators also hold classes in coordination at the University and visit the men on the job, in both cases answering questions and pointing out important practical and theoretical aspects of the jobs. In some cases the employment may be all with one concern, but in cases where the work supplied by one company is not extensive enough, the student may be moved to other companies. Jobs at the plants are kept filled by the principle of alternation in pairs, one or the other of the students of a pair being held responsible for filling the job at all times while this pair is assigned to this job. No university classes are held for the students at the shops, but a comprehensive report is required of each student upon his return to the University.

*The M. I. T. Plan—Inception and Purpose.* A plan, involving a more intimate application of the cooperative idea, differing from the Cincinnati Plan in purpose and scope and therefore in operating principles, was developed for electrical engineering conjointly by Mr. Magnus W. Alexander, then of the Lynn Works of the General Electric Company, and Professor Dugald C. Jackson, of the Massachusetts Institute of Technology, and was put into operation in 1917. The World War interrupted this initial attempt, but it was re-established in the summer of 1919 and its administration placed in the hands of Professor William H. Timbie. It was the result of ten years' observation of the Cincinnati Plan, consideration of European practises and opinions, and a careful study of the adaptation of the cooperative idea to the needs of the company and the educational facilities of both the company and the Institute. The purpose was to train a selected group of promising and scholarly young men for the technical and executive positions of the electrical manufacturing industry. It was apparent that the academic training needed by such men would involve not only a thorough study of the fundamental sciences and the application of those principles to the design and operation of machines, but at least an additional year of post graduate study in which creative ability and acquaintance with the frontiers of scientific knowledge would be developed. It was equally apparent that a prolonged and haphazard round of shop duty was a waste of time for the type of young man under consideration. For this reason, a course of "Manufacturing Practise" was laid out, covering the essential details of the manufacturing problem from the machine shop through the various tests of apparatus, production offices, and engineering development and research laboratories. Furthermore, a good foundation in mathematics, physics, chemistry, English, and drawing, was seen to be necessary before entering this coordinated course in theory and practise.

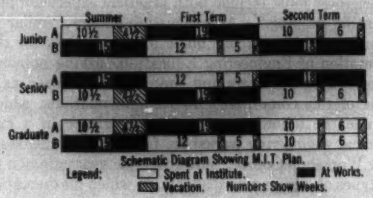


FIG. 2—SCHEMATIC DIAGRAM SHOWING M. I. T. PLAN

*The M. I. T. Plan—Structure.* In view of the above considerations, the Cooperative Course in Electrical Engineering, known at the Institute as Course VI-A, was constructed as follows: The successful completion of the first two years of basic scientific and humanistic studies is required for entrance to the cooperative years. At the beginning of the summer following the second year, the class jointly selected by the cooperating company with which the particular students will be related for three years, and the Electrical Engineering Department of the Institute, is divided into two groups,

7. "The Cooperative System of Education," Clyde W. Park, University of Cincinnati Studies, Series II, Vol. XI, Part 1, 1925.

designated Groups A and B, Group A remaining at the Institute and Group B going to the industrial plants. The groups alternate between industry and the Institute at the end of each academic term, fitting into the regular Institute calendar of studies, activities, and vacations when at the Institute, but responsible to their company during the complete term while on industrial assignments. The project includes continued scientific and general study, and instruction by members of the Institute staff, for students at the Works. The two groups are reunited at the Institute for the final term of the graduate year, during which they complete the requirements for the Master's degree. This last term away from industry places the student in an unbiased atmosphere at the time he is considering permanent employment, and promotes class activities preceding and including the commencement season. This plan has been called the "M. I. T. Plan," and has been adopted also by the Civil Engineering Department of the Institute in cooperation with the Boston and Maine Railroad, and is pending adoption by one or two other institutions having good graduate departments. We shall now discuss some of the operating principles of this plan, with special reference to Course VI-A.

*The M. I. T. Plan—Operating Principles.* It is desirable, although not requisite to the successful operation of the M. I. T. type of cooperative course, that a non-cooperative course carrying in its curriculum the same scientific training, be maintained for the following reasons:

1. In cases of more mature or experienced men coming out of industry for training in the fundamental sciences, it is usually advisable for them to pursue these studies as rapidly as is consistent with their ability and preparation. In some instances these men take heavier schedules than would be advisable for younger men, and by continuing their studies through the summers, they may return to their employment in the minimum possible time.

2. Ten per cent of the students in electrical engineering (1928-'29) at M. I. T. have come from foreign countries and a large proportion of these intend to return to their home countries after completing their technical education. The cooperating companies cannot as a matter of policy take these students into training, except by special arrangements in case they have foreign departments.

3. Some students cannot meet the physical or certain personal requirements of the cooperating companies, but are otherwise qualified to carry on engineering study.

4. Many students transfer to the Institute in the fourth year, too late to include a substantial course in industrial practise.

5. Many students desire an undergraduate engineering education but are neither desirous nor qualified to pursue graduate work; others prefer the scientific studies for themselves, and are not attracted by the works experiences at the time.

In some institutions operating on the cooperative plan only, some of these reasons have become urgent and are causing a serious consideration of establishing a non-cooperative, or "full-time" course, in parallel with the cooperative course.

The cooperating company must meet the following specifications for the M. I. T. cooperation:

1. It must be large enough and complete enough in its organization, training facilities, and range of production to provide a comprehensive course in its particular field. While a small company may be intensely interested in the project and may give very excellent experience in a limited field, the more important considerations involved in the organization and administration of a large enterprise and association with multifarious but related production cannot be gained. This point is well illustrated by a comparison of the small and the large manufacturing companies. A small concern tends to produce artisans, men who become adepts in some narrow field such as die-making, for example. It is an incorrect principle, however, to confine the early practical education to a highly specialized phase of a business. A general course in a well-ordered machine shop would give a broader view of this class of work and a good foundation upon which die-making or any other specialty could be built subsequently. Certainly the contact with the several departments of a large manufacturing concern with its diversified problems of materials, processes of fabrication, research, and personnel, will give a young man, under competent direction, a practical equipment for a professional career far superior to that obtainable in a small factory under the best possible conditions. The modern trend toward consolidation also suggests the importance of seeing commercial problems in the large.

2. The company must be competent and willing to assume its share of the responsibility in the administration of the project. This is probably the most vulnerable spot in the whole plan, and unless a responsible officer of the company constantly sees that the practical program is carried out, the ideals of the cooperation will not be realized. This company responsibility also means more than the interest of one man; it means the interest and effort of the whole organization from the president to the foreman under whom the students work.

3. The company must have a specific need for the type of man trained. If this is not the case, it is training men only for competitors, or at best for other concerns. Plainly enough, this is not good economy and cannot be justified on any ground except possibly that of creating good-will. Moreover, if there is no interest in the product, there can be little interest in its making, which means that eventually the cooperation must terminate. If, on the other hand, a substantial number of outstanding men is added to the organization from year to

year from this course, the course will be highly respected and will continue to be well administered.

These specifications are believed to be met by the companies associated with Course VI-A, each company occupying a prominent place in a special field of electrical engineering. The General Electric Company gives an unexcelled course in Manufacturing Practise, including shop work, testing of electrical and mechanical apparatus, factory production studies, and development and research on products and manufacturing processes. The Public Utility Practise is given in any one of three companies, the Edison Electric Illuminating Company of Boston, for generation and utilization of electric power, the Boston Elevated Railway, for electric transportation, and Stone & Webster, Inc., for the planning, construction, and operation of various kinds of power projects. The Communication Practise is given by three component companies of the Bell System, the Western Electric Company, Inc., in the manufacture and installation of communication apparatus, the New York Telephone Company, in the maintenance and operation of telephone plant and the Bell Telephone Laboratories, Inc., in the development and research in communication engineering, the relation to the three communication companies being coordinated by the American Telephone and Telegraph Company.

Similarly, the educational institution must match the above specifications with the following:

1. It must maintain an adequate and competent staff of teachers, administrators, and scientific investigators, classroom and laboratory equipment, and undergraduate and graduate educational program sufficient to provide the technical and cultural groundwork for the engineering profession in general, and for the better present and prospective industrial positions in particular. The cooperative method does not reduce to any considerable extent the necessity for laboratory facilities with which fundamental principles can be demonstrated and original research carried on.

2. It must of course not only carry the entire administration of the course while the students are in academic residence, but also must enter thoroughly into the cooperative spirit in the administration of both the academic and practical content of the curriculum. This cooperative spirit brings about an interchange of ideas, beneficial to the participating organizations as well as to the students. Through the medium of student theses, investigators of both institutions lend their aid to the solution of industrial scientific problems.

3. The educational institution must be situated not too far away from the cooperating industries. An expensive practise of transferring students several times over long distances would not be economically justified, and would give them an erroneous evaluation of their own importance. This does not mean that for the long-term arrangement the distance could not be so great as a night's train journey, but it should exceed this distance only in cases of special assignments toward the end of the course. Besides the interchange of students between employment and college, there is the necessity for frequent conferences on the part of administrators, and these are facilitated by the close proximity of the institutions represented.

Before a student is accepted for this cooperative course of training, he must successfully complete the first two years of groundwork in mathematics, physics, descriptive geometry, drawing, chemistry, and English. These have been termed the a b c's of engineering and ought to be well in hand before the principles of design and operation of electrical and mechanical apparatus are undertaken. It has been found the best policy at M. I. T. to concentrate on such basic subjects in the first two years, for upon these rests the whole structure of engineering. If a man cannot master these a b c's, he should not be encouraged to pursue a course of theory and practise, the successful completion of which rests so heavily upon this foundation. These two years also serve as an orientation period during which the requirements and opportunities in the several fields of electrical engineering are brought to the students in personal conferences with members of the teaching staff, in lectures by the president and heads of departments of the Institute and by men from the industries. It is upon the achievements of this two-year period that the Electrical Engineering Department bases its recommendations to the cooperating companies.

Late in the sophomore year, the candidates recommended by the Department of Electrical Engineering of the Institute are interviewed by representatives of the company with which the cooperative training is desired. The qualifications sought by these company representatives are in general the same as those considered important for regular permanent employment. Good health, good physique, strong personality, initiative, ability to cooperate, and adaptability to the work of the particular organization concerned, are qualities of importance in this selection. The companies are not expected to accept students who are reasonably sure of eventually going with other concerns, or upon whose future services they can see no probability of substantial returns. The mutual obligations of student and company cease, however, at the end of the course.

Although no contracts are signed, a company agrees to complete the training of each student it starts, except in cases of faulty conduct, and in return it is understood that under normal conditions a student is to complete his course of training with the company. This mutual understanding is necessary to the stability of the course.

The rates of pay for students in cooperative training are substantially uniform among the companies, slight compensations being made for variations in living expenses in different localities. In order to insure the transfer of students from one job to another on the basis of the best educational value, it is held to be essential that the rate of pay be fixed according to the class in which the student is registered, rather than

determined by prevailing rates for the kind of work he does. In several cases, students have been recommended by their foremen for advances in pay in recognition of exceptional ability or interest. Such advances are not allowed, as the student will soon be moved to a new job, but the incident is usually related to him by way of encouragement. A student's achievement in any cooperative assignment is recognized by the grade given in Industrial Practise, and this record is as much a requirement for graduation as a subject taken while at the Institute. Special coveted research or development assignments are often given as rewards for outstanding achievements or exceptional ability. The average total amount of money earned per student during the four cooperative periods is about eighteen hundred dollars.

During the Institute periods, the curriculum calls for a normal schedule of 48 hours per week. It is essential that the required load be normal, since overcrowding tends toward abbreviation and superficial work. Furthermore, a fair proportion of the men like to add to their normal schedule the courses of the Reserve Officer's Training Corps, or such general studies as the humanities, appreciation of music, etc., while others are interested in student activities of educational and broadening character. Several are members of the Electrical Engineering Honors Group, the object of which is to allow the men with acute intellects and sound judgment to study their required subjects most economically by permitting them to determine for themselves the amount of illustrative problem work and class attendance essential to their mastery of these subjects. The Honors men take the same quizzes and examinations as the other students, but pursue their studies with the counsel of a member of the Electrical Engineering Department, who directs their attention to more extended studies in the subjects of the curriculum or allied topics. Practising engineers and employers of engineering graduates are urging these types of broadening influences upon the engineering schools, but if the essential scientific and required cultural studies are all crowded into the Institute periods, no room is left in a five-year course for these desirable extra features. A six-year course is not proving attractive, although it has many points to recommend it, but fortunately it has been found practicable to accomplish a normal required Institute schedule by introducing studies at the plants.

During the practise periods, additional studies are required to the amount of eleven hours per week, classroom and study. Two subjects are conducted by members of the Institute staff on two afternoons or evenings each week after working hours. One of these subjects is given by the Department of Electrical Engineering and is classed as a scientific subject, and the other is given by the Department of English and History and is classed as a humanistic subject. Thus, the "Principles of Electrical Engineering" are studied almost continuously during the cooperative years, and such cultural subjects as "Modern Forms of Literature" are given while the men are in the more practical atmosphere of the plants. Cooperative arrangements often meet the criticism that they develop a materialistic attitude in the students, but examination of the results obtained under these conditions shows no such results. Besides the accomplishment of a whole term's study during the four periods at the plants, this plan performs the very important function of teaching men to use their spare time to advantage while in industry; that is, the studies are carried into the industries to produce in the young man as a worker correct habits of budgeting his outside time, and not to give him the status of a schoolboy at work. Another outstanding result of studies at the works is the alertness with which students assume the full Institute program. The two subjects in each Works term give enough mental exercise to keep the men's minds active, and yet not enough to fatigue them.

Close coordination must be maintained between the two kinds of work, academic and practical. This does not mean necessarily that every practise period must contain the practical application of the scientific principles of studies during the next preceding term; in fact, in some cases it is desirable to reverse this order, and make the contacts with certain apparatus a stimulus for the study of its principles of operation. This is not an argument, however, for a general laxity in coordination of theory with practise. It is desirable that these go hand in hand, each stimulating interest in the other. One of the important functions of the administrative officers of both the school and the company is to make sure that students take proper attitudes toward their work, and use their opportunities to observe the broader policies of the company, such as the inter-relations of departments, economic structure, and problems of personnel. In Course VI-A, members of the staff of the Department of Electrical Engineering work with administrative officers of the companies to see that the men are fitted, by age, temperament, and educational background, for the various jobs, in order that the greatest educational value may be gained.

Vacations average about five weeks a year during the cooperative years, and students are encouraged to take full advantage of these periods for rest and recreation. A vacation period never precedes an Institute term. This allows the student to take full advantage of the mental activity engendered by the two subjects pursued at the plants, as he swings into a full schedule of academic study.

*Values of the Project.* The ultimate value of the course to all parties concerned is best measured by its value to the students. Some of the chief benefits to the students are the following:

1. The regular four-year undergraduate course in Electrical Engineering plus an academic year of gradu-

ate study are accomplished in five years without condensation of Institute schedules. The Master of Science and Bachelor of Science degrees are awarded for this work.

2. In addition to the scholastic attainment, each student spends fifteen months, during the three years just prior to graduation, in a well-ordered course of practical training with one large company, where he learns to correlate fundamental scientific principles with their method and scope of application.

3. The opportunity to study the personnel relationships in organized industry provides a real course in industrial psychology, which should develop in the student a sound philosophy of organization and management.

4. A company loyalty is developed which is essential to the young man's progress and his value to any organization in which he is employed.

5. The whole cooperative scheme forces the student to evaluate his own personal characteristics, such as tact, persuasiveness, creativeness, cooperative ability, mechanical aptitude, and power of concentration, thus tending to improve his personality.

6. Valuable habits of evening study are attained, which persist after the young men leave college and obtain responsible positions in engineering.

7. Valuable acquaintances are formed with leading figures in a great industrial organization.

*Other Examples of Alternating Study and Practise.* The principle of alternating school and employment is becoming widely used. Several years ago it was introduced into the secondary schools of Fitchburg, Mass., and has since come into prominence in the Boston schools and those of other cities throughout the country. This principle is being applied in colleges of liberal and practical arts as at Cincinnati and Antioch. Some other examples approaching the cooperative idea are: Worcester Polytechnic Institute where 15 months of practise is advised between the junior and senior years, and the Pratt School of Naval Architecture at the Massachusetts Institute of Technology in which students work in the near-by navy yards during summer vacations. The School of Chemical Engineering Practise of the Massachusetts Institute of Technology represents still another variation of the cooperative feature. This school offers a graduate course, leading to the Master's degree and consisting of six months of plant study and testing at field stations of the Institute, established in the chemical industries, followed by six months advanced study at the Institute. This School of Practise is also made available to undergraduates pursuing studies leading to the Bachelor's degree only, by a special arrangement of the fourth year in which 22 weeks are spent in industry.

The outstanding features and points of difference of the Cincinnati and M. I. T. plans may be summarized as shown in the following parallel columns:

| Cincinnati Plan | M. I. T. Plan |
|---|---|
| Bachelor's or professional degree in five years. | Bachelor's and Master's degrees in five years. |
| All students cooperative. | Cooperative students selected. |
| Cooperation extends entirely or nearly throughout course. | Cooperation during last three years only. |
| Course in practise laid out by coordinators in college. | Course in practise laid out by officials of company and professional department of the college. |
| Classes discontinued at works. | Classes carried on at works. |
| Each student may be trained with several companies. | Each student is trained with one comprehensive company. |
| Short alternation periods (2 to 6 weeks). | Long alternation periods (15 to 19 weeks). |
| Each unit of study spread over several short college periods. | Each unit of study completed in each long college period. |
| Practical training greatly affected by business conditions. | Practical training slightly affected by business conditions. |

A clear understanding of these differences of plan will relieve many of the controversies concerning the cooperative method. For example, the question of long *versus* short alternation periods should be answered with reference to a definite situation. If freshmen and sophomores are placed in cooperative training, they should not be allowed too long at a time in the materialistic atmosphere of the shop, but on the contrary should be almost continuously under the influence of the idealism and imagination fostered at the college. Furthermore, if a youth gets a monotonous routine job for a long period, as is usually the case in the freshman year, he is likely to return to college with a sour attitude toward his studies and toward life in general. At the other end of the course the practise assignments become more interesting and are often important pieces of research which ought not to be broken up by the too early transfer from the company to college, while the work at the college should be pursued in continuous units, sometimes under the direction of specialists or visiting engineers of renown. If, then, cooperation is extended over the whole period, as the student progresses from the freshman through the graduate years, a change in length of period from four to six weeks in the early years to one of a term or more in the final years would be desirable. Clearly, from these and other arguments,[8] in the "M. I. T. Plan" where it has been found desirable to cooperate only during the junior, senior, and graduate years, the long term is educationally sound, while in the "Cincinnati Plan," where cooperation is placed in the early years, the short period becomes a logical policy.

*Results.* The writer has had the privilege of visiting several of the industrial plants of Cincinnati as well as the University, and believes that not only does the plan function efficiently but its graduates are filling the kind of responsible positions for which they are trained. The results of the M. I. T. Plan have been gratifying and have substantiated the ideals involved in the plan. The graduates of Course VI-A have taken prominent

8. *A New Method of Training Engineers*, M. W. Alexander, A. I. E. E. Trans., Vol. XXVII, 1908, p. 1459.

places in the engineering and commercial departments, and research laboratories of the large manufacturing and public utility companies. These men are all young yet, the first class having been out of college only eight years, but there is unmistakable evidence that they are proving the value of their training.

## Discussion

**A. Boyajian:** (communicated after adjournment) I have had the opportunity of watching at very close range the progress of the M. I. T. cooperative students in a large manufacturing plant and have seen splendid results from the system. In addition to the many obvious advantages of the cooperative system, which need not be repeated here, I have observed that such a system opens the door of opportunity to the student considerably earlier and puts him in a strategic position to avail himself of the best available opportunities for advanced engineering work as they arise.

The carrying on of some studies at the works is also very desirable. One big benefit that has been mentioned is the development of the habit of study while practising, a habit that should be carried through life. There is also the added benefit that studying, or problem thinking, has a little different tone in an industrial atmosphere than in an academic atmosphere, and it is desirable that the students familiarize themselves with both tones of analysis before their thinking gets too set. Scientific thinking in an industrial atmosphere tends towards physical analysis with ideals of simplicity and concreteness with plenty of latitude for approximations, while scientific thinking in an academic atmosphere tends towards mathematical analysis with ideals of rigor and completeness with plenty of latitude for abstractions. The students should benefit from exposure to both, whether or not they develop proficiency in both.

When systematic studies are carried on at the works, direct or indirect facilities automatically become available also for studies collateral with the practical work which the students are doing, even when the official course of study may be something different. The instructor perhaps furnishes the students the necessary guidance for such collateral study.

**R. W. Chadbourn:** (communicated after adjournment) Professor Wildes' discussion of the cooperative student problem particularly interests me, because we have in the laboratory of the Boston Edison Company men working under both the Cincinnati and M. I. T. plans, and have therefore had an unusual opportunity to compare the two systems. Of course, no system, however great its advantages, is ideal, and while I am heartily in favor of the cooperative scheme of education and appreciate fully the advantages of the two systems, as outlined by Professor Wildes, still I think it may not be amiss to point out one or two difficulties which have not been entirely overcome.

I will designate the school employing the Cincinnati plan as School A, that using the M. I. T. plan as School B. Men from School A work with us on alternate five week periods during the last four years of a five-year course; all their working time is spent in one department. Men from School B spend single terms of varying lengths in several departments of the company, their working periods being confined to the last three years of a five-year course. From School A we always have working with us a definite number of men who can be rotated through the department on a definite schedule. From School B, we have occasionally one or more men for an indefinite number of weeks, not exceeding three months. Our experience, covering a period of many years, has been that men from School A prove valuable helpers during their cooperative working periods, that in general they are enthusiastic over their work, and that they become favored candidates for permanent employment with us. Although their work has been restricted to one department, they have become sufficiently reconciled to the routine of business to be valuable even in other departments of the company. Their lack of variety of experience is made up to a certain extent by willingness to tackle any and all kinds of work. Unlike men without cooperative experience, who so often have to flounder around for a year or two before absorbing the atmosphere of business, they adjust themselves immediately to the job.

The men from School B are divisible roughly into two sorts. The first comprises men so keen for knowledge and so alive to all the opportunities presented to them that nothing can hold them back. Because of their ambition, their willingness to work, and their superior variety of experience and training, they become easily the most favored candidates for post-graduation employment. Undoubtedly, for this class of man, the M. I. T. system is ideal, because the system is designed to give him the broadest training possible. This very feature is, however, perhaps responsible for one of the weaknesses of the system.

For it appears that there is a second class comprising men, ambitious enough, it is true, but inclining to the belief that they are favored individuals, that their wide variety of training and experience fits them immediately for executive positions, that the routine matters of everyday work are beneath their dignity. Now, I would not decry the formation of a superiority complex so long as it does not become a "snob complex." Perhaps I may seem to be laying undue stress upon this point, but it is serious enough to have caused a distinct prejudice in my own department against men from School B. Some of these students have complained about the nature of their work, have looked down upon the more disagreeable tasks, and have conducted themselves as though they believed that the company owed them something but that they owed the company nothing in return. Some of them graduate with the idea that they should immediately qualify for executive positions. Obviously the function of cooperative education is not to qualify men to start near the top but to provide them the means for more rapid advancement than their less thoroughly trained associates.

Perhaps part of this attitude is the fault of the employing company, some departments of which may cater too much to the men and thereby tend to spoil them; part is undoubtedly due to the working schedule, which is laid out largely to benefit the student. I do not believe we should cater too much to the student. He should, during his working periods, be an employee, in every sense of the word, as well as a student; he should be made to realize his obligations to his employing company; he should be given enough routine work so that he will not develop a false sense of superiority over his fellow-employees. I believe that this difficulty can be partly overcome by a greater regularity of schedule, a redistribution of the working periods to benefit the company as well as the student,—perhaps a compromise between the Cincinnati plan, under which a student's experience is confined to one department, with frequently an excess of routine, and the present M. I. T. plan, under which a man's time is apportioned to various departments largely on the basis of benefit to himself, the result being an irregular schedule, with sometimes infrequent, sometimes overlapping, working periods in any one department. Perhaps the best average results would be obtained if the men are given the maximum variety of experience and training, and still be taught one of the most important fundamentals of business life, *viz.*, that all work has some routine, and that the widely trained man who shows a willingness and eagerness to tackle anything which may be placed before him is the man who will eventually land on top. I believe that such a modification of the present schme might give the student a better attitude toward business, resulting in diminished antagonism on the part of the employing company to the student, and thereby both student and company would materially benefit.

**D. C. Jackson, Jr.:** (communicated after adjournment) The cooperative plan is still young in all engineering schools using it. The first cooperative engineering class graduated from the University of Cincinnati in 1911. Owing to the slowness of the industries and the general public to recognize certain advantages of the cooperative system of engineering education, all of the early cooperative classes at Cincinnati were small, and

other institutions were cautious about adopting this method. The success of the graduates of an institution using a new method of education is a measure of the success of that method. Up to the time of the World War the number of graduates of cooperative engineering schools was too small for one to draw definite conclusions with the certainty of accuracy. Since the War the number of cooperative engineering graduates has increased to such an extent that the advocates of this method now have adequate data on which to base their claims.

There are now quite a number of engineering schools using the Cincinnati Plan, either substantially without change, or with certain modifications. Some of these modifications cause the individual cooperative course to approach in certain aspects the M. I. T. Plan.

Professor Wildes has given nine outstanding features and points of difference between the two types of plan. I agree with his comparison in the case of five points, namely, items 2, 4, 5, 6, and 9, but if the Cincinnati Plan is considered as it is employed in a number of engineering schools I am not in accord with him on items 1, 3, 7, and 8.

Item 1. There are several engineering schools using the Cincinnati Plan which grant a bachelor's degree in four years.

Item. 3. In those engineering schools having a four-year cooperative course leading to a baccalaureate degree the cooperation extends through only one or two years. These are ordinarily the sophomore and junior years.

Item 7. Many of the engineering schools conducting cooperative courses have periods longer than six weeks. At least one has a six-week period which can be combined with the succeeding period when desirable to have a twelve-week term. Others regularly use twelve-week, or even a sixteen-week period. The University of Pittsburgh uses a semester of approximately seventeen weeks as the basis of the cooperative term.

Item 8. Those cooperative engineering schools using a period of twelve weeks or more have the curricula so arranged that each unit of study is completed in a single college period.

As the two plans ordinarily are operated at present, the difference given in item 5 exists. However, this is not a fundamental difference when the engineering school is located in an industrial city, as is the case of the universities of Cincinnati, Pittsburgh, Akron, and Louisville. The question of conducting night classes during the cooperative periods, as is done under the M. I. T. Plan, has been considered by at least one of these institutions with no definite adverse decision.

In my opinion the important fundamental differences between the two plans are the following:

| Cincinnati Plan | M. I. T. Plan |
|---|---|
| Scholastic work is limited to undergraduate studies. | Scholastic work in the last year of the course is definitely graduate in character. |
| All students are cooperative at some time during the course. | Cooperative students are selected. |
| The course in practise is laid out by coordinators of the college, sometimes with the assistance of company officials. | The course in practise is laid out by officials of the company and the professional department of the college. |
| Each student may be trained with several companies. | Each student is trained with one comprehensive company. |
| Practical training is greatly affected by business conditions. | Practical training is only slightly affected by business conditions. |

The other four points are adaptable to either plan.

There is no single best plan of cooperative engineering education. The form to be used is dependent upon many factors. Some of these are:

Whether the college is a privately endowed, a state, or a municipal institution.

Whether it is an independent polytechnic institute or the engineering school of a university.

Whether it is a large institution drawing a sizable proportion of its students from all parts of the country, a large or medium-size institution with the large majority of its students from a definite region, such as a state or group of states, or a small or distinctly local institution.

Each of these must determine first whether any sort of cooperative method should be adopted, second (if the answer to the first question is affirmative) whether all or only part of the students should have cooperative work at some time during the college course, and finally the details of the method to be used, after a thorough study of the industries and the part of the country the school serves.

**K. L. Wildes:** Mr. Boyajian has pointed out the difference in point of view between studies in the educational institution where emphasis is placed more on the fundamental principles underlying a problem, and in the industrial concern, where economic limitations and immediate utility are important considerations. In thesis problems of the graduate year it often happens that a part of the work is done while the student is employed with the company, and a part while in residence at the educational institution. Thus both the academic and industrial standpoints are brought to bear on a single problem, or set of problems. The instructor at the works is a most important factor in helping the student to appreciate these points of view.

Referring to Mr. Chadbourn's discussion I should like to remark that I believe excessive opportunity is often a handicap, not only to students, but to men in permanent employment. The first few years of a young man's life should be characterized by achievement. Cases arise in which the positions given to young engineering graduates are so far above their abilities that these seeming opportunities become actual handicaps, and by them the young employees are prevented from doing work of outstanding quality.

This principle also applies to the training periods of the M. I. T. system of cooperative education. Apparently Mr. Chadbourn is satisfied that the ablest and best balanced students are receiving great profit from their periods of training and experience and become worth while members of the organization after graduation. I have not much use for his second class of men and therefore I do not primarily blame either the cooperating company or the M. I. T. plan of cooperative education for their lack of correct attitude while in training, or their exalted opinion of their ability to take on executive duties immediately after they complete their course of study. These qualities are inherent in the man himself and such a man does not, in my opinion, merit any kind of cooperative training. My solution of Mr. Chadbourn's problem is to eliminate this type of student from the course. The personnel departments of all the cooperating companies are becoming increasingly efficient in the selection of students, so that it looks as though this difficulty is well on its way to solution.

# Determination of Generator Speed
## and Retardation During Loss Measurements

BY O. E. CHARLTON* and W. D. KETCHUM*
Associate, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—This paper describes an instrument which was developed to make graphic records of generator revolutions and time as the generator slows down under the action of its losses during retardation tests. The construction of speed-time curves from the records thus obtained is outlined.*

*The principle of numerical differentiation is discussed and its application to the determination of the slope of the speed-time curve is pointed out.*

*A complete example illustrating the application of this principle is included in the paper.*

### Introduction

DURING the past two years efficiency tests have been made upon generating units in several hydro plants on the Alabama Power Company system. In determining generator efficiency the fundamental formula

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output plus losses}} \qquad (1)$$

was used.

The losses were determined by the retardation method as described by J. Allen Johnson[1] from the equation

$$\frac{dE}{dt} = \frac{WR^2}{g} \cdot 4\pi^2 \cdot s \cdot \left(\frac{ds}{dt}\right) \qquad (2)$$

Where

$\frac{dE}{dt}$ = power.

$WR^2$ = flywheel effect of rotating parts.
$g$ = acceleration of gravity.
$s$ = angular velocity of rotating parts.

$\frac{ds}{dt}$ = angular retardation of rotating parts.

The scope of this paper is limited to a description of the methods used in evaluating the speed ($s$) and the retardation $\left(\frac{ds}{dt}\right)$ for use in Equation (2).

### Measurement of Generator Speed

The precision of the results to be obtained from the retardation method depends primarily upon the accurate determination of the speed-time curve as the generator slows down and upon the most exact determination possible of the slope of this curve at various points. Experience has shown that a tachometer and a stop watch do not provide the necessary degree of precision, particularly when the generator under test has relatively low $WR^2$ and consequently slows down rapidly. An attempt was therefore made to develop an instrument which would record these quantities accurately.

The ideal device for this purpose would be a recording instrument, such as that suggested by V. Karapetoff,[2] which would measure retardation directly. No such instrument is on the market at the present time, however, and difficulties were encountered which prevented the construction of one for the tests.

As a substitute for this ideal instrument, a chronograph was constructed which in its original crude form, consisted essentially of three spark-gaps through which a paper chart was passed as it unrolled from a supply spool and was wound up on a motor-driven rewind spool. A contact on the shaft of the generator energized one spark coil, giving a puncture on the chart for each revolution of the generator. Another spark coil was energized through a contact made by a seconds pendulum giving a puncture every second. The third spark coil was energized through a manually operated switch and its function was to designate on the chronogram the instant at which all instruments were read.

The first form of chronograph, which is illustrated in Fig. 1, was used on several occasions and the results are believed to be of a reasonable degree of precision. Fig. 2 shows a specimen chronogram taken with this instrument and illustrates the type of record which it produced. It was felt, however, that the importance of the efficiency tests justified as high a degree of precision in the measurements as could be obtained practically, and, therefore, an instrument embodying numerous refinements was developed.

While operating on the same fundamental principle as the old chronograph, the new instrument differs widely in detail from its predecessor. It is mounted on an aluminum base approximately 16 in. by 48 in. and about 2½ in. deep. Essentially, it consists of a driving motor, an electrically operated tuning fork, and an electrically operated stylus. The record is made upon a strip of waxed paper which is unwound from a supply spool, passes under the stylus and tuning fork and continues around the two driving rollers to the rewind spool. The tuning fork is electrically driven at 100 vibrations per second, while the stylus is energized through a contact on the generator shaft. Fig. 3 is a

*Southeastern Engg. Co., Birmingham, Ala.

1. For references see Bibliography.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*



30-59

general view of this instrument, and Fig. 4 shows a typical record taken by it.

One refinement which has been found to contribute materially to the facility with which the records may be

Fig. 1—Chronograph as Originally Constructed

interpreted is the constant linear speed drive for the paper. This is accomplished by driving the paper strip directly through constant speed driving rolls, while a

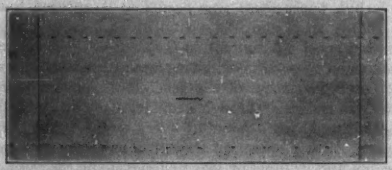

Fig. 2—Typical Record from Chronograph Shown in Fig. 1

friction clutch automatically varies the speed of rotation of the rewind spool.

Between the tuning fork and the magnetic stylus

Fig. 3—Improved Chronograph

there is located a spark-gap which is energized manually from a switch. The function of this gap is to designate on the chronogram the instant of taking readings on the instruments.

## Speed-Time Curve

The data supplied by the chronogram are in the form of two graphic records, one of revolutions and one of time. In order to obtain the speed of the generator, at any point, it is, of course, necessary to count the indications of each of these records over a period of time. Since the displacement between indications of successive revolutions is far greater than that between successive cycles made by the tuning fork, it is obviously much simpler from the standpoint of interpolation, to

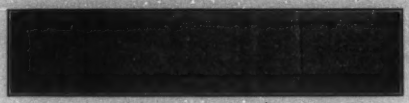

Fig. 4—Typical Record from Chronograph Shown in Fig. 3

count the cycles of the tuning fork record for a given number of revolutions. This process would have been very laborious if it had been necessary to count each cycle individually. However, by means of a transparent celluloid interpolator consisting of ten uniformly spaced radial lines, this work was facilitated materially. The data taken from the chronogram in this manner were tabulated as shown in Table I. Since it is probable that the true speed-time curve of a large machine

TABLE I

| I<br>Point number | II<br>Actual time in seconds for 3 revolutions | III<br>Average speed in revolutions per second | IV<br>Time elapsed since start of test (seconds) |
|---|---|---|---|
| 1 | 2.010 | | |
| 2 | 2.020 | | |
| 3 | 2.025 | | |
| 4 | 2.035 | | |
| 5 | 2.045 | 1.467 | 10.135 |
| 6 | 2.055 | | |
| 7 | 2.065 | | |
| 8 | 2.070 | | |
| 9 | 2.085 | | |
| 10 | 2.090 | 1.435 | 20.500 |
| 11 | 2.100 | | |
| 12 | 2.110 | | |
| 13 | 2.120 | | |
| 14 | 2.130 | | |
| 15 | 2.140 | 1.402 | 31.100 |
| 16 | 2.150 | | |
| 17 | 2.160 | | |
| 18 | 2.170 | | |
| 19 | 2.180 | | |
| 20 | 2.190 | 1.370 | 41.950 |
| 21 | 2.200 | | |
| 22 | 2.210 | | |
| 23 | 2.225 | | |
| 24 | 2.230 | | |
| 25 | 2.245 | 1.337 | 53.060 |
| 26 | 2.255 | | |
| 27 | 2.265 | | |
| 28 | 2.275 | | |
| 29 | 2.285 | | |
| 30 | 2.300 | 1.304 | 64.440 |
| 31 | 2.310 | | |
| 32 | 2.325 | | |
| 33 | 2.330 | | |
| 34 | 2.345 | | |
| 35 | 2.360 | 1.271 | 76.110 |
| 36 | 2.370 | | |
| 37 | 2.380 | | |
| 38 | 2.390 | | |
| 39 | 2.405 | | |
| 40 | 2.420 | 1.240 | 88.075 |
| 41 | 2.430 | | |
| 42 | 2.445 | | |
| 43 | 2.455 | | |
| 44 | 2.470 | | |
| 45 | 2.480 | 1.210 | 100.355 |

as it slows down is a continuous curve, the data taken from the chronogram were plotted and a smooth curve, as shown in Fig. 5, was determined from the plotted points with the idea that this curve would be more nearly a true representation of the speed-time curve of

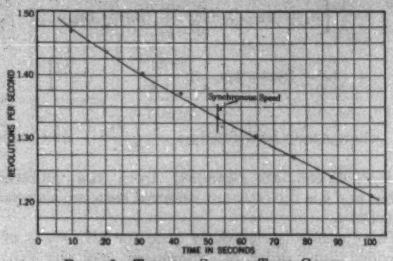


Fig. 5—Typical Speed—Time Curve

the machine than the actual plotted points. The use of this curve also facilitated the determination of the slopes, as the method of numerical differentiation involves the use of values of speed taken at constant intervals of time.

## Method of Obtaining Slope of the Speed-Time Curve

The slope of the speed-time curve for any retardation run should be determined with the greatest amount of accuracy possible from the data available, because the value of the losses varies directly as this slope.

In finding the slope of a curve, the equation of which is unknown, the usual method is to construct a tangent to the curve at the point where the slope is desired. This graphical differentiation is at best inaccurate for most empirical curves and especially so when the curve approaches a straight line.

Instead of this somewhat crude and inexact method, the principles of numerical differentiation have been applied, and it is believed that a considerably higher degree of precision has been obtained in this way than would have been possible using the strictly graphical method. The principles of numerical differentiation are thoroughly described in many standard mathematical works[2, 4, 5, 6] and hence, the derivation and proof of this process lie outside the scope of this paper. However, a practical outline of the method is included in order that its application to the determination of angular retardation may be clearly understood.

In applying this method to an empirical curve of unknown equation $y = f(x)$, values of $x$ are taken (throughout the range of the curve under consideration) with a constant increment $h$, as shown in Fig. 6, so that

$$\begin{aligned} x_1 - x_0 &= h; \\ x_2 - x_1 &= h \\ &\cdots \\ x_n - x_{n-1} &= h \end{aligned}$$

Corresponding values $y$ are then taken from the curve (*i. e.*, $y_0, y_1, y_2, \ldots y_{n-1}, y_n$).

Differences between successive values of $y$ are then computed, thus:

$$\begin{aligned} y_1 - y_0 &= a_0 \\ y_2 - y_1 &= a_1 \\ y_3 - y_2 &= a_2 \\ &\cdots \\ y_n - y_{n-1} &= a_{n-1} \end{aligned}$$

The values $a_0, a_1, a_2, \ldots a_n$ obtained in this manner are known as differences of the first order. In the same fashion, the differences of the second order are computed, thus:

$$\begin{aligned} a_1 - a_0 &= b_0 \\ a_2 - a_1 &= b_1 \\ a_3 - a_2 &= b_2 \\ &\cdots \\ a_n - a_{n-1} &= b_{n-1} \end{aligned}$$

This process is continued until the desired number of differences has been taken. The Difference Table (Table II) is then constructed, with the values thus obtained.

The question of how many differences to include in the table requires some attention. In the somewhat special case where the original curve can be exactly represented in the range under consideration, by a polynomial of $n$th degree, the $n$th order of difference will be constant and the $n + 1$st order will vanish. In such a case the slope as calculated from the Difference Table will be rigorously correct.

More frequently, however, it is found that some

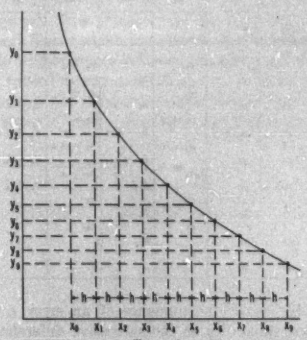


Fig. 6

order of difference is approximately constant, while successive orders tend to disperse irregularly. Such behavior as this is due to discrepancies between some of the tabulated values of $y$ and the corresponding values of a polynomial which approximately, but not exactly, coincides with the original function in the

range under consideration. Such discrepancies may be the result of either errors in the empirical data, or of the fact that the original function cannot be represented exactly by a polynomial in the interval being studied. The magnitude of such deviations from the

TABLE II
DIFFERENCE TABLE

| $x$ | $y$ | $\Delta_1$ | $\Delta_2$ | $\Delta_3$ | $\Delta k$ |
|---|---|---|---|---|---|
| $x_0$ | $y_0$ | | | | |
| | | $a_0$ | | | |
| $x_1$ | $y_1$ | | $b_0$ | | |
| | | $a_1$ | | $c_0$ | |
| $x_2$ | $y_2$ | | $b_1$ | | $m_0$ |
| | | $a_2$ | | $c_1$ | |
| $x_3$ | $y_3$ | | $b_2$ | | $m_1$ |
| | | $a_3$ | | | |
| $x_4$ | $y_4$ | | | | |
| | | | | | $m_{n+1-k}$ |
| | | | | $c_{n-2}$ | |
| $x_n$ | $y_n$ | | $b_{n-1}$ | | |
| | | $a_n$ | | | |
| $x_{n+1}$ | $y_{n+1}$ | | | | |

Where:

$$x_1 - x_0 = h \qquad y_1 - y_0 = a_0 \qquad a_1 - a_0 = b_0$$
$$x_2 - x_1 = h \qquad y_2 - y_1 = a_1 \qquad a_2 - a_1 = b_1 \qquad \text{etc.}$$
$$\cdots \qquad \cdots \qquad \cdots$$
$$x_{n+1} - x_n = h \qquad y_{n+1} - y_n = a_n \qquad a_n - a_{n-1} = b_{n-1}$$

polynomial function may be determined for each of the tabulated values of $y$ by the use of a correction term (which is evaluated by trial) multiplied by the binomial coefficients.[6]

An inspection of Table III will make this clear.

TABLE III
SHOWING THE INFLUENCE OF AN ERROR $\epsilon$ IN ONE VALUE OF $y$ ON THE SUCCESSIVE DIFFERENCES

| $x$ | $y$ | $\Delta_1$ | $\Delta_2$ | $\Delta_3$ | $\Delta_4$ |
|---|---|---|---|---|---|
| $x_0$ | $y_0$ | | | | |
| | | $a_0$ | | | |
| $x_1$ | $y_1$ | | $b_0$ | | |
| | | $a_1$ | | $c_0$ | |
| $x_2$ | $y_2$ | | $b_1$ | | $d_0 + \epsilon$ |
| | | $a_2$ | | $c_1 + \epsilon$ | |
| $x_3$ | $y_3$ | | $b_2 + \epsilon$ | | $d_1 - 4\epsilon$ |
| | | $a_3 + \epsilon$ | | $c_2 - 3\epsilon$ | |
| $x_4$ | $y_4 + \epsilon$ | | $b_3 - 2\epsilon$ | | $d_2 + 6\epsilon$ |
| | | $a_4 - \epsilon$ | | $c_3 + 3\epsilon$ | |
| $x_5$ | $y_5$ | | $b_4 + \epsilon$ | | $d_3 - 4\epsilon$ |
| | | $a_5$ | | $c_4 - \epsilon$ | |
| $x_6$ | $y_6$ | | $b_5$ | | $d_4 + \epsilon$ |
| | | $a_6$ | | $c_5$ | |
| $x_7$ | $y_7$ | | $b_6$ | | $d_5$ |
| | | $a_7$ | | $c_6$ | |
| $x_8$ | $y_8$ | | $b_7$ | | |
| | | $a_8$ | | | |
| $x_9$ | $y_9$ | | | | |

This table shows the influence of an error $\epsilon$ in any tabulated value of $y$ on the successive differences. It will be seen that the original error is multiplied by the binomial coefficients in each order of difference.

The discrepancies between the original curve and polynomials of several different degrees may be determined as outlined above. These discrepancies will be found to be a minimum for a polynomial of say the $k$th degree. The Difference Table is therefore extended to include the $k$th order of differences, but is terminated at this point.

Having completed the Difference Table the following formula for the derivative which was obtained from Newton's Interpolation formula may be used:

$$\frac{dy}{dx} = \frac{1}{h}\left[a_0 + (2n-1)\frac{b_0}{\underline{|2}} + (3n^2 - 6n + 2)\frac{c_0}{\underline{|3}} + (4n^3 - 18n^2 + 22n - 6)\frac{d_0}{\underline{|4}} \cdots\right] \qquad (3)$$

where $n$ may be defined as $\dfrac{x - x_0}{h}$, and where $a_0$, $b_0$, $c_0$, $d_0$, etc. are obtained from the Difference Table, and $h$ is the constant interval between successive values of $x$.

This formula is rigorously true for all values of $n$, provided some order of differences (say the $k$th) is constant. It is approximately true if the $k$th order of differences is approximately constant, particularly for fractional values of $n$. Since it is only the sequence of the subscripts in the Difference Table that is significant, any value of $x$ may be designated as $x_0$ provided the following value is called $x_1$, etc. Thus it is clear that $n$ may always be made fractional.

In the particular case where the derivative at a tabulated point is desired, $n$ vanishes and Equation (3) reduces to

$$\frac{dy}{dx} = \frac{1}{h}\left[a_0 - \frac{b_0}{2} + \frac{c_0}{3} - \frac{d_0}{4} + \cdots\right] \qquad (4)$$

Using Equations (3) and (4), the slope of the original curve may be calculated at as many points as may be desired.

In determining generator losses, the slope of the speed-time curve might be calculated for the point corresponding to synchronous speed only, since this is the only value used in the calculations. However, the slopes were calculated for a number of points along the speed-time curve, and a curve of retardation against time was plotted. From this curve the value of the slope at synchronous speed was read. A curve of retardation against time was used instead of a single calculated point in order that any deviation from its general trend might be detected, and checked for errors.

## Application of Numerical Differentiation

In order to clarify the foregoing explanation and at the same time illustrate the use of "Numerical Differentiation" when applied to a practical problem, an example will be given of an actual retardation run taken on a generator during an efficiency test.

The generator revolutions and a timing wave were recorded by the chronograph shown in Fig. 3, making a record similar to the specimen shown in Fig. 4. From this record, the data were tabulated as shown in Table

TABLE IV

| $x$ Time in seconds | $y$ Rev. per sec. | $\Delta_1$ | $\Delta_2$ | $\Delta_3$ | $\Delta_4$ | $\Delta_5$ | $\Delta_6$ | $\Delta_7$ | $\Delta_8$ | $\Delta_9$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 1.4725 | | | | | | | | | |
| | | −0.0363 | | | | | | | | |
| 20 | 1.4362 | | 0.0026 | | | | | | | |
| | | −0.0337 | | −0.0004 | | | | | | |
| 30 | 1.4025 | | 0.0022 | | −0.0001 | | | | | |
| | | −0.0315 | | −0.0005 | | 0.0012 | | | | |
| 40 | 1.3710 | | 0.0017 | | 0.0011 | | −0.0044 | | | |
| | | −0.0298 | | 0.0006 | | −0.0032 | | 0.0106 | | |
| 50 | 1.3412 | | 0.0023 | | −0.0021 | | 0.0062 | | −0.0188 | |
| | | −0.0275 | | −0.0015 | | 0.0030 | | −0.0082 | | +0.0248 |
| 60 | 1.3137 | | 0.0008 | | 0.0009 | | −0.0020 | | 0.0060 | |
| | | −0.0267 | | −0.0006 | | 0.0010 | | −0.0022 | | |
| 70 | 1.2870 | | 0.0002 | | 0.0019 | | −0.0042 | | | |
| | | −0.0265 | | 0.0013 | | −0.0032 | | | | |
| 80 | 1.2605 | | 0.0015 | | −0.0013 | | | | | |
| | | −0.0250 | | 0.0000 | | | | | | |
| 90 | 1.2355 | | 0.0015 | | | | | | | |
| | | −0.0235 | | | | | | | | |
| 100 | 1.2120 | | | | | | | | | |

I. The average speed in revolutions per second was then calculated at intervals of 15 revolutions and the points plotted against time. That is, columns III and IV of Table I were plotted to give the speed-time curve of the retardation run. This curve is shown in Fig. 5.

The next step was to construct a "Difference Table" from the data of the speed-time curve. In doing this, values of time were taken every 10 seconds and the corresponding values of speed read from the curve. These values were tabulated as shown in Table IV.

An inspection of Table IV shows that there is no order of differences which is constant. The third order, however, appears to be of smaller magnitude than the succeeding differences, and this fact suggests that the table should be terminated there. In order to determine how far the tabulated values of speed deviate from a polynomial of the third degree the method previously discussed and illustrated in Table III is applied. Table V is therefore constructed, using Table IV as a base, but terminating the difference table with the third difference. The column $C_1$ compensates for a discrepancy in the value of $y$ corresponding to a value of $x$ at 60 seconds; $C_2$ for a discrepancy in the value of $y$ at point when $x$ equals 70 seconds, etc. This table, therefore, shows that the given curve differs from a cubic curve to the following extent:

| Time (seconds) | Discrepancy |
|---|---|
| 10 | 0 |
| 20 | 0 |
| 30 | 0 |
| 40 | 0 |
| 50 | 0 |
| 60 | −0.0011 |
| 70 | −0.0023 |
| 80 | −0.0035 |
| 90 | −0.0065 |
| 100 | −0.0118 |

If desired, this process may be repeated using a Difference Table which includes $\Delta_4$, and it will be seen that the discrepancies between the given curve and a quartic exceed those tabulated above. This shows that differences of the third order should be the highest used in the slope formula. Similarly, the Difference Table

TABLE V

| $x$ Time in seconds | $y$ Rev. per sec | $\Delta_1$ | $\Delta_2$ | $\Delta_3$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_1+C_2+C_3+C_4+C_5$ | $\Delta_3+C_1+C_2+C_3+C_4+C_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 1.4725 | | | | | | | | | | |
| | | −0.0363 | | | | | | | | | |
| 20 | 1.4362 | | 0.0026 | | | | | | | | |
| | | −0.0337 | | −0.0004 | | | | | | | −0.0004 |
| 30 | 1.4025 | | 0.0022 | | | | | | | | |
| | | −0.0315 | | −0.0005 | | | | | | | −0.0005 |
| 40 | 1.3710 | | 0.0017 | | | | | | | | |
| | | −0.0298 | | 0.0006 | −0.0011 | | | | | −0.0011 | −0.0005 |
| 50 | 1.3412 | | 0.0023 | | | | | | | | |
| | | −0.0275 | | −0.0015 | 0.0033 | −0.0023 | | | | 0.0010 | −0.0005 |
| 60 | 1.3137 | | 0.0008 | | | | | | | | |
| | | −0.0267 | | −0.0006 | −0.0033 | 0.0069 | −0.0035 | | | 0.0001 | −0.0005 |
| 70 | 1.2870 | | 0.0002 | | | | | | | | |
| | | −0.0265 | | 0.0015 | 0.0011 | −0.0069 | 0.0105 | −0.0065 | | −0.0018 | −0.0005 |
| 80 | 1.2605 | | 0.0015 | | | | | | | | |
| | | −0.0250 | | 0.000 | | 0.0023 | −0.0105 | 0.0195 | −0.0118 | −0.0005 | −0.0005 |
| 90 | 1.2355 | | 0.0015 | | | | | | | | |
| | | −0.0235 | | | | | | | | | |
| 100 | 1.2120 | | | | | | | | | | |

might have been terminated with $\Delta_3$, in which case the discrepancies would also have been found larger than those tabulated above. This signifies that three terms of Equation (4) should be used in computing the slope.

Performing this computation for the case of $x = 30$ seconds, we have:

$$\frac{dy}{dx} = \frac{1}{10}\left[-0.0315 - \frac{0.0017}{2} + \frac{0.0006}{3}\right]$$

$$= -0.00321 \text{ rev. per sec. per sec.}$$

In like manner the slopes were calculated for other points, and the results appear in Table VI.

TABLE VI

| Time in sec. | Slope in rev. per sec. per sec. |
|---|---|
| 10 | −0.00377 |
| 20 | −0.00350 |
| 30 | −0.00321 |
| 40 | −0.00314 |
| 50 | −0.00281 |
| 60 | −0.00264 |
| 70 | −0.00272 |

These data were plotted as shown in Fig. 7. The slope at synchronous speed was read from this curve and was used to calculate the power loss by Equation (2).

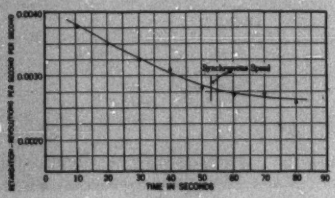


Fig. 7—Typical Retardation Curve

## Conclusions

It is believed that the chronograph is considerably more accurate than the tachometer and stop watch. Experience has shown that the chronograph, using a tuning fork for a timing element, is far preferable to the instrument which depends upon a seconds pendulum for its timing.

In addition to being more accurate than the stop watch, the chronograph is applicable to tests upon generators whose $WR^2$ is relatively low and which therefore slow down rapidly, whereas the stop watch method is not well adapted to use on such tests.

Due to the inherent accuracy of the chronograph, it is not necessary to take data throughout as great a range of speed during a retardation run as in the case of the stop watch method. Experience with generator tests on the Alabama Power Company system has shown that a range of from 10 per cent above synchronous speed to approximately 10 per cent below synchronous speed is adequate. The average time required for such a retardation run is approximately 3 minutes.

An additional advantage inherent in the use of the chronograph is the fact that it produces a permanent graphical record, thus reducing the chance for personal errors to creep in.

While the method of numerical differentiation is not new, it is felt that its advantages in connection with the determination of the retardation of generators have not been generally recognized. This principle constitutes a useful tool which may be readily employed.

It is realized that the method of determining slopes as outlined above is not mathematically rigorous unless some order of difference becomes constant. The type of curves encountered when considering the speed-time characteristics of a generator under the retarding forces of its losses, in general, does not give a constant set of differences. This is not surprising when it is remembered that the windage loss, which is always present, varies as a variable power of the speed.

It is felt, however, that the results obtained from this admittedly approximate method are of a considerably higher degree of precision than would have been obtainable from a strictly graphical method, and that they are well within the range of engineering accuracy. This, of course, is all that may be expected from data obtained from measurements made in the field where laboratory methods are inapplicable.

The use of this principle has produced consistent results wherever it has been applied by the authors. Typical results of two tests, each of which were duplicated, are tabulated below:

| Run No. | Retardation rev. per sec. per sec. | Per cent deviation from the average |
|---|---|---|
| 1 | −0.001763 | 0.45 |
| 2 | −0.001747 | 0.45 |
| Average | −0.001755 | |
| 1 | −0.001549 | 0.16 |
| 2 | −0.001554 | 0.16 |
| Average | −0.001552 | |

The close agreement between the duplicate runs seems to justify considerable confidence in the accuracy of this method of recording the speed of the generator and of obtaining the slope of the speed-time curve.

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6. "Theory and Practise of Interpolation," by H. L. Rice.

**J. A. Johnson:** I am always glad to see a paper on improvements in the retardation method of testing generators, which I have advocated for a long time. I am particularly glad to see the development of more accurate instruments which will promote the use of this method in testing generators, where it is suitable, for it is a beautiful method and remarkably accurate and easy to apply.

I am rather disturbed, however, to see that this paper may give the impression that the application of this method calls for what appears to be a rather complicated mathematical computation in order to produce a satisfactorily accurate result. I gather that the only excuse for using this method of arithmetical differentiation is greater accuracy. Now, I should like to call attention to Table IV on page 1099. The third column of that table headed $\Delta_1$ gives the loss in revolutions per second for each ten second interval. Dividing these figures by ten will give figures which represent the rates of retardation in revolutions per second per second which are the average rates of retardation during the corresponding ten second intervals. In the method used in evaluating the tests which I made some years ago and presented in the paper referred to by Messrs. Charlton and Ketchum, it was assumed that this average value matched up in time with the middle of the corresponding interval. Of course, this is not scientifically correct but is more nearly so the shorter the interval.

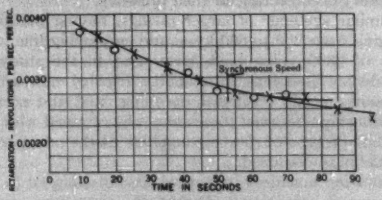


Fig. 1—Typical Retardation Curve

○ = Arithmetical Differential Method
× = Direct Method

Plotting these values (the third column of Table IV with the decimal point moved one place to the left) on Fig. 7, the first value at 15 seconds, the second at 25 seconds, and so on, it appears that these points coincide with the authors' curve more closely than their own points do above synchronous speed, and by giving two more points than the authors' method below synchronous speed, clearly indicates that the arithmetical differentiation method has given very questionable results in this part of the curve. I therefore claim that the authors have not demonstrated that their method of arithmetical differentiation gives more accurate results than the much simpler method I have used.

I bring up this point because I should be very sorry to see the retardation method handicapped by an erroneous impression that it requires laborious computations to get accurate results. On the contrary, I claim that all the accuracy necessary can be built into the chronograph recording instrument, and that this having been done, the instrument record can be interpreted in retardation and loss values in a very simple manner, involving a minimum of computation.

**W. D. Ketchum:** I should certainly be quite unjust if I did not acknowledge gratefully the benefits which we in our retardation tests have derived from Mr. Johnson's paper. We started out extremely inexperienced and his paper was a guide which we fell back on time and time again and it is only fair that I acknowledge it, because without it we would have had much more difficulty than we had.

As to his criticism of the method of numerical differentiation as being a needless refinement, it seems to me that this is a question which has to be answered in each specific case. It certainly appears from the curve which was flashed on the screen that in the example which we gave in our paper, a simpler method would have been almost as accurate. I say, it appears this is true because the scale at which this curve was reproduced is somewhat small and it is difficult to tell much about it. However, it seems to me that since the shape of that curve will vary somewhat with each individual test, and certainly with each individual machine, this is a matter which has to be settled in each instance.

Now, Mr. Johnson's wide experience in this type of work as compared to our relative inexperience, certainly lends weight to his criticism. We felt, however, that if we went ahead and applied the principle of numerical differentiation we would have obtained as accurate an answer as we could with the instruments and facilities at our disposal and we felt that had we stopped with the simplification which Mr. Johnson pointed out, we would have overlooked something which might or might not have changed the results. That was our justification for going into this type of method.

I frankly think that on close inspection it will be found that this method is not as intricate as my description may lead you to believe. If you will follow the example given in the paper I believe you will find you can go through the various operations in a comparatively short time.

Certainly the last thing we would want to do would be to discredit the retardation method for all the experience we have had indicates that it is a very ready and relatively simple means of determining generator efficiency and we would hate to do anything to throw it in disfavor.

**O. E. Charlton:** I should like to emphasize the fact that the application of numerical differentiation to the speed-time curve does not require any complicated mathematics and the increase in labor is negligible.

After the necessary information has been obtained from the chronogram to plot a speed-time curve, which is necessary before slopes can be found, by any method, the difference table can be constructed by subtraction. The retardation is then determined by substituting the proper values taken from the difference table in a simple formula. I have found from actual practise that once the data are worked up from the chronogram, the actual calculation of the slopes requires only about fifteen or twenty minutes for each point.

The error introduced in the loss measurement by assuming the speed-time curve to be a straight line between any two points, varies with the type of curve and with the size of the interval between points. We have found from a number of tests, however, that with an interval of ten seconds the error will vary from three to six or seven per cent.

It might be argued that an error of six per cent in the losses would make very little difference in the efficiency of the machine, but a six per cent error in all the losses determined by retardation if they should be accumulative, would change the resultant efficiency by one-tenth of one per cent, or more, and it is not uncommon to find a penalty clause in generator contracts for each tenth of a per cent that the efficiency drops below the guaranteed value.

Numerical differentiation of the speed-time curve gives a very accurate value for slopes and it can be applied with as much ease as the tangent method and with very little more work.

# The M. I. T. Network Analyzer

## Design and Application to Power System Problems

BY H. L. HAZEN,* O. R. SCHURIG,† and M. F. GARDNER*

*Synopsis.—Previous network-computing devices with their uses and limitations are reviewed briefly, following which is a statement of the requisites for an effective a-c. calculating table. The M. I. T. Network Analyzer, a static miniature a-c. power system, designed and constructed jointly by the Massachusetts Institute of Technology and the General Electric Company for the computation of actual power networks, is described in detail and its operation outlined. The fields of its application are enumerated and include the study of normal operating conditions, stability, and short circuits. An example illustrating its application to the solution of a normal-operation problem is given.*

* * * * *

### Introduction

To determine the behavior of a power system under various conditions of operation necessitates numerous solutions for the distribution of current, voltage, real and reactive power in its network. The advantages of experimental methods over lengthy and usually impracticable mathematical calculations for the determination of these quantities have long been recognized and several types of experimental computing devices or miniature systems for network analysis have been developed and have proved their usefulness.

The following paper deals with an improved form of network-computing device designed and built jointly by the Massachusetts Institute of Technology and the General Electric Company. The Network Analyzer, as this device is called, is installed in the Electrical Engineering Research Laboratory of the Massachusetts Institute of Technology at Cambridge, Mass.

Most of the network computing devices developed have been in the form of miniature systems. These are imitations on a small scale of those features of the real system considered significant or indispensable for solution of the class of problem for which the model was developed. One of the earliest developed was the d-c. short-circuit calculating table.[1] Due to the use of direct current, it is limited in its application to those problems in which phase angles can be neglected, as for example in short-circuit studies involving only questions of current magnitudes. Its simplicity has made it almost indispensable for this purpose.

The first miniature to employ alternating current was a three-phase representation of one particular system.[2] Like the d-c. table it was a static duplication, containing no rotating elements. Although the phase angles at generating points were not adjustable, it afforded an ingenious means of investigating relay performance with unbalanced short circuits at a date when the usefulness of symmetrical-component analysis was as yet unappreciated.

The necessity for representing angle differences between synchronous machines led to the use of a-c. miniature systems with three-phase generators, motors, static loads, and lumped three-phase artificial lines. One such system[3] used synchronous machines of 3.75 kv-a. rating and normal system currents of 10 amperes at 440 volts. This scale was considered the minimum which would permit the use of the usual types of portable indicating ammeters, voltmeters, and wattmeters for measuring quantities in the circuits without the necessity of correcting for their presence.

Similar systems[4] of larger ratings, having machines ranging from 200 to 600 kv-a. and employing line voltages of 2300 volts, have been used in the study of stability. Questions of stability involve mechanical momentum and electrical damping, and the normal relationships between these cannot be retained with the customary type of rotating machine as the model scale is indefinitely reduced.

Rotating machines in general are not adapted to use in network computing devices of laboratory convenience and accuracy because of their cost, space and power requirements, and their instability when an attempt is made to employ more than three or four units.

The limitations of the foregoing schemes for network representation led to the experimental development at M. I. T. of a static type of miniature system[5] incorporating features which could be applied to the solution of normal-operation problems in extensive systems on laboratory scale. It was demonstrated that generating stations are adequately represented by static phase-shifting transformers, thereby eliminating the difficulties associated with rotating machines.

The Network Analyzer described in this paper is a comprehensive a-c. calculating table incorporating these ideas. While it has been built primarily for educational and research purposes, careful consideration has been given in its design to make it suitable for commercial engineering service.

### General Design Considerations

For a network computing device to adequately achieve its purpose it must embody such complete representation of significant electrical constants and terminal conditions that such errors in method as are inherent in the d-c. table are eliminated. Furthermore, for practical usefulness it must be sufficiently extensive and flexible to represent numerous actual systems; it

*Massachusetts Institute of Technology, Cambridge, Mass.
†General Electric Company, Schenectady, N. Y.

1. For references see Bibliography.

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must yield results of suitable accuracy with a reasonable expenditure of time; its operation should be simple; its space and weight requirements must be reasonable; and its cost should be a minimum consistent with these requirements.

The principal features of the design follow:

1. Representation of one phase line-to-neutral.
2. Representation of the lumped impedance and admittance equivalents of lines, transformers, cables, and loads by adjustable resistors, reactors, and capacitors.
3. Representation of either the terminal or excitation voltage of a synchronous machine by the single-phase terminal voltage of a phase-shifting transformer, this voltage being adjustable in magnitude and phase.
4. Use of minimum electrical scale consistent with direct measurements by portable indicating instruments.
5. Use of such portable indicating instruments—ammeters, voltmeters, and wattmeters—that they can be plugged into or removed from the network without materially altering the voltage drop and current distribution.
6. Provision for interconnecting the units to represent complete power transmission networks.

The selection of the relative sizes and ranges of line and load units required an analysis of the constants of modern transmission systems. Moreover the determination of the voltage and current scales of the Network Analyzer called for a consideration of the impedances of series and shunt elements of measuring instruments.

The results of these analyses will be briefly presented.

*Results of Analysis of Transmission System Constants.* The analysis of a number of overhead as well as underground transmission systems gave the percentage distribution of line and load resistance and reactance values shown in Table I. In general, the two lower ranges of resistance and reactance are for lines, and the two higher ranges for loads.

TABLE I
DISTRIBUTION OF RESISTANCE AND REACTANCE VALUES OF TYPICAL SYSTEMS

| | Per cent of lines and loads in transmission system |
|---|---|
| Resistance less than 2.5% | 25 |
| Resistance from 2.5% to 25% | 38 |
| Resistance from 25% to 1000% | 27 |
| Resistance from 1000% to 5000% | 10 |
| Reactance less than 5%* | 20 |
| Reactance from 5% to 30% | 40 |
| Reactance from 30% to 1000% | 30 |
| Reactance from 1000% to 5000% | 10 |

*Values of per cent resistance and per cent reactance of an impedance element are computed on the basis of a reference kv-a. value, and are equal to the per cent drop in the element in terms of normal voltage when carrying a current corresponding to the reference kv-a. at normal voltage.

The electrical ranges of the line and load units were chosen in accordance with these data.

*Selection of Current and Voltage Scales.* Upon selection of a suitable voltage scale for the Analyzer, its current scale was chosen as small as possible consistent with the requirement that certain portable indicating instruments—voltmeters, ammeters, and wattmeters—could be inserted without materially disturbing currents and voltages in the circuit. For current measurements thermocouple type ammeters were chosen because of their relatively low series resistance in the lower current ranges when compared with other portable ammeters. Likewise thermocouple type voltmeters were chosen because of their low current requirements. Suspended-armature type wattmeters were chosen because their current and voltage elements could be made to meet these requirements. In Table II are given the voltage drops of the series elements of such instruments, and in Table III the currents taken by their shunt elements, expressed as per cents of various voltage and current bases. Corresponding data relating to other types of instruments have been published previously.[6]

TABLE II
VOLTAGE DROPS OF AMMETERS AND WATTMETER CURRENT COILS AT RATED CURRENT

| | Volts drop | Percentage of base voltage | | | |
|---|---|---|---|---|---|
| Base volts | | 400 | 200 | 100 | 50 |
| Thermocouple ammeter | 0.12 | 0.03 | 0.06 | 0.12 | 0.24 |
| Suspended-armature wattmeter | | | | | |
| 1-ampere current coil | 0.08 | 0.02 | 0.04 | 0.08 | 0.16 |
| 2-ampere current coil | 0.04 | 0.01 | 0.02 | 0.04 | 0.08 |

TABLE III
CURRENT REQUIREMENTS OF VOLTMETERS AND WATTMETER POTENTIAL CIRCUITS AT RATED VOLTAGE

| | Amperes | Percentage of base current | | | |
|---|---|---|---|---|---|
| Base amperes* | | 2 | 1 | 0.5 | 0.25 |
| Thermocouple voltmeter | 0.002 | 0.1 | 0.2 | 0.4 | 0.8 |
| Suspended-armature wattmeter | 0.003 | 0.15 | 0.30 | 0.6 | 1.2 |

*The base current or nominal current of the miniature system designates the general order of magnitude of the currents in the principal lines. The operating currents of these lines will of course cover a wide range, of from say one-fifth to four times the nominal value.

A high operating voltage for the Analyzer appears desirable of course to reduce the effects of series-connected instruments on line impedances at a given operating current, as will be seen from Table II. An operating voltage of 200 volts was chosen because it was not desired to subject the operators to the hazards of a higher voltage.

The voltage scale having been fixed, the nominal operating current (see footnote of Table III) was chosen at a value which would give relatively small errors due to the insertion of instruments. It was of course desirable to keep the current as low as possible so as to have a low kv-a. rating of the Analyzer equipment.

It is seen from Table II that the voltage drops in the thermocouple ammeter and in the one-ampere current element of the suspended-armature type wattmeter are 0.12 volt and 0.08 volt, or 0.06 per cent and 0.04 per cent respectively, when carrying one ampere in a 200-volt circuit. If the impedance of the line itself in which these instruments are to be placed is, say, 2.5 per cent (on a one-ampere, 200-volt basis) the increase of total impedance due to the addition of either instrument would be about 2 per cent, *i. e.*, the total impedance would be approximately 2.55 per cent instead of 2.5 per cent. For lines of smaller impedance carrying one ampere in a 200-volt system the additional impedance due to the instruments would of course become more significant and would in some cases require correction or adjustment.

Fig. 1—The Network Analyzer

General view of Analyzer plugged for a problem showing the layout of the four sections and the accompanying instrument tables

On the other hand, if the one-ampere wattmeter of Table II is used in a circuit carrying 0.5 ampere and having an impedance drop of 2.5 per cent at 0.5 ampere and 200 volts, the addition of the wattmeter current element would cause an increase in the circuit impedance drop of only about 1 per cent. A value of the same order of magnitude would of course apply in the case of the one-ampere thermocouple ammeter similarly used at 0.5 ampere.

These considerations point toward the selection of a nominal current of not less than 0.5 ampere for a miniature system in which significant errors due to, or frequent adjustments on account of, impedances of the series-connected instruments of the types covered by Table II are to be avoided.

## Description of Network Analyzer and its Operation

Based on the analysis and general requirements set forth in the foregoing section, a device has been built which is proving very satisfactory in the solution of actual engineering problems. The equipment in the present installation includes a sufficient number of units to represent in its electrical essentials a system consisting of as many as 8 generating stations, 60 lines and cables or other connecting elements, 40 loads, 4 ratio-changing transformers for closing loops, and any desirable number of synchronous condensers. In general it may be assumed that any network whose number of elements falls within the above limits can be represented on the Analyzer with a completeness adequate for the engineering study of the problems for which it was designed.

This equipment is assembled in four steel frames each with cabinet enclosures on all sides except the front. The four sections are arranged facing inward on three sides of a square as shown in Fig. 1. Any of the assembled units can be removed from these section frames merely by taking out four screws, and as they are mechanically interchangeable a very flexible assembly results. Each unit has its own panel and when placed in the frame these panels, together with strips bearing outlets for the busses, form the front face of the section. In front of each section stands a table with a center recessed portion containing instruments. (See Fig. 2.)

*Description of Component Parts.* Having thus considered the more general features of the Analyzer, the various types of units and other parts will be described giving the significant design details and constants.

Fig. 2—A Single Section

Line- and load-unit panels are at top and center, two phase-shifter panels are at lower left and right, and capacitor and synchronous-reactor panels are immediately above phase-shifter panels. Instruments are located in recess in the table top

a. Generators. The six principal phase-shifting transformers, used to represent an equal number of generating stations, are rated at 0-500 volts, 6 amperes with 0.5-volt steps, while two smaller additional units used in previous work rated at 0-300 volts, 1 ampere, are available if needed. Both types are very similar in design and one of the larger units will be described in detail. This phase-shifting transformer or phase shifter, as it is called, is built on a standard wound-rotor induction-motor frame of about 7 kv-a. capacity with

an ordinary two-pole, three-phase, delta-connected rotor winding designed as a 230-volt primary. Its rotor can be adjusted to any desired angular position by a manual worm-gear drive operated at the unit panel, and the angle read from a convenient scale graduated in tenths of degrees. (See Fig. 3.)

The secondary two-pole single-phase winding is provided with taps for 0.5-volt steps. It is of the concentric-coil type, thus making the time phase of the secondary induced voltage essentially independent of the number of coils in the circuit, *i. e.*, of the voltage setting. The angular adjustment of the rotor provides the time-phase adjustment of the secondary voltage,

FIG. 3—ARTIFICIAL GENERATING STATION

A phase-shifter unit showing truck mounting of transformer with control panel, which bears voltage-control switches, angle-control handle and indicating dials, and terminals

hence by means of the tap switches and the angle control, the vector representing this voltage can be made to terminate at any point within a circle of 500 volts radius. This secondary voltage can be used to represent either the terminal or the excitation voltage of a synchronous machine under transient as well as steady-state conditions.

By the use of low flux densities, suitable windings, and a power source of particularly good wave form, the harmonic content of the phase-shifter terminal voltage for all load conditions has been kept under one per cent. The phase shifter with its control panel is assembled similarly to a truck type switchboard section making it very accessible. Suitable jacks are provided for terminals and for the insertion of instruments to indicate its output.

b. Line and load units. These are considered together since the different sizes of resistor or reactor units differ only in winding details. Ordinarily a resistor unit is paired with a reactor unit, the two being connected in series by removable leads in the case of the line units, and in parallel in the case of the load units.

In Table IV the number, range, and principal constants of these units are given.

TABLE IV
LINE AND LOAD UNITS

| | Number | Max. ohms | Ohms per step | Max. capacity |
|---|---|---|---|---|
| Line units | 60 | | | |
| Resistors | 25 | 10 | 0.1 | 4 amp. |
| | 35 | 100 | 1.0 | 2 |
| Reactors | 20 | 20 | Approx. 1% of setting | 4 |
| | 40 | 120 | Approx. 1% of setting | 2 |
| Load units | 40 | | | |
| Resistors | 30 | 4,000 | 4 | 1 amp. or 200 v. |
| | 10 | 20,000 | 200 | 200 v. |
| Reactors | 30 | 4,000 | Approx. 1% of setting | 1 amp. or 200 v. |
| | 10 | 20,000 | Approx. 1% of setting | 200 v. |

*R/X* ratios of reactors

| Size | Setting | *R/X* in per cent at 60 cycles |
|---|---|---|
| 20 ohms | 20 ohms | 3.5 |
| | 1 | 5 |
| 120 | 120 | 3.5 |
| | 20 | 4.5 |
| 4,000 | All | 6 |
| 20,000 | All | 7 |

*Saturation.* For a 20-to-1 change of ampere turns the reactance at any setting within the working range changes not more than 2 per cent.

The resistor units are assembled of resistor tubes, each consisting of high-resistivity, low-temperature co-efficient wire wound on a porcelain tube covered by

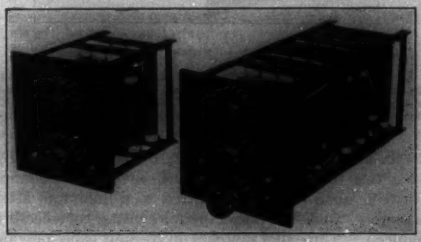

FIG. 4—RESISTOR UNITS

Line unit (left) and load unit (right) showing resistor-tube assembly and control panel bearing decade switches, taper-socket terminals, and current jack (load unit only). These units are self contained and mounted in section frame with four screws

vitreous enamel. The number of tubes varies from 4 in the 10-ohm unit to 28 in the 4000-ohm unit, the design depending on the amount of power which must be dissipated as heat from the most heavily loaded tube. (See Fig. 4.) All units are calibrated, and a step can be selected whose resistance is within ½ per cent of the desired value. Variations of resistance due to changes in load and ambient temperature have been kept considerably less than one per cent. Hence under all

conditions of operation the actual resistance of a unit is within one per cent of the desired value.

The design of reactance units whose inductance and resistance are properly related and sufficiently independent of variation with current, and whose size and cost are at the same time reasonable, was one of the major problems in the development. All of the line- and load-reactor units are approximately identical in size and weight, varying only in the number of turns and size of wire in the coil. The core consists of two stacks of nickel-iron alloy E-punchings so assembled that the magnetic circuit resembles a wide block figure 8 split by a vertical cut forming the air-gaps. The coil is placed around the central air-gap, making the reactor look like a shell type transformer with an air-gap in each of its three legs. Each reactor weighs approximately

FIG. 5—REACTOR UNIT

Load-unit assembly showing reactor tilted in trunion mounting behind control panel bearing tap switches, terminals, and current jack. Reactor is of shell type design with central air-gaps. Glass guard protects operator from high voltage on large-step dial due to auto-transformer action.

25 lb. and occupies a space 6½ by 7 by 8½ in. By mounting the reactors in trunions the mutual reactance between units could be adjusted to a minimum after assembly, and the space requirements considerably reduced. Three dial switches on the unit panel provide for reactance adjustment. (See Fig. 5.) Current jacks are placed in all line and load units except the line resistors, which are always in series with their corresponding reactors if used at all.

It is essential that the ratio of resistance to reactance be small over a large range of reactance. This was accomplished with minimum space and weight by a suitable grading of wire sizes and arrangement of taps. (See Table IV.)

The calibration of reactance units, where more than one set of taps is used to adjust the reactance, is an interesting problem. Since the reactance added by the addition of a given number of turns depends on the number already in use, and the reactance varies only approximately as the square of the number of turns, it is theoretically necessary to calibrate each combination of taps of every reactor. A method was developed, however, whereby only a relatively small number of measurements was required, and a simple calibration chart for each size gives the setting for any reactance, taking into account the small effect due to current if desired. These calibrations are accurate to about ¼ per cent, which justifies the correction for current if accuracy better than one per cent is warranted by the problem under consideration.

The maximum flux density used is approximately 6000 gausses.

c. Synchronous-impedance units. Special reactor units are needed to represent the synchronous impedance of generators because of the large rating of these units, and to secure a lower $R/X$ ratio than is needed for the line units. These units, which are about three times the size of the other reactance units, are rated at 0-500 ohms, 6 amperes or 500 volts (whichever gives the lower rating), and have practically a constant $R/X$ ratio of 3 per cent from 50 to 500 ohms.

d. Capacitors. Considering the fact that 20 miles of present-day 132-kv-a. cable requires a charging current which is approximately equal to its allowable operating current, it will be seen that a device which is to be used in the solution of metropolitan networks must have an amount of capacitance comparable with the full-load generator ratings. There have been incorporated in the Network Analyzer 32 capacitance units of 12 $\mu$ f. each, adjustable in 0.1-$\mu$ f. steps, which at 200 volts can draw approximately 80 per cent of the combined phase-shifter ratings. This capacitance can be used not only for representing the constants of lines and cables but for the representation of synchronous condensers in all normal-operation problems.

The capacitors, which are a wax-paper type of high quality, are rated at 350 volts, 60 cycles, alternating current.

e. Auto-transformers. To represent the effect of ratio-changing transformers used to control the reactive kv-a. distribution in closed loops of transmission circuits, four auto-transformers adjustable from 0 to 10 per cent voltage buck or boost by 0.5 per cent steps are included. Their magnetizing currents, which must be small, range from 1.7 to 4 milliamperes; their impedances vary from zero at unity ratio, to 0.3, 0.7, or 1.5 ohms (depending on rating) at 10 per cent buck or boost.

f. Bus structure. At the rear of each section, 37 No. O B. & S. solid copper bus-bars are placed longitudinally in horizontal rows. These busses have frequent taper-socket outlets along the face of the sections between the rows of unit panels. Units are connected together by plugging their terminals to outlets of the same busses with short leads having tapered brass terminals. The bus structure and the connectors are made of such size copper that the total resistance between two units at widely separated

points is at most a few milliohms, which on the scale used is entirely negligible.

g. Primary power. The primary power is obtained from a sine-wave alternator driven by a d-c. motor, the controls of both machines being available at the Analyzer. This alternator is rated 75 kw., 230 volts, three-phase, 60 cycles, and has a wave form differing from a sine curve by about 1 per cent under the worst conditions.

A three-phase auto-transformer makes voltages of 100, 30, and 10, in addition to the usual 230-volt supply, available for the phase-shifter primaries. By using one of these low-voltage taps, short-circuit studies can be made on a system set up for normal operation without changing the scale or materially altering the set-up, since the reduction of the primary voltage reduces the large network currents due to short-circuit conditions to reasonable ampere values. The power can be thrown on or off the primaries of the phase shifters by means of numerous conveniently located push-button stations.

h. Instruments. The requirement that all measurements be made by portable indicating instruments without disturbance of the network due to their presence, has been adhered to with the result that the measurement of all quantities is a simple and convenient process. There are two groups of instruments: (1) those used at the terminals of the phase shifters which are standard portable instruments, and (2) those used for making measurements in the lines and at the loads when the restrictions on current-coil impedance drops and potential-circuit currents are most severe. The instruments of the second group are portable indicating thermocouple ammeters and voltmeters and portable indicating suspended-armature wattmeters. The use of a separate set of instruments for each phase shifter greatly facilitates the adjustment of the network terminal conditions since the operators can tell at a glance the conditions at all generating stations without having to re-plug instruments and change scales. Table V is a list of the instruments with their principal constants.

TABLE V

INSTRUMENTS FOR NETWORK ANALYZER

Number, Range, and Principal Constants

| Item | No. used |
|---|---|
| 1. Voltmeters (used at phase-shifter terminals) | 6 |
| Ranges 300/600 volts | |
| Current at 200/400 volts 0.0125 ampere | |
| 2. Ammeters (used at phase-shifter terminals) | 6 |
| Ranges 2/6 amperes | |
| Resistance (on both ranges) 0.30 ohm | |
| 3. Wattmeters (used at phase-shifter terminals) | 6 |
| Potential-circuit ranges 200/400 volts | |
| Potential-circuit current at 200/400 volts 0.013 ampere | |
| Current ranges 2/6 amperes | |
| Resistance (on both ranges) 0.45 ohm | |
| 4. Voltmeters, thermocouples* | 2 |
| Ranges 5, 10, 25, 50, 100, 250 volts | |
| Current at full scale 0.002 amperes | |
| 5. Ammeters, thermocouples.* | 4 |
| Ranges 0.1, 0.25, 0.5, 1.0, 2.5, 5.0 amperes | |
| Potential drop at full scale (all ranges) 0.12 volt | |
| 6. Wattmeters, suspended-armature type | 3 |
| Potential-circuit ranges 100/200/400 volts normal | |
| Normal potential-circuit current 0.003 ampere | |
| Current ranges† 1.0/2.0 ampere normal | |
| Impedance drop (normal current) 0.08/0.04 volt | |
| 7. Wattmeters, suspended-armature type | 2 |
| Potential-circuit ranges 200/400 volts normal | |
| Normal potential-circuit current 0.007 ampere | |
| Current ranges 0.2/0.4 amperes normal | |
| Impedance drop (normal current) 0.1/0.05 volt | |
| 8. Wattmeter, suspended-armature type | 1 |
| Potential-circuit ranges 200/400 volts normal | |
| Normal potential-circuit current 0.003 ampere | |
| Current ranges 0.2/0.4 ampere normal | |
| Impedance drop (normal current) 0.4/0.2 volt | |

*The thermocouple voltmeters and ammeters will withstand a 100 per cent overload for short periods without affecting the calibration and have an accuracy of 1 per cent of full scale.

†The current coils of items 6, 7, and 8 have an ample overload current-carrying capacity. The potential circuits have a maximum rating 50 per cent above the normal voltage.

The reactive power, and phase angles of currents and voltages are quantities measured readily by means of a phase-shifting transformer and a wattmeter, preferably of the sensitive suspended-armature type. With the same equipment, the components of the complex expression of a current referred to any axis are read easily.

*Procedure in Solving a Network Problem.* The solution of a power-network problem on the Network Analyzer involves several distinct steps: (1) the determination of the scale on which the system will be represented, (2) the connection and adjustment of units to represent this network to the scale selected, (3) the adjustment of the terminal conditions such as generator outputs, loads, and voltages to such values that they represent the desired operating condition, (4) the measurement of the desired results by means of instruments, and (5) the conversion of these results from the Analyzer base to the actual system base. These various steps will be considered in order.

In selecting a base for setting up a system, 200 volts is chosen as nominal voltage for all but short-circuit studies. Such a base of current, and thereby of power, is selected that the actual system per cent constants, when applied to this base, result in current magnitudes which lie within the convenient working range.

After scale selection, working connection diagrams are prepared on which are noted the numbers and settings of the units selected to represent the different system parts—such as generators, lines, and loads—and from these the connections and unit settings are made. If a problem involves the study of several different connections of a system this process is repeated for each connection.

Usually for each connection, a number of different operating conditions is to be studied. These operating conditions are represented one at a time by setting the quantities at generators, loads, and other points in the system to prescribed values. With the settings made, the distribution of current, voltage, and power throughout the Analyzer circuits, is a miniature replica of that existing on the power network for the given operating condition.

After adjusting the terminal conditions to the

prescribed values, the quantities desired can be read directly. The final step consists in expressing these quantities as fractions of the Analyzer base. These same fractions apply directly to the actual system.

Several methods of rapidly checking the final results are used whereby possible errors in connecting or setting the units, making readings, or converting results become apparent. These checks, and the accuracy of the Analyzer which their application shows, appear in the discussion of the example.

## Fields of Application of the Network Analyzer

The chief function of the Network Analyzer is to serve as an experimental substitute for the lengthy and generally impractical calculations of normal-frequency current, voltage, power and phase relations in electric power networks for which the resistance, inductance, and capacitance constants of lines, generators, transformers, and loads are known. Before considering its fields of application it is well to point out that it will *not* serve for the determination of circuit constants of lines, generators, transformers, or of other system apparatus, but rather requires for its use a knowledge of these electrical circuit constants. Moreover since it has lumped line units, and phase shifters to represent synchronous machines, it is not applicable to the study of high-frequency transient phenomena, corona problems, arcing grounds, lightning induction, synchronous machine characteristics, harmonics due to transformers or generators, etc.

The various applications of miniature a-c. systems have been discussed in previous publications[7] and will be only briefly reviewed here. They may be classified as follows:

1. Determination of voltage, current, and power data for normal operating conditions in a network of interconnected lines, stations, and load centers. Such data are necessary for the most economical layout of systems, and for the determination of operating procedure.

2. Solution of problems concerned with the stability and power limits of systems for loads slowly or suddenly added, during short circuits, etc.

3. Determination of currents during short circuits for relay settings, rating of current-limiting reactors, duty of oil circuit breakers, electromechanical stresses, etc.

*Studies of Normal System Operation.* One of the important problems requiring solution by means of a miniature system is the determination of load division among the various branches and stations of a power network. This is frequently desirable for the best design of new systems as well as for the study of additions or changes and the best operation of existing systems. While a study of this nature may require only a knowledge of the current at various points in the network, in general it requires also a knowledge of voltage, and real and reactive power.

Two problems closely related to the foregoing are (1) voltage regulation in power networks and (2) power factor correction. Power factor correction requires a study of the effect of certain classes of terminal apparatus, such as synchronous condensers, when added at different points of a system.

*Studies of System Stability.* The growth of power systems, the advent of wide-spread interconnection, and the consequent increase in length of transmission lines in order that the interconnected systems may be supplied from large hydroelectric developments have resulted in bringing the problem of system stability to the fore. Designers and operators are interested in system power limits for slowly-applied loads and during short circuits or other disturbances.

Problems of static stability can be studied with the Network Analyzer even beyond the stable point of the power system because synchronous machines are represented by stationary phase shifters. Although it will not serve to reproduce actually the transient swings of generating and receiving machinery, problems of this class can be studied by the point-by-point method[8] with its aid. In this method the rotor-position changes, together with field-current and prime-mover torque changes, are computed for successive arbitrary short intervals of time, the progress of the transient thus being developed by small steps. Since a change in field current and the angular position of the rotor changes the armature current and power in every machine, it is necessary to determine the values of these armature currents and powers as they exist at the beginning of each interval. These are fixed by the rotor positions and field currents found to exist at the end of the previous interval. In other words a normal steady-state electrical solution of the network with the known terminal conditions must be made for the end of each interval, and the result used to compute the changes which will occur in the following interval. The calculation of these numerous steady-state conditions is the most laborious part of the point-by-point method and is the type of calculation for which the Analyzer was developed.

As mentioned above, the Analyzer is not applicable to the determination of synchronous machine characteristics, reactance values, saturation effects, etc. These data must be separately obtained.

*Short-Circuit Studies.* Experimental solutions of short-circuit problems have been extensively discussed in earlier publications.[9] The principal points bearing on the application of the Network Analyzer are the following:

Since the short-circuit calculating table ordinarily serves adequately for the more common short-circuit studies of systems, the Analyzer will not supplant this simple and effective d-c. device. The errors[8] of the latter are commonly below 10 per cent and rarely in excess of 20 per cent. The errors of the Network Analyzer will, in general, be less than 3 per cent.

The solution of unbalanced short circuits on the Analyzer may be accomplished either by successive single-phase setups with the aid of symmetrical-coordinate analysis, or in an approximate manner by a three-phase setup with a three-phase power supply with or without the use of the phase shifters.

*Educational Uses.* Perhaps the application of the Analyzer most far reaching in its effect is its educational use not only in the solution of sample problems by classes but as a computation tool which opens fields of research to graduate students otherwise closed by excessive labor requirements. Furthermore, the presence of a device regularly used in the solution of actual engineering problems has a very real educational value. These uses make the Analyzer a valuable asset for an electrical engineering laboratory.

## Example

It is the purpose of this example to illustrate the way in which the Network Analyzer can be used in the solution of a typical problem which may arise in the growth of a power network. The example does not illustrate the limit in complexity of circuits, or range of conditions

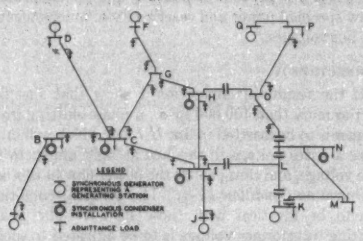


Fig. 6—System Used in Example

One-line diagram of sample network in which effect of ratio-changing transformer and phase-shifting equipment on required synchronous condenser capacity and power flow were examined. For constants see Table VI

which can be studied on the Analyzer, but is given to be suggestive of the possibilities of the device. The one-line diagram of the system which is used for this example, is shown in Fig. 6. It includes three loops and a number of radial lines connecting the generating centers $A$, $D$, $F$, and $J$ with the load center at $K$ and vicinity, and with another system to which power is supplied at $Q$. Both $K$ and $Q$ represent large load and steam-generating centers to which the network furnishes the power used in excess of that generated at these points. At busses $B$, $C$, $H$, $I$, and $N$ synchronous condensers serve to maintain voltage.

The problem is to determine the reductions in synchronous condenser installations which can be effected by using a ratio-changing transformer in the main loop $C\,G\,H\,I$; also to determine what phase-shifting equipment, if any, is needed to properly distribute the power flow between the various parallel paths.

Specifically, four cases are to be examined. (1) With the network as shown in Fig. 6 and all of the stations delivering specified loads, the size of the condensers at $C$, $H$, and $I$ required to maintain normal voltage is to be determined in relation to the setting of a ratio-changing transformer in line $C\,I$. (2) With station $D$, which is of large capacity, disconnected from the network at $C$, the size of the synchronous condensers at $C$ and $I$ is to be determined in relation to the transformer ratio in $C\,I$. This case fixes the size of these condenser installations before station $D$ comes into service; thereafter they presumably will have to be considerably increased. (3) With line $C\,I$ removed by opening the circuit breakers at both ends, voltage at the major busses and power in the principal lines are to be determined when the condenser outputs are limited to the values found most suitable in the first case. (4) If any of the lines in the major loop $C\,G\,H\,I$ are overloaded under any of the above conditions, the beneficial effect of phase-shifting equipment, located preferably at $I$, is to be considered.

The problem having been thus briefly described, the next step is to state the constants and the operating conditions which are to be represented to obtain the desired information To accomplish this in an orderly way, the problem is resolved into the study of one or more operating conditions on each of several connections. Here a *connection* is considered as one configuration of the network, and an *operating condition* as one set of terminal conditions applied to this configuration with the resulting current, voltage, and power distribution. The data describing a connection are given first, then follow the terminal conditions which apply to each operating condition included under this connection. This is repeated for each different connection studied.

The numerical statement of the data for the various connections in the problem will be given.

CONNECTION I (corresponds to the first case mentioned above)

In Fig. 6 is shown the diagram of connections. The constants are tabulated in Table VI. The ratio-changing transformer in $C\,I$ at $C$ has 0 to 10 per cent voltage buck or boost.

*Operating Condition I-1.* The necessary terminal conditions to establish operating condition I-1 include the generating-station power outputs (Table VII), the power and reactive kv-a. taken by loads (Table VIII), and the voltage maintained at points where it is under control. These points must in general be busses to which are connected synchronous machines. Busses $A$, $D$, $F$, $J$, $K$, and $Q$ are maintained at 100 per cent voltage by the synchronous generators, and busses $B$, $C$, $H$, $I$, and $N$ at 100 per cent by synchronous condensers. The ratio-changing transformer at $C$ is set at the one-to-one ratio, *i. e.*, it has no effect on the reactive kv-a. distribution.

*Operating Condition I-2.* The terminal conditions

are identical with those for operating condition I-1, but the ratio-changing transformer is set at 5 per cent step-up of voltage from bus $C$ to the line $C\ I$.

It may be mentioned that any other terminal conditions could be set with equal ease, but merely to make the statement of the example as simple as possible, essentially the same terminal conditions are used throughout.

TABLE VI
CONSTANTS

Constants of the equivalent —π circuits* representing the lines, transformers, etc., connected between adjacent busses. All quantities are expressed as a per unit on a 100,000-kv-a. base.

| Circuit element | Architrave impedance* | Pillar admittance* (at each end) |
|---|---|---|
| $A\ B$ | $0.0113 + j\,0.132$ | $+j\,103 \times 10^{-3}$ |
| $B\ C$ | $0.0082 + j\,0.079$ | 62 |
| $D\ C$ | $0.0176 + j\,0.208$ | 162 |
| $C\ I$ | $0.0098 + j\,0.0915$ | 71 |
| $C\ G$ | $0.0054 + j\,0.0620$ | 46 |
| $F\ G$ | $0.0041 + j\,0.0470$ | 35 |
| $G\ H$ | $0.0071 + j\,0.084$ | 65 |
| $H\ I$ | $0.0141 + j\,0.134$ | 103 |
| $J\ I$ | $0.0091 + j\,0.174$ | 140 |
| $I\ L$ | $0.0058 + j\,0.0640$ | 0 |
| $L\ K$ | $0.0010 + j\,0.0190$ | 0 |
| $K\ M$ | $0.038 + j\,0.581$ | 0 |
| $M\ N$ | $0.106 + j\,0.487$ | 0 |
| $L\ N$ | $0.056 + j\,0.513$ | 0 |
| $N\ O$ | $0.0195 + j\,0.376$ | 18 |
| $H\ O$ | $0.0108 + j\,0.160$ | 0 |
| $O\ P$ | $0.0109 + j\,0.121$ | 5.6 |
| $P\ Q$ | $0.024 + j\,0.037$ | 0 |

*For explanation of terms see L. F. Woodruff, "Electric Power Transmission and Distribution," John Wiley and Sons, Inc., 1925, pp. 139 and 155.

TABLE VII
GENERATING-STATION OUTPUTS

Power expressed as a fraction of base kv-a.

| Station..... | $A$ | $D$ | $F$ | $J$ | $K$*† | $Q$* |
|---|---|---|---|---|---|---|
| Output..... | 1.95 | 2.30 | 0.52 | 2.42 | −2.2<br>−2.6 | −0.62 |

*Bus $K$ represents a large load center with extensive steam generating equipment, which is, however, insufficient to carry the entire load at $K$. The combination of generators and loads at this point is represented by an admittance load and a synchronous machine which absorbs the difference between the locally generated power and that consumed exclusive of the admittance load. The machine at $Q$ represents a similar combination.

†The synchronous machine at $K$ takes the difference between the power generated in the network and that consumed by losses and the other loads. It should lie within the limits given.

TABLE VIII
LOADS

Power and reactive kv-a. (lagging) taken by loads, expressed as a fraction of base kv-a.

| Point | Power | Reactive kv-a. | Point | Power | Reactive kv-a. |
|---|---|---|---|---|---|
| $B$ | 0.36 | 0.320 | $K$ | 0.82 | 0.82 |
| $C$ | 0.58 | 0.192 | $M$ | 0.45 | 0.238 |
| $D$ | 0.29 | 0.204 | $N$ | 0.38 | 0.345 |
| $I$ | 0.68 | 0.60 | $P$ | 0.32 | 0.206 |

CONNECTION II

The diagram of connections and the constants are the same as for connection I except that station $D$ and line $D\ C$ are not connected to the system.

*Operating Condition II-1.* The power consumed by the synchronous machine at bus $K$ is reduced by approximately the amount of power which was fed into the network by line $D\ C$ in connection I, otherwise the terminal conditions are unchanged. The transformer at $C$ is set at unity ratio.

*Operating Condition II-2.* Same as II-1 except that the transformer at $C$ is set to step up the voltage 5 per cent between bus $C$ and line $C\ I$.

*Operating Condition II-3.* Same as II-2 except that the transformer ratio is set for 10 per cent step-up of voltage instead of 5 per cent.

CONNECTION III

Line $C\ I$ is disconnected from the network at both ends, otherwise the network is identical with connection I.

*Operating Condition III-1.* The terminal conditions are the same as in I-1 except that the outputs of the synchronous condensers at $C$ and $I$ are limited to the values fixed by the results secured in connection I. This limits the control of the voltage at busses $C$ and $I$ to those values which are attainable with the restricted condenser outputs. The voltages at these points are to be as near 100 per cent as possible, and the loads are to draw specified power and reactive kv-a. independent of the bus voltages.

CONNECTION IV

If the results of connection I show that line $G\ H$ carries more than 100,000 kv-a., a phase-shifting transformer is to be inserted in line $H\ I$ at $I$ which will introduce a series voltage in this line at right angles to the line voltage, and thus change the power flow in this line.

*Operating Condition IV-1.* The terminal conditions are to be identical with those in I-1. The phase-shifting transformer voltage is to be adjusted to such a value that the load on line $G\ H$ is reduced to 100,000 kv-a.

This completes the numerical statement of the problem and the first step in its solution is the selection of a suitable Analyzer scale. This is usually done by inspection, noting the range of currents and impedances and then choosing a round-figure Analyzer base which will give convenient magnitudes. Since normal Analyzer voltage is 200 volts, it is necessary to consider only scales for current and impedance. An inspection of Tables VI, VII, and VIII shows that a current base of one ampere (and the corresponding 200-ohm impedance base) results in suitable impedance ranges, and magnitudes of current and power within the range of accurate measurement.

It may be noted here that with the constants of the lines given for one phase line-to-ground, power read on the Analyzer is phase power if the Analyzer voltage is considered as line-to-ground voltage, and total power if it is considered as line-to-line voltage. The latter method is slightly more convenient for the interpretation of results.

The second step in the solution is the connection and adjustment of the units to represent connection I. As the third step, the terminal conditions are adjusted to represent operating condition I-1, after which, as the fourth step, the results desired are read from the various instruments. The last step consists of converting the current, voltage, and power readings to fractions or per units of the Analyzer base, these fractions also applying directly to the system base.

These various steps have been carried out for the problem stated above, and the results obtained are tabulated in Tables IX and X, being arranged in the same order as the statement. A rather complete set of results is given for operating condition I-1, while for the others only those results are given which are of immediate use.

*Discussion of Results.* A brief résumé of the results will be given, interpreting them in terms of the questions included in the statement of the problem. Considering connection I, it is seen that operating condition I-2 requires approximately equal synchronous condenser installations at $C$ and $I$, this division of condensers being accepted as most suitable.

The synchronous condenser requirements at $C$ and $I$ for connection II can be plotted as a function of the transformer ratio from the tabulations and the best distribution fixed upon for this stage of the system development. Conditions in the other lines were changed inappreciably by altering the transformer ratio.

Removing line $C\,I$ in connection III had no serious effects other than reducing the voltage at several busses. Increased synchronous condenser installations at $C$ and $I$ would have made possible the maintenance of normal voltage at $C$, $H$, and $I$.

As anticipated, line $G\,H$ is overloaded in connection I (*i. e.*, carries in excess of 100,000 kv-a.), and in connection IV the magnitude of quadrature voltage necessary to remove the overload was found to be 0.17, as shown in Table X.

Since the example is merely illustrative no further analysis of the specific results will be given. Of more interest are the time requirements and accuracy. Table XI gives the approximate time spent on the various operations of solving this problem starting from

TABLE IX

RESULTS FOR OPERATING CONDITION $I-1$

All quantities are expressed as fractions of base quantities

a. Generating-Station Outputs (Power + $j$ leading kv-a. as a fraction)

| Station | Output | Station | Output |
|---|---|---|---|
| $A$ | $1.95 + j\,0.07$ | $J$ | $2.42 - j\,0.22$ |
| $D$ | $2.30 - j\,0.32$ | $K$ | $-2.22 - j\,1.74$ |
| $F$ | $0.52 + j\,0.09$ | $Q$ | $-0.62 - j\,0.47$ |

b. Voltages at Unregulated Busses

| $G$ | $M$ | $O$ | $P$ |
|---|---|---|---|
| 1.00 | 0.893 | 0.990 | 1.000 |

c. Power, Reactive Kv-a., and Current in Branches

Power and reactive kv-a. are at point designated by the first letter, flowing in the direction from first to second letter. Leading kv-a. is positive. Architrave currents are given.

| Branch | Power | Reactive kv-a. | Current | Branch | Power | Reactive kv-a. | Current |
|---|---|---|---|---|---|---|---|
| $A\,B$ | 1.95 | $+j0.07$ | 1.95 | $J\,I$ | 2.42 | $-j0.22$ | 2.43 |
| $B\,C$ | 1.48 | $+j0.09$ | 1.48 | $I\,L$ | 3.57 | $-j0.28$ | 3.60 |
| $D\,C$ | 1.99 | $-j0.12$ | 1.99 | $L\,K$ | 3.26 | $+j0.60$ | 3.31 |
| $C\,I$ | 1.92 | $+j0.14$ | 1.92 | $K\,M$ | 0.25 | $-j0.18$ | 0.31 |
| $C\,G$ | 0.88 | $+j0.13$ | 0.89 | $L\,N$ | 0.23 | $+j0.03$ | 0.23 |
| $F\,G$ | 0.52 | $+j0.09$ | 0.53 | $O\,N$ | 0.37 | $+j0.01$ | 0.37 |
| $G\,H$ | 1.40 | $+j0.13$ | 1.41 | $O\,P$ | 0.96 | $+j0.13$ | 0.93 |
| $H\,I$ | 0.03 | $+j0.10$ | 0.10 | $P\,Q$ | 0.63 | $+j0.45$ | 0.78 |

d. Synchronous-Condenser Outputs (lagging kv-a.)

| $B$ | $C$ | $H$ | $I$ | $N$ |
|---|---|---|---|---|
| 0.53 | 0.53 | 0.23 | 1.66 | 0.62 |

e. Angles of Bus Voltages

| | | | |
|---|---|---|---|
| $A$ | 49.5° | $J$ | 42.4° |
| $B$ | 34.5 | $K$* | 0.0 |
| $C$ | 27.6 | $L$ | 3.7 |
| $D$ | 52.5 | $M$ | −9.0 |
| $F$ | 25.8 | $N$ | 0.2 |
| $G$ | 24.3 | $O$ | 4.8 |
| $H$ | 17.5 | $P$ | −2.0 |
| $I$ | 17.1 | $Q$ | −4.2 |

*Used as reference for angles.

TABLE X

RESULTS FOR OPERATING CONDITIONS I-2, II-1, II-2, II-3, III-1, AND IV-1

Power and reactive kv-a. are at first point in the direction from first to second point. Leading kv-a. is positive. Architrave currents are given. All values are fractions of base quantities. The quantities in the rectangles are arranged as follows: upper left, power; upper right, reactive kv-a.; lower, current.

| Operating condition | Condenser outputs | | | | | Lines | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $B$ | $C$ | $H$ | $I$ | $N$ | $C\,G$ | $C\,I$ | $G\,H$ | $H\,I$ | $I\,L$ |
| I-2 | 0.53 | 1.06 | 0.23 | 1.09 | 0.64 | 0.89 $+j0.12$<br>0.90 | 1.90 $-j0.40$<br>1.94 | 1.41 $+j0.12$<br>1.42 | 0.041 $+j0.08$<br>0.09 | 3.56 $-j0.26$<br>3.58 |
| II-1 | 0.49 | 0.23 | 0.08 | 1.03 | 0.64 | 0.325 $+j0.066$<br>0.33 | 0.53 $+j0.09$<br>0.54 | 0.85 $+j0.095$<br>0.85 | −0.311 $+j0.053$<br>0.316 | 1.86 $-j0.05$<br>1.86 |
| II-2 | 0.49 | 0.64 | 0.08 | 0.60 | 0.64 | " | " | " | " | " |
| II-3 | 0.49 | 1.06 | 0.08 | 0.15 | 0.64 | " | " | " | " | " |
| III-1* | 0.53 | 1.09 | 0.25 | 1.10 | 0.65 | 2.80 $-j0.36$<br>2.85 | 0 $+j0$<br>0 | 3.29 $-j0.54$<br>3.43 | 1.52 $+j0.19$<br>1.65 | 3.15 $+j0.28$<br>3.34 |
| IV-1† | 0.53 | 1.09 | 0.15 | 1.09 | 0.64 | 0.49 $+j0.12$<br>0.51 | 2.31 $-j0.48$<br>2.36 | 1.00 $+j0.10$<br>1.00 | −0.46 $+j0.09$<br>0.47 | 3.47 $-j0.22$<br>3.48 |

*Voltages at:

| $C$ | $H$ | $I$ | $P$ | $N$ | $M$ |
|---|---|---|---|---|---|
| 0.99 | 0.931 | 0.950 | 0.990 | 0.968 | 0.871 |

†Phase-shifting transformer voltage is 0.17 advancing terminal voltage of line $I\,H$ at $I$ with respect to bus I.

the data as given. It should be noted that in the time stated a problem on an unfamiliar network has been solved and the results checked as outlined below to eliminate errors.

Although a direct determination of the over-all accuracy by comparison with precise computed solutions is impracticable, the possible errors introduced in various steps of the procedure can be approximately evaluated. The methods used to detect mistakes and inaccuracies and to determine the limits of normal error will be briefly considered, together with the range of these errors.

Several checks on the final results are conveniently made, among which are the summing of power and reactive kv-a. at busses, a comparison of the impedance of a branch with the quotient of the voltage drop by the current, and the closure of the line-drop vector diagrams for loops. The application of these checks to this example and to other problems show that the measured power and reactive kv-a. inflow and outflow at a bus differ by not more than two per cent and usually by less than one per cent. The impedance of network branches as measured by voltmeter and ammeter is usually within one per cent of the given value even though no correction for current is made when setting the reactors. Loop line-drop vector diagrams ordinarily close within one per cent of the line voltage.

Whereas the foregoing checks make apparent any appreciable errors in measurements or settings of units, they do not demonstrate the accuracy of the solution with respect to a perfect solution. That is, it is possible for small errors which may compensate in these checks, and errors due to small deviations of the terminal settings from stated values to appear combined in particular individual results. Thus it is difficult to determine what the maximum departure of a given experimentally measured quantity is from its true value because of the labor involved in computing a check to the necessary precision. However, the following statements can be made: Line voltages are relatively precise, and are ordinarily well within one per cent. Power and reactive kv-a., on the other hand, may differ from the true values by as much as 5 per cent when the quantities themselves are small. Currents are probably correct to 2 per cent or less. These statements apply to results as ordinarily taken. With additional precautions, which have been used in some problems, better accuracy by a factor of two or three can be obtained at the expense of considerable time, but the data seldom justify this expenditure.

TABLE XI
TIME REQUIRED FOR SOLUTION OF THE ACCOMPANYING EXAMPLE

| | |
|---|---|
| 1. Preparatory Work | |
| Selection of scale, conversion of constants to Analyzer scale, preparation of plugging diagrams with unit settings, preparation of data sheets | |
| Total (one man) | 15 hr. |
| 2. Use of Analyzer | |
| Plugging connections, setting units, and checking both | 2 |
| Setting first operating condition | 2 |
| Taking data first operating condition | 4 |
| Setting remaining operating conditions | 5 |
| Taking remaining results | 4¼ |
| Total (2 men and Analyzer) | 17¼ hr. |
| 3. Conversion of results to nominal base and checking results | |
| Total (one man) | 10¼ hr. |

## Summary and Conclusions

1. An improved a-c. network computing device, called the Network Analyzer, is described in this paper, its purpose being to determine by direct measurements in the laboratory the voltage, current, power, reactive power, and phase angle at any point of a network. Its scope of representation in its present form is 8 generating stations, 60 lines and cables with their capacitance, 40 loads, 4 ratio-changing transformers, and the usual number of synchronous condensers.

2. The Analyzer uses phase-shifting transformers rather than rotating machines to represent synchronous machines and generating stations. Its operation is thus greatly simplified and speeded up in comparison with previous miniature systems.

3. A voltage scale of 200 volts at 60 cycles is used, the nominal current scale being 0.5 ampere.

4. Portable indicating instruments are used throughout, including thermocouple voltmeters and ammeters and suspended-armature wattmeters, by means of which current, voltage, and power are read directly at any point of the system without materially disturbing current distribution and voltage drops in the network and without necessitating corrections or adjustments for the presence of the instruments. The accuracy of the instruments is one per cent of full scale.

5. The accuracy with which a given set of circuit constants can be reproduced is approximately one per cent. The accuracy with which the instrument readings represent the quantities which are uniquely determined by a given set of circuit constants and terminal conditions is one per cent or better in the case of voltages, approximately 2 per cent in the case of currents, and 3 per cent—with a maximum of 5 per cent for small magnitudes—in the case of power and reactive kv-a. This accuracy has been attained by providing (a) steps as low as one per cent or smaller for the adjustment of the impedance units and in the settings of the phase-shifting transformers, (b) a value of effective resistance in the reactors of the order of 4 per cent of the reactance, (c) a design of magnetic circuit in the reactors such as to give not over one per cent change of inductance due to change of current throughout the entire operating range.

6. The Network Analyzer is intended to be used:

(a) For purposes of teaching and research by students and research staff of the Massachusetts Institute of Technology, and

(b) For commercial engineering service in the solution of network problems for engineers in operating and designing work.

In its design major consideration was given to the requirements for the use by students. As a tool for engineers, it is adapted to the solution of system problems arising in normal operation, growth, and interconnection; to the point-by-point computation of stability problems including the effects of symmetrical or unsymmetrical short circuits and sudden circuit changes; to the determination of steady-state load limits and to short-circuit studies in the relatively few cases where the d-c. calculating table will not yield adequate results.

7. The ability of the Analyzer to accomplish the purpose for which it was designed has been demonstrated by the solution of actual network problems which it has been called upon to solve. Results are obtained not only with relative ease, but with a dispatch that appeals to one who has experienced the tediousness, the delay, and in some cases the hopelessness of arithmetical solutions.

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## Discussion

**R. C. Bergvall:** I was very much interested in hearing the paper on the *M. I. T. Network Analyzer* because an a-c. calculating board was recently put into service at our East Pittsburgh works. It has been used on typical problems covering load distribution, voltage regulation, phase angle control, and stability with an over-all accuracy of from 1 to 3 per cent which checks very closely with the degree of accuracy mentioned by Mr. Hazen.

Our board differs from the M. I. T. network analyzer in that a central metering table is used and the frequency is 480 cycles. This frequency was chosen because it is the highest that could be used with dynamometer type meters and the high frequency permitted smaller reactors and condensers to be used. The board had 10 generating sources and about 240 circuits equipped with suitable units of resistance, reactance, and capacity. The voltage and phase angle control for each source is obtained from two phase shifters in series. I will not take up more time describing the board because this was covered by an article in the May 1930 issue of the *Electric Journal* by Mr. H. A. Travers and Mr. W. W. Parker.

The board was used in solving a complicated stability problem with a considerable saving in time. The generating sources, transmission and distribution network, load impedances, etc., were set up with the proper phase relations between the generating sources to obtain load and wattless current distribution corresponding to normal operation. A short circuit was then applied and the power outputs from each of the generating sources measured. The difference between the normal output and the output under short circuit conditions represents the energy available for accelerating or retarding the rotor. The angular position of each rotor after a short period of time can be calculated assuming that the output remains constant. The phase shifters are then set to the new angular position and new power output measurements obtained so that oscillations of the entire system of five or six elements can be plotted. The board gives the voltage at various points on the system and makes it possible to change the impedance of the induction motor loads to correspond with the slowing down of the motors as a function of low voltage and time. The increasing complexity of power systems will undoubtedly extend the usefulness of a-c. calculating boards in the future.

**I. H. Summers:** One of the fields of application of the network analyzer is that of large power system stability analysis. It is particularly valuable in transient stability analysis on a large power system where the behavior of the number of stations is to be investigated. The reasons for this may be brought out by a comparison of the methods which might be used for the analytical calculation and those which might be used on the analyzer. Analytical methods are given in *The Calculation of Alternator Swing Curves*, by F. R. Longley (see p. 1129). Equations **8** to **28** of this paper and the procedure outlined in items 1 to 8 at the end of the main body of the paper give the essence of this method.

While this method may be considerably simplified in many cases as has been brought out before in the literature, there seem to be some cases when the full analysis as given by Longley, or some equivalent, is considered necessary. An inspection of Equations **28** shows that each step of the calculation as given, requires the solution of a determinant of the order of the number of machines being included in the calculation or an equivalent amount of work, in order to find new voltages "behind quadrature reactance" in the machines after an angular swing has taken place. While this process is perfectly possible and has been to my knowledge carried out in many cases in regular work on system stability analysis, it does require the expenditure of considerable time and labor if many machines are being included in the calculation.

It would seem that this step of the procedure could be considerably shortened by the use of the network analyzer. In addition, the analyzer should shorten the work of finding the torques acting on the rotors of machines. It should also facilitate the calculation of driving point and transfer impedances in the system connections between machines.

**F. O. Urban:** This paper states that one of the fields of application of the network analyzer is that of system stability analysis. The analyzer affords a very attractive means for making the steady-state solutions of the network necessary at each point in a step-by-step transient study, and I have been working on this application as a Master's thesis problem at the Massachusetts Institute of Technology. Both graphical and analytical methods for a point-by-point study of machine swings have been well outlined in the literature. The method where the

network analyzer is used as an adjunct is but slightly modified, although many tedious calculations are eliminated.

Briefly, the method is as follows. The network is set up on the analyzer. Certain terminal conditions of synchronous machine power and reactive kv-a. output, and system voltages are given. A steady-state solution is made and the power, excitation, and phase angle of each machine are determined. The disturbance to be studied is then reproduced on the analyzer. That is, if a generator is suddenly dropped off, the corresponding phase shifter is disconnected; if a short circuit is to be studied, the proper line-to-neutral impedance is connected at the point of fault to correctly reproduce the positive phase-sequence conditions in the network with fault on and so on for whatever disturbance is to be studied. The angle of each phase shifter is left unchanged and the magnitude of its voltage is adjusted to correspond to holding machine flux linkages constant. The electrical power of each machine is then determined by means of wattmeters connected to the phase-shifter terminals. This is the power the first instant after the disturbance, and the difference between it and the power obtaining in the steady-state solution is the differential power to accelerate or retard the rotor of the corresponding machine. Knowing the inertia of the machine rotor, the change in time-phase of the excitation voltage vector for some small time interval is calculated on the assumption that the differential power (difference between shaft and electrical power) is constant over the interval. The amount by which the field linkages change during the first interval due to decay of induced field current, exciter, and voltage regulator action is also calculated. Knowing the new linkages and phase angles of each machine at the beginning of the second interval, the corresponding phase-shifters are properly adjusted in magnitude and angle. The electrical power on each machine following these changes is determined directly by the wattmeters and the differential power effective over the second interval of time obtained as for the first interval. The process is continued for as long a time as desired. The effects of governor characteristics, if known as functions of some quantity such as speed or slip, can easily be brought into the problem at the proper point in the same manner as in a strictly analytical solution. Damping is handled similarly. Static loads, if their characteristics are known as functions of positive-sequence voltage, can also be properly handled.

In order to represent synchronous machine characteristics by means of the phase shifters the Blondel two-reaction theory as extended by Doherty and Nickle and by Park and Robertson was adopted. Saturation effects are neglected. On the basis of the theory developed by these writers, the vector diagram of a synchronous machine having no excitation in the quadrature axis and having equal transient and synchronous reactances in the quadrature axis is shown. More complicated cases can also be handled, but this one was chosen for purposes of illustration (Fig. 1).

The excitation voltage, corresponding to the field current, is $e_d$; $x_d$ and $x_q$ are direct and quadrature synchronous reactances respectively; $x_d'$ is transient reactance in the direct axis; and $e_d'$ is a fictitious voltage which corresponds to the total field linkages.

By inspection of the diagram it was decided that $O\,Q$ (following the notation of Park and Bancker) could most advantageously be represented by the phase-shifter. If the phase-shifter is connected to the network through a reactance $x_q$, $O\,Q$ will be correctly represented by the terminal voltage of the phase shifter. The magnitude of $O\,Q$ for the steady state is determined by a solution on the analyzer with the given terminal conditions. The excitation is then $O\,Q + i_d\,(x_d - x_q)$. The current $i_d$ can be easily measured, if a spare phase shifter is available, by connecting the current coil of a wattmeter to the terminal of the phase-shifter representing $O\,Q$ and by exciting its potential coil with a unit voltage at right angles to $O\,Q$. The voltage $e_d'$ is $O\,Q - i_d\,(x_q - x_d')$, and this, representing total field linkages, remains constant for the first instant after the disturbance. Following the adjustment of the analyzer for the steady-state conditions, the $e_d'$ for each machine is calculated. The disturbance is then produced in the network and the $O\,Q$'s held constant in phase and adjusted in magnitude until the condition $O\,Q = e_d' + i_d\,(x_q - x_d')$ is satisfied for each machine. This can be arrived at by a series of successive approximations performed on the analyzer. The electrical power of each machine for the first instant is then determined by means of a wattmeter. This makes possible the determination of differential torque and hence the angular swing of each machine during the first time interval. The value of $e_d'$ at the beginning of the second interval is the value at the beginning of the first interval plus the change due to field transients and exciter and regulator action, and must be determined analytically. The vector $O\,Q$, representing rotor angle, is shifted in phase in accord with the calculated swing and adjusted in magnitude so that the condition $O\,Q =$ ($e_d'$ at beginning of second interval) $+ i_d\,(x_q - x_d')$ is satisfied for each machine. The process is repeated for the successive time intervals.

At present it is not possible for me to make any comparison between the amount of time required by the analyzer in a problem of this nature and that required for a purely analytical solution where the same factors are taken into consideration. Information in this regard will, however, soon be available.

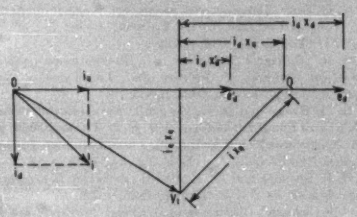


Fig. 1

**C. F. Scott:** The thing which has impressed me most with regard to the elaborate network analyzer has not been brought out in the general discussion although it may be inferred from the photographic illustration. That feature is the large size. A space equivalent to a good sized room is surrounded by devices that look like filing boxes of some sort. It is really a very big thing and the thing itself is much more impressive than the description.

I had opportunity a few weeks ago to see a circuit device of a comparatively very simple sort made by Mr. H. S. Baker of the Ontario Power Company at Niagara Falls. The units of the network here are not adjustable but correspond to the actual constants of the various elements of the circuit. Hence, when a new line is to be added to the system it can be added to the model and determinations made as to the characteristics of the proposed system. This device was said to be particularly useful in determining the effects which would be produced by short circuits at particular points.

**O. R. Schurig:** The discussions have clearly indicated the value of the network analyzer for solving in a relatively short time and with good accuracy a variety of network problems, some of which would require an enormous amount of work if solved by mathematics. Thus transmission engineers can now analyze their systems in regard to stability, load distribution, and regulation problems as they have never done before and will thereby accomplish improved service and better economy in the use of equipment.

# Calculation of Protection of a Transmission Line by Ground Conductors

BY HERBERT BRISTOL DWIGHT[1]

Fellow, A. I. E. E.

*Synopsis.—This paper discusses the well-known calculation of the degree of protection afforded to a transmission line by ground conductors, on the assumption of the sudden disappearance of a vertical potential gradient caused by a charged cloud. Formulas are given for the protective ratio due to one and two ground conductors. It is shown that for any number of ground conductors, it is not necessary to compute the charges on the power conductors.*

* * * * *

IN calculating the degree of protection afforded to a transmission line by its ground conductors, a calculation which is frequently used by electrical engineers is that based on the assumed sudden disappearance of a large potential gradient from the earth upward. Such a calculation was described by R. P. Jackson[2] in 1907, and by E. E. F. Creighton[3] in 1916.

In this paper are given some formulas for particular cases, and some methods for shortening the work of calculation.

The calculation of protective factor is based on the assumption that a vertical potential gradient is induced by a charged cloud, and that this causes charges to collect on all the conductors; then the gradient is suddenly removed when the cloud discharges. The charges on the ground conductors go to earth very quickly to a sufficient degree to bring the potential of the ground conductors to zero. The charges on the insulated conductors remain long enough to raise the potential of those conductors, and if the potential is high enough, to cause a flashover of an insulator. The protective factor is the ratio of the potential of the power conductor when protected by ground conductors, to its potential if it were not so protected.

In the calculation described by Mr. Creighton, the values of the charges on all the conductors in the system were found. It will be shown that by finding charges on the ground conductors when the power conductors are considered absent it is possible to calculate the protective factor according to the standard theory. This reduces the number of simultaneous equations to be solved and shortens the work considerably.

Let there be ground conductors $G_1 G_2 \ldots\ldots$ and insulated power conductors $A. B. C \ldots\ldots$ all parallel to each other.

If there is a voltage gradient, each conductor takes up a charge so that when a unit charge is carried from the image of a given conductor to that conductor, the work done by all the charges is equal to the voltage gradient multiplied by twice the height of the given conductor. The power voltage is neglected. If the gradient is suddenly removed and none of the charges is changed, the voltage on each conductor is equal to the gradient times its height.

Now the ground conductors are presumed to have their charges reduced or changed very quickly, so that each ground conductor has zero potential, before any appreciable change takes place in the charges on the insulated power conductors.

The reduction in the work done by the charges in carrying a unit charge from the image of a given ground conductor to that conductor is dependent upon the reduction in charge of the ground conductors. It is not dependent upon the presence or size of the charges on the power conductors, since, according to the assumption made, those charges do not change. The reduction in the charge on each ground conductor is therefore not dependent upon the size or position of the power conductors, and may be calculated by assuming the power conductors to be absent.

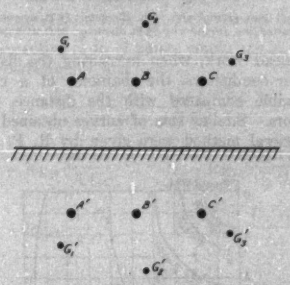


FIG. 1—GROUND CONDUCTORS AND POWER CONDUCTORS AND THEIR IMAGES

The reduction in voltage on a given power conductor such as $A$ is equal to one-half the reduction in the work done on a unit charge carried from the image of $A$ to $A$. This is dependent upon the reduction in the charges on the ground conductors, and this has been shown to be unaffected by the presence of the power conductors. Since the charge on $A$ does not change, the reduction in voltage on $A$ does not depend upon the shape or diameter of $A$, but merely on the position of $A$. The protective ratio of $A$ is obtained directly from the reduction of voltage on $A$, described above.

It is possible, therefore, to calculate the protective

1. Massachusetts Institute of Technology, Cambridge, Mass., and New England Power Construction Company.

2. R. P. Jackson, A. I. E. E. TRANS., 1907, p. 873.

3. *Theory of Parallel Grounded Wires*, by E. E. F. Creighton, A. I. E. E. TRANS., 1916, p. 845.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

ratio for one power conductor near a group of ground conductors by assuming that the other power conductors do not exist. It is also possible to plot curves showing the protective ratio around a group of ground conductors, and these curves will be the same for power conductors of any diameter. (See Figs. 2, 3, 4, and 5.)

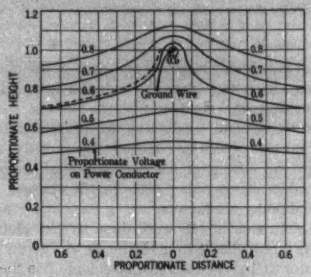


FIG. 2—SINGLE GROUND WIRE

Full lines, ground wire ½ in. diameter; 80 ft. average height
Dotted line, ground wire ⅜ in. diameter; 35 ft. average height

In overhead work, when measuring the distances to the other conductors. the diameter of a conductor is negligible compared with the distance to other conductors. Similar sets of curves obtained by this same general method were given by R. P. Jackson. (Ref. 2.)

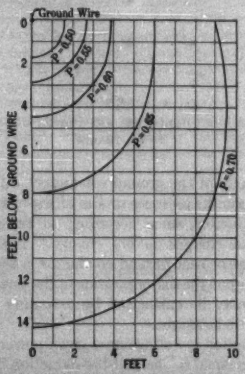


FIG. 3—PROTECTIVE FACTOR, $P$, DUE TO ONE $^7/_{16}$-INCH GROUND WIRE; 65 FT. AVERAGE HEIGHT.

Typical of a steel pole line

The above paragraphs show that in computing the protective ratio for the power conductor $A$, it is not necessary to find the value of the charge on $A$. This makes the number of simultaneous equations to be solved equal to the number of ground conductors. In most cases, the arrangement of the ground conductors is symmetrical when all the power conductors are considered absent, and some pairs of charges can be put equal to each other. The number of simultaneous equations to be solved is then equal to approximately one-half the number of ground conductors. The one main calculation will give the protective ratio for all the power conductors. Thus, the calculation becomes as follows:

Find the charges on the ground conductors due to the

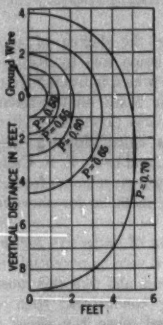


FIG. 4—PROTECTIVE FACTOR, $P$, DUE TO ONE ⅜-IN. GROUND WIRE, 28 FT. AVERAGE HEIGHT.

Typical of a wood pole line

voltage gradient, all the power conductors being considered absent. Then carry a unit charge from the image of any of the power conductors to that conductor. This gives the reduction in voltage on that conductor due to suddenly grounding the ground conductors,

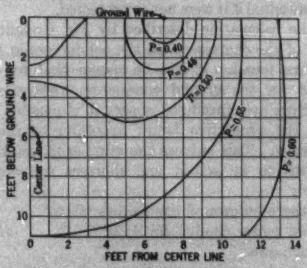


FIG. 5—PROTECTIVE FACTOR, $P$, DUE TO TWO $^7/_{16}$-IN. GROUND WIRES, 14-FT. SPACING AND 40 FT. AVERAGE HEIGHT.

Typical of H-frame transmission lines

assuming them to be first insulated and holding the charges left by the gradient. By subtracting this reduction from the original voltage at the power conductor $A$ caused by the gradient, one finds the final voltage on $A$, and hence the protective ratio for $A$.

This shorter method of calculation has been checked for some practical numerical examples by solving them by both the shorter and the longer methods, the same result being obtained by both methods.

It has been found by Mr. H. H. Spencer of the New

England Power Construction Company, that considerable time and effort in performing the calculation and checking it are saved in most cases by expressing the result of the simultaneous equations by determinants which are symmetrical about a diagonal, and then employing the Doolittle Method of evaluating the determinants.

The mirror symmetry which this method of solution of ground wire problems involves leads to a simplification in the evaluation of the charges on the ground conductors through the so'ution of the simultaneous equations.

Regardless of the arrangement of the ground conductors, the simultaneous equations for their charges can be so arranged that the determinant of the equations will be symmetrical about the principal diagonal; that is, the equations can always be so arranged that they will be of the form:

$$a_1 Q_1 + b_1 Q_2 + c_1 Q_3 + d_1 Q_4 + \ldots + r_1 Q_n - K_1 = 0$$
$$b_1 Q_1 + b_2 Q_2 + c_2 Q_3 + d_2 Q_4 + \ldots + r_2 Q_n - K_2 = 0$$
$$c_1 Q_1 + c_2 Q_2 + c_3 Q_3 + d_3 Q_4 + \ldots + r_3 Q_n - K_3 = 0$$
$$d_1 Q_1 + d_2 Q_2 + d_3 Q_3 + d_4 Q_4 + \ldots + r_4 Q_n - K_4 = 0$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$
$$r_1 Q_1 + r_2 Q_2 + r_3 Q_3 + R_4 Q_4 + \ldots + r_n Q_n - K_n = 0$$

Equations of this form are much used in statistical work and a form of solution for them, well known by statistical men but not much employed by engineers, is the Doolittle Method.[4] This method consists of so tabulating and arranging the work that it becomes self-checking and at each step of the operation, columns are footed and lines extended so that the sums obtained give a numerical check on all the work done up to that point. This removes to a large measure the tediousness of solving large numbers of simultaneous equations, since the computer is relieved of the dread that an error may have been made, necessitating the repetition of a large volume of labor. In a ground wire problem involving a large number of ground conductors, 13 simultaneous equations were solved by this method in rather less than one-half the time required for solution and checking by the usual determinantal methods.

For one or two ground conductors, formulas for the protective ratio are advantageous, but for more ground conductors it is probably better to use numerical coefficients and solve the simultaneous equations.

The protective ratio with one ground conductor is

$$1 - \frac{h_G}{h_A} \frac{b}{a} \qquad (1)$$

where

$$a = \log_{10} \frac{G\,G'}{r_G}$$

$$b = \log_{10} \frac{A'\,G}{A\,G}$$

4. Frederick C. Mills' "Statistical Methods," Henry Holt and Company, 1924; pp. 577-581.

$h_G$ = height of ground conductor above the earth,
$h_A$ = height of power conductor $A$ above the earth,
$r_G$ = radius of ground conductor,
$G\,G'$ = distance of ground conductor to its image, and so on.

Equation (1) corresponds to Equation (28a) of Reference 3, which contains an error.

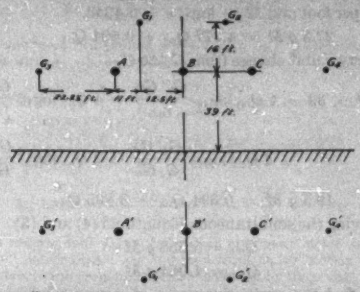


Fig. 6—Transmission Line with Four Ground Conductors

The protective ratio of power conductor $A$ with two ground conductors $G_1$ and $G_2$ is

$$1 - \frac{(b\,e - c\,d)\,h_{G2} + (c\,e - b\,f)\,h_{G1}}{(e^2 - d\,f)\,h_A} \qquad (2)$$

where

$$b = \log_{10} \frac{A'\,G_1}{A\,G_1} \qquad e = \log_{10} \frac{G_1'\,G_2}{G_1\,G_2}$$

$$c = \log_{10} \frac{A'\,G_2}{A\,G_2} \qquad f = \log_{10} \frac{G_2'\,G_2}{r_{G2}}$$

$$d = \log_{10} \frac{G'_1\,G_1}{r_{G1}}$$

If $h_{G1} = h_{G2}$ and $r_{G1} = r_{G2}$

$$\text{Protective ratio} = 1 - \frac{h_G}{h_A} \frac{(b + c)}{(d + e)} \qquad (3)$$

Example—Four ground conductors (see Fig. 6).

$$r_{G1} = r_{G2} = 0.02083 \text{ ft.}$$
$$r_{G3} = r_{G4} = 0.015 \text{ ft.}$$

First assume that the power conductors are absent.

By symmetry, $Q_{G2} = Q_{G1}$ and $Q_{G4} = Q_{G3}$, these being charges per cm. of conductor.

Carry a unit charge from $G_1'$ to $G_1$.

The work done against any charge such as $Q_{G3}$ and its image is

$$4\,Q_{G3} \log_n \frac{\text{old distance}}{\text{new distance}}$$

where "old distance" is the distance of the unit charge from the center of $G_3$ before the motion, and "new distance" is the distance from the center of $G_3$ after the motion takes place, and where $\log_n$ denotes natural logarithm. Thus,

$$2\,g\,M \times 55 = 4\,Q_{G1} \log_{10} \frac{G_1' G_1}{r_{G1}} + 4\,Q_{G1} \log_{10} \frac{G_1' G_2}{G_1 G_2}$$

$$+ 4\,Q_{G3} \log_{10} \frac{G_1' G_3}{G_1 G_3} + 4\,Q_{G3} \log_{10} \frac{G_1' G_4}{G_1 G_4}$$

where $g$ = the gradient induced by the cloud, in statvolts per foot and $M = \log_{10} e = 0.4343$.

$$27.5\,g\,M = 4.377\,Q_{G1} + 0.694\,Q_{G3} \qquad (4)$$

Carry a unit charge from $G_3'$ to $G_3$

$$2\,g\,M \times 39 = 4\,Q_{G3} \log_{10} \frac{G_3' G_3}{r_{G3}} + 4\,Q_{G1} \log_{10} \frac{G_3' G_1}{G_3 G_1}$$

$$+ 4\,Q_{G1} \log_{10} \frac{G_3' G_2}{G_3 G_2} + 4\,Q_{G3} \log_{10} \frac{G_3' G_4}{G_3 G_4}$$

$$19.5\,g\,M = 0.694\,Q_{G1} + 3.835\,Q_{G3} \qquad (5)$$

Solving the simultaneous Equations (4) and (5)

$$Q_{G1} = 5.638\,g\,M$$

and

$$Q_{G3} = 4.064\,g\,M$$

To find the protective ratio of power conductor $A$, carry a unit charge from $A'$ to $A$ against the four charges on the ground conductors and their images which have just been derived, and let the voltage so found be $\overline{V}_{AA}'$.

$$\overline{V}_{AA}'\,M = 4\,Q_{G1} \log_{10} \frac{A' G_1}{A\,G_1} + 4\,Q_{G1} \log_{10} \frac{A' G_2}{A\,G_2}$$

$$+ 4\,Q_{G3} \log_{10} \frac{A' G_3}{A\,G_3} + 4\,Q_{G3} \log_{10} \frac{A' G_4}{A\,G_4}$$

$$\overline{V}_{AA}'\,M = 4 \times 9.18\,g\,M$$

$$\frac{1}{2}\,\overline{V}_{AA}' = 18.36\,g = \text{reduction in voltage on } A$$

$$39\,g = \text{voltage on } A \text{ left by gradient}$$
$$20.64\,g = \text{final voltage on } A$$

$$\text{Protective ratio of } A = \frac{20.64}{39} = 0.529$$

It is desired to make acknowledgment to Mr. L. O. Waite of the Stone and Webster Engineering Corporation for a number of contributions to this paper, among them Formulas (1) and (3) and Figs. 3, 4, and 5.

## Discussion

**L. V. Bewley:** Ground wires are of interest to the transmission line engineer from at least seven different standpoints:

(1) Protection against induced potentials,
(2) Protection against direct strokes,
(3) Protection against incoming high-voltage surges,
(4) Effect on telephone interference,
(5) Effect on zero phase sequence reactance in connection with stability calculations,
(6) Effect on corona loss,
(7) Effect on arcing grounds.

Of these, Dr. Dwight's paper is concerned with the first, protection against induced potentials, and in common with several previous investigations along this line is based on the simplifying assumptions that:

(a) The cloud discharge is instantaneous, so that the conditions are inherently static.

(b) The ground wires are ideal, that is, perfectly grounded throughout their length.

Actually, the cloud discharge is not instantaneous and the ground wires are not ideal, but are grounded at intervals through tower resistances, so that a complete analysis of the situation involves:

(1) The law of cloud discharge,
(2) The distribution of bound charge,
(3) The presence of traveling waves, during both their formation and developed stages, on both line and ground conductors,
(4) Residual charges, up until the completion of cloud discharge,
(5) Length of the spans,
(6) Resistances of the tower footings,
(7) Successive reflections at the towers,
(8) Corona,
(9) Number of ground wires,
(10) Number of line wires.

I have recently submitted to the Meetings and Papers Committee of the A. I. E. E. the manuscript of a paper covering these points, in which it is proved mathematically that as far as ideal ground wires are concerned, the protective ratio is absolutely independent of the law of cloud discharge, distribution of bound charge, and presence of traveling waves, and depends only on the size and position of the ground wires and the position of the particular line conductor under consideration. The general system of equations involving all of these factors finally reduced, after considerable manipulation, to the static equilibrium equations of the conventional method of solution. Incidentally, as Dr. Dwight reasoned, the protective ratio of any line conductor is independent of the presence of the other line conductors,—a fact which is also true in the case of traveling waves. In this same paper there is given a general method of solution applicable to ground wires which are periodically grounded. To handle this much more difficult case it was necessary to develop the theory of traveling waves on any number of mutually coupled wires, and to devise a means for taking into account the multiplicity of reflections which occur on the spans between towers. The most important conclusions of this analysis were:

(1) The voltage crests of the traveling waves on the line wires, a span or two from the zone of bound charge distribution, are practically reduced by the same amount as is computed in the case of ideal ground wires.

(2) Within the zone of bound charge distribution, the potentials on both line and ground conductors may be of the order of four times as great as that of the traveling wave crests.

In other words, a calculation of protective ratio based on ideal ground wires is all right as far as the protection of station apparatus is concerned, but is not a correct criterion of what is happening at the center of disturbance.

The equation for the protective ratio in the case of $m$ ideal ground wires numbered from No. $l$ to No. $m$ inclusive is

$$P_l\,R_l = \frac{1}{h_o} \begin{vmatrix} p_{ll} & \cdots & p_{ml}\,h_l \\ \cdots & \cdots & \cdots \\ p_{lm} & \cdots & p_{mm}\,h_m \\ p_{lo} & \cdots & p_{mo}\,h_o \\ p_{ll} & \cdots & p_{ml} \\ \cdots & \cdots & \cdots \\ p_{lm} & \cdots & p_{mm} \end{vmatrix}$$

where the $p$'s are Maxwell's potential coefficients, and the $h$'s are the heights of the conductors. Subscripts ($l$) to ($m$) refer to the ground wires, and subscript ($o$) to the line wire under consideration. Note that the other line conductors do not enter. Since in most practical cases only a few ground wires will be

used, it is only necessary to solve a relatively simple determinate. In the case of a great number of ground wires (Dr. Dwight mentions a case of 13 ground wires), it will undoubtedly be worth while to acquaint oneself first with the Doolittle method of evaluation.

**J. E. Clem:** This paper is very interesting and encouraging to me because it apparently gives a rigorous proof of certain of the principles that the writer worked out by simple algebra a few years ago and has used since that time. These are: (a) the voltage induced by a cloud field on any insulated wire is independent of the presence of all other insulated wires in the field; (b) the reduction in the induced voltage of any insulated wire occasioned by a ground wire is not affected by the presence of any other insulated wires; (c) the reduction in the induced voltage of any insulated wire by any one of a number of ground wires numerically equal to the voltage which would be induced on the insulated wire in question by a charge on the ground wire equivalent to the charge which would appear on the ground wire if the line wires were all absent. This pseudo charge on the ground wire is numerically equal to the charge on the ground wire before cloud discharge minus the charge on the ground wire after cloud discharge. These principles are useful in estimating the protective value of ground wires.

Contrary to the statement in the paper the application of (c) of the preceding paragraph does not reduce the work required for the calculation of all because, according to (b), only one line wire need be considered at a time and it is not necessary at all to calculate the charges on the ground wires or line wires. Working along these lines the writer has developed independently the following general formula for the protection afforded by any number of ground wires.

$$R_n = \frac{D_{n+1}^{n+1}}{h_{n+1}\, D_n} \tag{1}$$

$R_n$ = protective ratio which is defined as the ratio of the voltage induced on an insulated wire in the presence of $n$ ground wires to the voltage which would be induced if the ground wires were not there.

$h_{n+1}$ = height of line wire

$D$ = determinant defined as follows

$$D_n = \begin{vmatrix} A_1 & B_{12} & B_{13} & \cdots & B_{1n} \\ B_{21} & A_2 & B_{23} & & \\ B_{31} & B_{32} & A_3 & & \\ \vdots & & & & \vdots \\ B_{1n} & \cdots & & \cdots & A_n \end{vmatrix} \tag{2}$$

$$D_{n+1}^{n+1} = \begin{vmatrix} A_1 & B_{12} & B_{13} & \cdots & B_{1n} & h_1 \\ B_{21} & A_2 & & & & h_2 \\ B_{31} & & & & & \\ \vdots & & & & \vdots & \\ B_{1n} & \cdots & & \cdots & A_n & h_n \\ B_{1,n+1} & \cdots & & \cdots & & h_{n+1} \end{vmatrix} \tag{3}$$

$A$ = Coefficient of self capacitive inductance.

$$= \frac{1}{0.03883} \operatorname{Log} \frac{2\,h}{r}$$

$B$ = Coefficient of mutual capacitive induction (4)

$$= \frac{1}{0.03883} \operatorname{Log} \frac{R}{S} \tag{5}$$

$h_1$, $h_2$ etc. = height of ground wire in question

$r$ = radius of wire

$R$ = distance from line wire to image of ground wire

$S$ = distance from line wire to ground wire.

This is a general formula applying to any number or arrangement of ground wires. If there were one ground wire $n = 1$

$$D_n = A_1 \qquad D_2 = \begin{vmatrix} A_1 & h_1 \\ B_{21} & h_2 \end{vmatrix} \tag{6}$$

$$R_1 = \frac{\begin{vmatrix} A_1 & h_1 \\ B_{21} & h_2 \end{vmatrix}}{h_2\, A_1} = 1 - \frac{h_1}{n_2}\,\frac{B_{12}}{A_1} \tag{7}$$

If there were two ground wires $n = 2$, or if there were three ground wires $n = 3$, and then

$$R_2 = 1 - \frac{h_1}{h_3}\,\frac{D_3'}{D_3} - \frac{h_2}{h_3}\,\frac{D_3''}{D_3} \tag{8}$$

$$R_3 = 1 - \frac{h_1}{h_4}\,\frac{D_3'}{D_3} - \frac{h_2}{h_4}\,\frac{D_3''}{D_3} - \frac{h_3}{h_4}\,\frac{D_3'''}{D_3} \tag{9}$$

$$R_n = 1 - \frac{h_1}{h_{n+1}}\,\frac{D_n'}{D_n} - \frac{h_2}{h_{n+1}}\,\frac{D_n''}{D_n} \cdots \text{etc.} \tag{10}$$

The determinant $D_n$ is defined as previously noted and the "prime" determinants are obtained from $D_n$ by writing $B_{1,n+1}$, $B_{2,n+1}$ etc. in the proper column as indicated by the prime. Thus

$$D_2' = \begin{vmatrix} B_{12} & A_1 \\ B_{22} & A_2 \end{vmatrix} \qquad D_2'' = \begin{vmatrix} A_1 & B_{12} \\ B_{21} & B_{22} \end{vmatrix} \tag{11}$$

From these expressions it is clear that the analytical determination of protective ratio is merely a matter of dimensions and the pseudo charge on the ground wires need not be calculated. The same results can be obtained by calculating the pseudo charge but a little algebra is needed to put the results into the same form.

The preceding formulas can be greatly simplified on the assumption that average values of the capacity coefficients can be used. The general formula will then be

$$R_n = 1 - \frac{h_g}{h_w}\,\frac{n\, B_{wg}}{A_g + (n-1)\, B_g}$$

$h_g$ = average height of ground wires

$= \sqrt[n]{h_1\, h_2\, h_3 - - - h_n}$

$h_w$ = height of line wire

$A_g$ = average coefficient of self capacitive induction of ground wires

$B_{wg}$ = average coefficient of mutual capacitive induction between line wire and ground wires

$B_g$ = average coefficient of mutual capacitive induction between ground wires

$$A_g = 25.75 \operatorname{Log} \frac{2\, h_g}{r_g}$$

$$r_g = \sqrt[n]{r_1\, r_2 - - - r_n}$$

$$B_g = 25.75 \operatorname{Log} \frac{R_g}{S_g}$$

$$R_g = \sqrt[n]{R_{12}\, R_{23} - - - R_{n1}}$$

$$S_g = \sqrt[n]{S_{12}\, S_{13} - - - S_{n1}}$$

$$B_{wg} = 25.75 \operatorname{Log} \frac{R_{wg}}{S_{wg}}$$

$$R_{wg} = \sqrt[n]{R_{w1}\, R_{w2} - - - R_{wn}}$$

$$S_{wg} = \sqrt[n]{S_{w1}\, S_{w2} - - - S_{wn}}$$

For one, two, and three ground wires the following simple expressions result:

$$R_1 = 1 - \frac{h_g}{h_w} \frac{B_{wg}}{A_g}$$

$$R_2 = 1 - \frac{h_g}{h_w} \frac{2\,B_{wg}}{A_g + B_g}$$

$$R_3 = 1 - \frac{h_g}{h_w} \frac{3\,B_{wg}}{A_g + 2\,B_g}$$

These simplified expressions are exact for one and two ground wires when the heights and diameters are the same and give very close results for the usual configuration found in practise.

In the analytical determination of ground wire protection certain assumptions are necessary. These are as follows: (a) the surface of the earth is assumed to be the neutral plane and the capacitances considered are all in reference to this neutral plane. This is equivalent to considering the earth as a perfect conductor which obviously is not the case. However, since ratios are involved this may not introduce much error. (b) It has been assumed that the ground wire always remains at ground or zero potential. This assumption requires that the ground wire have no impedance and that the resistance of the earth connection be zero, also that the charge on the ground wire will change from its initial value to its final value in zero time. Of course, these conditions can never be realized so, if nothing else entered in, the actual protection could be expected to be lower than the calculated. Laboratory tests[1] have shown that the protection is reduced as impedance of the ground wire is increased and as the resistance of the earth connection is increased. For these factors theory and practise unite in indicating that it is desirable to use ground wires of low impedance and to have low ground resistance.

An interesting method of calculation has been included by Peek[1] in the latest revision of his book on High-Voltage Engineering.

Laboratory determination of protective ratios has been made by Peek.[1] These protective ratios are better than the analytical calculations would indicate. The writer and C. A. Woodrow about the same time independently suggested that the difference might be due to corona on the ground wires and line wires. The action of the corona would be to increase the effective diameter of the wires. Later laboratory tests indicated that the protective ratio varied with the field gradient and thereby seemed to confirm the theory that corona was a factor. Mr. Hunter has made calculations in which the effect of corona on the ground wires has been approximated on the basis of certain simplifying assumptions.[2]

During the field investigations of lightning carried on during the past few years considerable attention has been given to the effect of ground wires. It is generally conceded that the use of ground wires will materially improve service, and that the reaction of several years ago against ground wires was due to improper methods of insulation and the use of unsuitable material. It was noted previously that the laboratory tests gave better protective ratios than the analytical calculations indicated. Studies of the field data indicate that the ground wires in service have a protective ratio somewhere between the two values, tending however to be closer to the laboratory value. Protective ratios based on Peek's tests for average circuit conditions have been published[2] and in studying the effect of ground wires on the induced voltage on any line it is best to determine both values and then consider the protective ratio based on the laboratory test as the optimistic figure and the protective ratio based on the analytical calculations as the pessimistic figure.

1. "Dielectric Phenomena in High-Voltage Engineering," McGraw Hill Co.

2. Hunter, *General Elec. Rev.*, Feb. 1930.

3. W. W. Lewis, *Relation Between Transmission Line Insulation and Transformer Insulation*, A. I. E. E. Quarterly Trans., Oct. 1928, Vol. 47, p. 992.

**E. M. Hunter:** In the method of calculating ground wire protection described in this paper and the methods described in the references to the paper, no attempt has been made to include the effects of corona in the calculations. On most high-voltage transmission lines, corona appears at a comparatively low gradient.

The potential gradient at the surface of the conductors and ground wires under lightning conditions greatly exceeds the rupturing potential gradient of air. The air breaks down, forming corona, thus in effect enlarging the diameter of the conductors and ground wires. This in turn increases the capacitance between the conductors and ground wires, and correspondingly decreases the induced voltage on the conductors.

The potential gradient at the surface of a wire is proportional to the charge on the wire.

When a charged cloud is over a portion of a transmission line, an electrostatic field is established between the cloud and ground. Charges, of sign opposite to that of the cloud, will be on the conductors in the cloud field and on the earth. With the collapse of the electrostatic cloud field, due to the discharge of lightning, the charge which was bound by the cloud field is set free and begins to travel along the transmission line. The voltage which appears on the transmission line will depend upon the capacitance between the line and ground. It would be equal to the potential gradient of the cloud field multiplied by the height of the line above earth if the circuit were without ground wires. The presence of the ground wires increases the capacitance to earth; and with cloud gradients sufficient to cause corona, the capacitance is further increased as the effective diameter of the ground wire is increased.

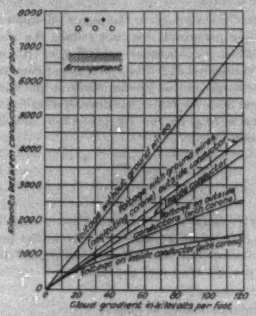


Fig. 1—Potential Between Conductor and Ground for Various Cloud Gradients

$$\text{Protective ratio} = \frac{\text{Voltage with ground wires}}{\text{Voltage without ground wires}}$$

The charge on any ground wire in a group of line and ground wires is proportional to the charges on all of the conductors in the group. Thus it is necessary to write the usual system of simultaneous equations for the charges on the conductor and ground wires, to determine the charge on the wire in question in order to determine its increased diameter. Hence the method of calculating ground wire protection described by Dr. Dwight cannot be used when the effects of corona are to be included.

An approximate method of including the effects of corona in the standard theory of ground wire protection is described in an article, "The Effects of Corona on Ground-Wire Protection of Power Transmitting Circuits" by E. M. Hunter, appearing in the February 1930 issue of the *General Electric Review*.

There exists considerable discrepancy between authorities as

to the amount of protection to be expected from ground wires. There is a fairly general agreement as to the theoretical protection, as calculated from the standard formulas, but the results of tests by Mr. F. W. Peek, Jr. in the High-Voltage Engineering Laboratory in Pittsfield, Mass. show a much better protection than can be obtained from these standard formulas. However, there is a close agreement between the values of the protective ratios calculated by including the effects of corona with those obtained from tests on miniature laboratory set-ups.

The protective ratio, as calculated by the usual standard formulas, is given as constant for all cloud gradients. It is interesting to note that when the effects of corona are included in the calculations, the protective ratio is no longer a constant but varies with the cloud gradient; the higher the cloud gradient the better the protection obtained. This was also noticed in the laboratory experiments.

The induced voltage on a three-phase transmission line protected by two ground wires as a function of cloud gradient is shown in Fig. 1 of this discussion. The protective ratio as calculated by the standard formulas is a constant for any cloud gradient but when the effects of corona are included in the calculations the protective ratio varies with the cloud gradient, the higher the cloud gradient the higher the protective ratio to be expected.

**H. H. Spencer:** In regard to Dr. Dwight's paper I should like to say a little more about the Doolittle method of solving equations. This method has long been used by statistical engineers in getting what they call "regression coefficients in a multiple correlation equation." I have not the faintest notion what the names of those things are but a statistician associated with our organization pointed out the method used to me and it is exceedingly valuable where the protective ratio due to a large number of ground wires is desired. In one installation, a crossing over a deep gorge with a very high average distance of the power conductors above the earth, we have considered a screen of 26 ground wires surrounding 12 power conductors. This involves 26 simultaneous equations to determine the change of charge on each of the ground conductors. Actually, in this case, the symmetry of configuration enabled us to proceed with 14 simultaneous equations.

In setting up the problem for solution by the Doolittle method probably no actual labor is saved. It is probably true that substantially double the number of actual computations are made over and above the number which would be made in solving the 14 equations by the usual algebraic methods. The real advantage of the Doolittle method is that you can rule up a form on a large sheet of paper, write down the coefficients in the various equations and then pass the sheet of paper to anyone who can run a Monroe Calculating Machine and the results are more or less automatically produced. The beauty of the method lies in the fact that it is self-checking and every time a mistake is made it is automatically brought to the computer's attention, so that by the time the form is filled out, the value of each unknown has been determined and checked so that it is unnecessary to substitute back in every equation to be absolutely certain of the precision of the work. This relieves you of all the worry that you may have to do on the laborious algebra over again; and therein, to my mind, lies the real value of the Doolittle method.

**R. P. Jackson:** The paper presented by Professor Dwight is another one of the efforts begun by myself in 1907, in an Institute paper read in Chicago of that year to evaluate the protection against lightning obtainable by the use of overhead grounded conductors. All such calculations must, of course, be based on certain assumptions. Two of these are that the surface of the earth is of uniform zero potential and that the potential gradient upward is reasonably uniform.

The above assumptions are essential to the mathematical calculations and, furthermore, they seem reasonable and are probably near enough to the truth to afford validity to the results as far as potential values are concerned.

Another assumption has been made, however. That is that the release of the charge on the transmission as a result of the disappearance of the potential gradient is really an important source of lightning trouble on such lines and in the apparatus connected to them. Recent data collected in connection with lightning investigations have thrown grave doubt on this assumption. In fact, many engineers who have been closely associated with research on lightning disturbances have come to the conclusion that direct strokes or, at least, side strokes or filaments of the main discharge are the chief causes of trouble on high-voltage transmission lines. If this is the case such calculations become of minor importance no matter how correct mathematically.

It appears, in fact, that what we want is a "continuous lightning rod" up high enough to make it highly probable that all direct strokes will reach the rod or overhead conductor and be carried to ground thereby. My paper of 1907 and Professor Dwight's present paper would imply that several comparatively small grounded conductors spanned over a transmission line would afford a low potential field below them which should be a safe place for power conductors. If, as now appears to be the case, direct strokes, or their approximate equivalents, are the source of trouble, one grounded conductor large enough not to be easily damaged by direct-stroke, high enough to be likely to attract the stroke, and of enough conductivity to carry it away, is what we want.

All our earlier calculations in regard to lightning had largely to be based on some assumptions. This practical one, however, that direct strokes were rare and that potentials induced by the electric field of an overhead closed and then released were the commoner cause of our troubles now appears to have been incorrect. If direct strokes are the main thing to be guarded against, such interesting calculations as Professor Dwight has given us and as I indulged in over twenty years ago are beside the point. To repeat, what we need is strong, non-corrosive, sufficiently massive conductors of proper conductivity placed high enough above the line to catch the stroke and usher it politely to the ground. How high this should be affords material for further mathematical calculations and practical experiment.

**H. B. Dwight:** The flashovers of transmission line insulators during thunderstorms may be divided into those caused by induced voltages and those caused by strokes of lightning or branches of such strokes, reaching the transmission line. Mr. R. P. Jackson published the calculation of protective factor in 1907 on the basis of induced voltages, and it has been used by engineers for many years with little change. It is still used to a large extent.

Mr. Jackson now states in his discussion that data have been collected which show that induced voltages are of little importance and that direct strokes are the main factor. A similar statement is to be found near the end of the paper on *The Lightning Laboratory at Stillwater, N. J.*, by R. N. Conwell and C. L. Fortescue (see p. 872). A description of the data on which this conclusion is based would be of considerable interest.

The increase in protection when there is corona on the ground wires, calculated by Mr. Hunter in his article in the *General Electric Review* of February 1930, was suggested by corresponding increases measured in impulse tests on models. The calculations indicate that a ground wire with corona is very much more effective than one without corona.

The question arises as to how much the space charge within the corona envelop around a wire behaves like a charge on a very large metallic wire. When it is determined to what extent the charge represented by the corona returns to the ground wire, and how fast it returns, the items might possibly be used as an extension of the interesting calculations given by Mr. Bewley on the effect of ground conductors, using the theory of traveling waves.

# A New Transmission Line Construction

## Post Type Towers

PERCY H. THOMAS[1]

Fellow, A. I. E. E.

***Synopsis.***—*The new construction described is intended to secure a sturdy and simple tower, not sensitive to irregularities in footing conditions; it is generally applicable where a horizontal arrangement of conductors is feasible. The tower consists of an articulated overhead transverse bridge carrying the conductors and hinged at the tops of the footings. Two or three intermediate towers are used between stabilizer towers. Transverse strength is secured by crossed internal ties and longitudinal stresses are taken up in the stabilizer towers by heavy guys and in the intermediate towers by the ground wires and conductors, which transmit these stresses to the stabilizer towers.*

*The wide base structure thus secured has substantially no resultant uplift on the footings, offering a very large saving in foundation costs. This saving, together with the lesser material and erecting costs and the great ease with which it is adapted to varying ground conditions make this a very economical type of tower.*

CONSIDERING the wide variety of conditions under which power transmission lines are installed, the very limited number of types of structures actually used is surprising. No one type of structure, such for example as the usual four legged, rigid, narrow base, cantilever tower, would naturally be expected to be the most satisfactory and economical design for all services and yet except for the well known so-called flexible type almost no other steel tower is used. In order to discover whether a different form of line support might not have real advantages over the usual type for some services, the author has made a careful survey of the requirements and the most available alternative forms and has worked out what may appropriately be called the "post type tower," a type contrasting sharply in a number of important features with the usual designs. It is intended primarily as a rugged, simple structure, not requiring special skill in erection and having the most favorable electrical characteristics, together with the lowest reasonable cost.

Engineers recognize the inherent weakness of the four footed rigid tower set on earth stubs, this being in effect a light, exceedingly rigid structure placed on an uncertain, non-rigid base. The difficulty of framing a wide base rigid structure with the relatively light structural sizes available, as well as side hill conditions, and sometimes also the value of the land occupied, have led to the development of the present narrow base tower, such towers having in many cases, especially on important high-voltage lines, a ratio of height to base most unfavorable for resisting the severe stresses imposed by high winds and broken conductors and resulting in greatly magnified vertical stresses on footings. The conditions imposed upon the foundations are particularly severe because the stresses on the footings alternate from compression to tension. If any inequality of bearing is thus developed, undeterminable but dangerous weakness is inevitably introduced. Unfortunately there is no way of discovering or remedying such inequality. It may not be unreasonable to surmise that were all the towers of the average existing transmission line subjected as they now stand to the maximum conditions of wind, ice, and broken conductors for which they were theoretically designed, many would fail. I think we may safely conclude that the very satisfactory results as to tower performance now secured are due to the fact that the severe conditions assumed in design very rarely occur.

Recent researches have shown that the height of a transmission line conductor above ground is one basic factor in determining the severity of the exposure to lightning, so that the vertical arrangement of conductors, helpful toward economy of right of way, is decidedly unfavorable from the point of view of service in country subject to lightning. Furthermore the difficulty in sleet country of avoiding arcing due to jumping of cables with the vertical arrangement is well known, due to widespread trouble from this source. These facts have been borne in mind in working out the new type tower.

The post type tower is fundamentally a broad base structure. Such a broad base in a transmission tower can be secured only by the use of tension members for bracing. The wide tower base and the fact that the conductors have a minimum height above ground serve practically to eliminate all direct resultant uplift on the footings.

The post type tower, which is almost equally well suited for one circuit or two circuit lines (see Figs. 1 to 4), consists of a long transverse crossarm carrying the conductors, supported near the two ends by independent upright posts, taking only axial stresses. The transverse stresses on the line are taken by internal tension cross ties located between the posts, and the longitudinal stresses by guys. The mechanical connections between the tops of the posts and the crossarm and between the bottoms of the posts and the footings are hinged, the tops for motion in a transverse plane, the bottoms for motion in a longitudinal plane. The tension members or guys taking up longitudinal stresses are connected to the crossarm in the same horizontal plane as the insulator strings and are located

1. Consulting Engineer, New York, N. Y.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

approximately over the posts. Therefore, while the crossarm must take up in a horizontal plane the longitudinal stresses from broken conductors transferring these stresses to the guys, there is no bending thus caused in the posts. The pull of a broken cable acting on the inclined guy, produces a downward component, but as the guys are connected near the post tops little downward strain is produced in the crossarm.

Ground wires are preferably connected to the lower chord of the crossarm in the same plane as the insulator strings and substantially at the same location as the guys. They may, however, be connected at a higher level on the crossarm, in which case the posts will have to be designed to take up the resultant bending moment developed in a vertical plane between the ground cables and the guys.

A moment's consideration will show that this structure is exceedingly favorable for supporting conductors on earth foundations, for no settling of a post footing or yielding of a guy anchor, and no error of leveling or locating of footings or anchors, within any reasonable limit, would cause any material over-stresses in the

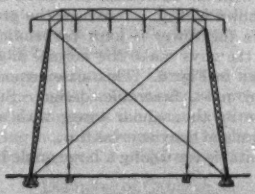

Fig. 1—Front Elevation, 132-Kv. Double-Circuit Post Type Tower Showing Guys and Cross Ties

structure. At most a certain slackness of cross ties or guys may be caused, easily remedied by tightening turnbuckles.

In considering the field of utility of the post type tower the question of the right of way assumes unusual importance. It will be clear that a wider right of way is required for any horizontally arranged circuits than one which would be sufficient for a line with vertically arranged conductors. The post type is at a disadvantage, therefore, where lines must be run through woods for long distances or in thickly settled districts. On the other hand in open fields, whether used for pasture or agriculture, in which the obstruction to the land is merely that caused directly by footings and anchors, the post type tower may even have an advantage since the footings and anchors are so widely separated from one another that it is possible to work around them and very little ground area is actually obstructed. With the ordinary four footed tower, the whole area between the four footings is usually lost.

The post type tower is especially notable for its sturdiness. On account of the flexible connections at the top and bottom of the posts, movements of the foundations or stretching of guys or yielding of anchors cause no bending moments in any part of the structure. Furthermore, the stresses are all definite and calculable so that all members, including the guys, may be proportioned for their individual stresses with the assurance that no unknown and dangerous overload may be introduced by settlings of footings or irregularity of setting as with rigid towers. The single heavy crossarm further has a greater reliability than the usual single cable crossarms.

The post type tower is notable also for its simplicity

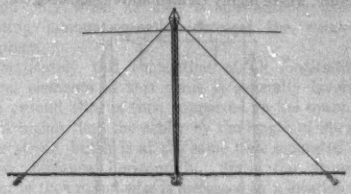

Fig. 2—Side Elevation, 132-Kv. Double-Circuit Post Type Tower

and adaptability, manifest both in layout work and in the field. On moderate sidehill slopes the normal towers are merely skewed up hill somewhat and all the same material used as on level ground. On steep slopes a taller post is used on the downhill side. A limited number of unit crossarms, posts, and guys may be combined in different ways to obtain constructions suitable for all special towers, such as angle, long span, dead end, etc. This shows the flexibility of the design.

It will be noticed that the same tower, for example the tower shown in Figs. 1 to 3, can be used for two

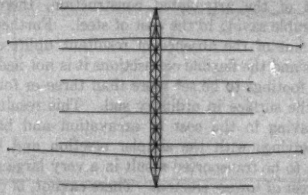

Fig. 3—Plan 132-Kv. Double Circuit Post Type Tower

circuits 110 kv. or 132 kv. at the original installation and afterward changed to one 220-kv. circuit. In the change over, the positions of the outside conductors would be abandoned and three conductors hung between the posts instead of the four for 132 kv. As a matter of fact the total spacing distance between posts will be very closely the same for three 220-kv. conductors as for four 132-kv. conductors so that there would be very little increase in weight or complication in design in laying out the tower to serve alternatively for either voltage.

Considering installation operations, since the towers are finally trued up after erection by means of turnbuckles in the cross ties and guys, there is no reason why post footings or guy anchors should be accurately located nor is there any object in carefully leveling the footings. Variations of a foot or two either in horizontal position or in the vertical setting of footings are unimportant.

Towers may be entirely assembled on the ground and ended up on the stub hinges at the bottom of the posts.

Thus where sturdiness is of value in the tower structure, where highly trained and responsible erectors

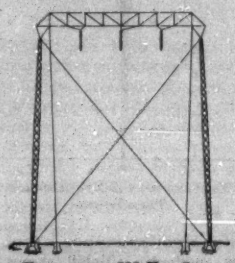

Fig. 4—Front Elevation, 220-Kv. Single-Circuit Post Type Tower

are not available, or where there may be difficulty in soil conditions, the post type tower has an advantage and it was for such conditions that it was originally devised.

The post type tower has a further advantage in its cost saving which is very material in amount. On account of the wide base in both directions and on account of the articulated construction, there is a considerable saving in the cost of steel. Furthermore, on account of the absence of resultant uplift on the footings and the flexible connections it is not necessary for the footings to be set more than three or four feet below the surface in ordinary soil. This results in a great saving in the cost of excavation and backfill. These savings with the simpler erection and lighter weights to be transported result in a very large saving in the cost of towers erected. There cannot, of course, be any saving in the cost of conductors *per se*.

There is a modified form of the post type tower which is especially favorable from the point of view of cost and simplicity, this being especially applicable to two circuit lines. By relying on two ground wires connected respectively near the post tops and secured firmly to the crossarm to take up longitudinal stresses, it is practicable to omit the longitudinal guys on a majority of the towers, the ground wires serving the function of the guys for these towers. In this construction on account of the long spans the towers will not be held strictly rigidly in position, but being hinged at the bottom they are free to adjust themselves to the pull of the ground wires and conductor cables and no abnormal stresses are introduced. On towers where the guys are omitted a broken conductor will cause a slight displacement of the crossarm sufficient to tighten up on the ground wires in one span while slackening off in the other. No bending stresses are introduced in the posts and no mechanical instability.

Analysis shows that a series of more than three successive unguyed towers is not desirable. The latter means, however, the omission of all longitudinal guys on three-quarters of all towers on normal tangent sections.

The importance of this omission of guys, leaving the ground unobstructed except for post footings, four or five thousand feet in a stretch, is obvious. There is also a very material saving in cost. This is practically clear gain since the guyed towers serving as stabilizer towers need be no stronger than with all towers guyed.

The construction of the tower and its use on side hill slopes is shown in Figs. 5 and 6. The normal tower is used on a moderate side hill slope with the crossarm parallel to the ground. A tower on a steeper side hill is provided with an additional extension in the down hill leg as shown in Fig. 5. Where the ground slopes with the line the tower is kept perpendicular to the ground and the guys make the normal angle with the post as shown in Fig. 6. This arrangement gives the simplest and most favorable design. Small angles can be taken on the regular tower with a somewhat wider crossarm and heavier cross ties.

A tower suitable for taking a large angle in the line is

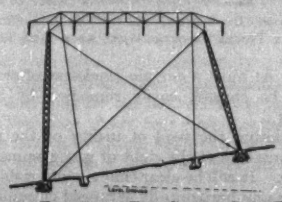

Fig. 5—Front Elevation, Two-Circuit Post Type Tower on One-in-Five Transverse Ground Slope

shown in Fig. 7. Two pull-offs, one connected to each post, are used. Both are secured to the same anchor, but through a whiffletree arrangement by which the total pull-off stress is divided between them in the desired ratio.

## Proper Horizontal Spacing of Conductors

This is an important matter with post type towers since this horizontal spacing occurs three times cumulatively and largely determines the length of crossarm.

With the usual four legged two-circuit tower with a "basket" carrying the crossarms, each cable must be so far spaced from the basket that in the position of maximum swing it still has the proper clearance to

tower. This condition usually determines the horizontal spacing of conductors, since it gives a spacing out in the span considerably more than necessary to prevent contact. There are other types of line, however, as for example wood pole lines and lines with six conductors horizontally spaced on one crossarm (such for example as the Davis Bridge Line of the New England Power Company) where horizontal spacing is determined by the danger of contact out in the span as

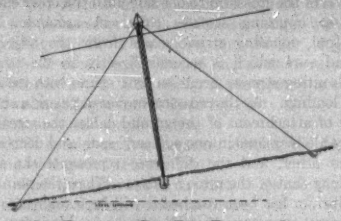

Fig. 6—Side Elevation, Post Type Tower on Longitudinal Side-Hill Slope

with the post type tower. Practise in these cases indicates that from 6 to 12 ft. between conductors is safe on from 60 kv. to 110 kv.

Since a more flexible and consistent method of determing the proper spacing should, however, be available, the author suggests the formula[2] proposed by him for calculating horizontal spacing, reading as follows:

$$\text{Horizontal Spacing} = C \times \text{Sag in per cent} \times \frac{\text{Diameter of Cable in in.}}{\text{Class "A" Loading in lb.}} + D + \tfrac{1}{2}\ \text{Length of Insulator String in ft.}$$

Where

$C$ = A constant chosen arbitrarily for each line to take account of the sort of metal of conductors, wind conditions, character of terrain, etc.

$D$ = Jumping distance of line voltage—one foot for each 11 kv.

"Sag in per cent" is for class "A" loading.

Constant suggested for copper cable — 4.0

Constant suggested for A. C. S. R. — 3.5

This formula takes account of the variation in jumping distance of various line voltages, the length of insulator string, and the very important matters of cable tension and span length. A 0000 copper wire with a normal span of 800 ft. requires according to this formula about 10 ft. horizontal spacing for 110 kv. and a 336,400-cm. A. C. S. R. cable with 1000 ft. span about 11 ft. for 132 kv. These horizontal spacings fit well into the post type tower design.

2. *Formula for Minimum Horizontal Spacing of Transmission Line Conductors as Affected by Danger of Contact in the Span*, A. I. E. E. Trans., Vol. 47, October, 1928, p. 1323.

## Structural Design

There are many interesting design details to be considered in the post type tower, none presenting any serious difficulty. As a fundamental principle there is a horizontal plane of resistance at the bottom of the crossarm which takes up longitudinal stresses. All longitudinally acting elements, *viz.*, conductors, ground wire, guys, and insulators are attached in this plane. If this condition is not maintained there will be a resultant tendency for the crossarm to turn on a horizontal axis, which tendency can be resisted only by stiffness in the posts. The post can be of economical design only when its load is substantially axial as bending moment greatly increases the weight of members.

Fortunately this connecting of all longitudinally acting elements in this plane is generally favorable. The ground wire is then supported on the tower at a point higher than the cables by the length of the insulator string, but it is at the same time separated by a larger distance horizontally. Since the protective effect of the ground wire is increased by a location close to the conductors this relationship is favorable. A greater separation between ground wire and cable out in the span can be obtained by drawing the ground wire somewhat tighter than the conductor as is often done with other types of towers.

Attention should be called to the fact that the longitudinal guys of the post type tower are not to be compared to the usual twisted wire steep angle guys so much used in wood pole construction. They are tension members carrying definite calculated stress just as the bracing does in the usual tower. The guy anchors are designed and proportioned for their specific

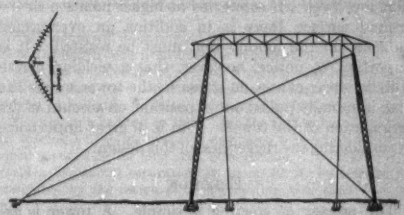

Fig. 7—Front Elevation, Post Type Tower for Heavy Angle in Line, Showing Two Pull-offs and Whiffletree

loads just as are the footings of the four legged tower. These guy anchors are more reliable than such footings as already stated, since the stress is always in one direction and not alternating and since any yielding of the foundation is shown by slackening of the guy and can be easily remedied by tightening the turnbuckle without disturbing the tower.

The size of the tension rods used in post type towers is so large as to be substantial and not easily injured,

and furthermore not greatly weakened by quite severe mistreatment. The use in the common type of tower of angles as bracing subject to compression is far less advantageous from the load carrying point of view than the tension rod.

As solid rods are not flexible special provision must be made for their convenient use. This may be secured by using the rods in fixed lengths, each length having a button upset on each end with suitable loose socket connectors for holding them together. These connectors will give an angular freedom of ten to twenty degrees each, so that a complete guy or cross tie made up of several lengths will have a very considerable flexibility. Somewhat similar methods of connection are now in use in somewhat similar service and provide a very simple and economical method of developing the full strength of the rod.

Two regular lengths of rod, 25 ft. and 12½ ft., may be used to advantage. The necessary number of such rods will be specified in the drafting room for each site and listed with the tower material. In the field the cross ties and guys will then be a few feet short. To cover this shortage there is carried by the erecting crew an assortment of lengths varying by 1 ft. steps up to 6¼ ft., which with the long screw turnbuckles will complete the ties and guys without any cutting or fabrication in the field.

Although there is no resultant uplift of material consequence on the post footings, the windward footing must take the full transverse horizontal shear on the tower, to this extent giving an advantage to the four legged tower where the shear is divided between two or more footings. If the cross ties be carried down to the earth bearing parts of the footings, the shear occurs at that low level. If connected at higher points near the ground surface there is in addition an overturning moment on the footing that must be resisted. It is important to notice, however, that a yielding of the stub to shear causes no stress in the tower unless the stub is actually pulled out of position, on account of the articulation of the tower. This is of great importance in considering the ruggedness of this design.

## Erection

The process of erecting is simple. A tower is assembled complete with insulators on blocks on the ground with the posts hinged to the footings. A divided bridle is connected to the tops of the two posts and carried over a single shear stick in the center of the line. The tower may then be raised by a windlass or truck, the guys being used as back stays. If the construction in which the guys are omitted from a certain portion of the towers is used, temporary guys may be provided until the ground cables are strung. When the structure is erected the cross ties and guys are tightened so that the structure is made taut and rigid; in fact, it is the most rigid type of tower available.

## Towers with Guys Omitted

The behavior of a line in which the guys are omitted from a certain portion of the towers on normal tangent line, as for example three towers out of four, is interesting. The most critical case is the breaking of a cable near the end of the crossarm, for example the outside conductor. In this case a stress equal to the final stress in the cable is imposed horizontally on the end of the crossarm. The horizontal broken cable stress pulls the end of the crossarm to one side until the other cables develop opposing stresses equal in amount. The principal opposing stress comes from the adjacent ground wire which is secured directly to the tower. The limiting stresses occur on long spans with ice and wind loading. As the crossarm moves to the side at the point of attachment of the ground cable, the stress in this cable increases in one adjacent span and decreases in the other, and the difference represents the pull opposing that of the broken cable. When the point of equilibrium has been reached it will be found that the end of the crossarm where the broken cable is located has moved some two or three ft. only. The point of attachment of the broken cable is out at the end of the crossarm while the nearest ground cable is attached several feet inside. As a result there will be a slight stress in the far ground cable in the opposite direction from that in the near ground cable. The crossarm at the far end then has a slight movement in the reverse direction.

In the case of a broken ground wire, presumably a less likely contingency, the same action occurs except that the displacement of the crossarm is somewhat greater on account of the necessity of taking up the swing of the insulator string before the development of the necessary opposing pull in the several conductors. In this case the outside conductor cable takes the greatest stress as the crossarm will as before revolve in a horizontal plane about a point near the far ground wire.

Even in the extreme position of the crossarm with a broken cable, the strength of the tower to carry stresses, transverse or vertical, is unimpaired and no weakness is introduced.

## Tower Heights Available

It will be evident, no doubt, that a certain advantage results in spotting towers in a transmission line, where there is a large number of tower heights available differing by small steps. If, for example, a span is so located that the low point lies just over a depression in the ground, the neighboring high spots on the two sides cannot be used as tower sites to advantage unless there are available towers of the right heights.

It is difficult to determine the importance of this advantage, which apparently amounts, however, to several per cent in the total number of towers required, when as many as eight or ten heights are available over a range of 100 per cent in height. Such a large number of tower heights is very easily obtained with post type

towers by the use of varying length parallel sided center sections in the posts as shown in Fig. 5.

Modifications of the various details here described may be made to advantage to adopt the post type tower to various line conditions. The general scheme is obviously very flexible in application. There are numerous other details arising in the design and use of post type towers that are of interest or practical importance but space will not permit their discussion here.

The only serious objections urged against the post type are the greater width of line structure, which is controlling in only a few cases, and the use of guys, which while exceedingly effective and economical, make a widespread base. The utility of the post type tower can be summed up very briefly as follows:

1. Sturdy and simple design.
2. No special skill or accurate leveling required in setting footings or tower erection.
3. Best arrangement of conductors electrically and as a safeguard against uneven ice loads.
4. Not sensitive to foundation movements.
5. A very material saving in weight and cost of steel and in cost of footings, anchors, and erection.

It may be added that obviously many modifications of the post type structures here shown may be made to meet different conditions or uses.

## Discussion

**F. E. Andrews:** There are several points on Mr. Thomas' paper which I wanted to make some inquiries about. It is interesting to consider that we have a suggestion for construction like this which is radically different from the conventional designs that usually go along with tower construction; it is a healthy condition to have some suggestions like this because they are conducive to thinking in new lines which are usually very profitable.

Mr. Thomas spoke of the use of the ground wires for stabilizing intermediate towers in cases where the longitudinal guys on the intermediate towers were omitted. I should like to ask if any additional allowance is made for strength of the ground wires when they are so used, over and above that usually made for the normal wind and ice loading and whether or not any different factor of safety is used for the ground conductors like this. I should also like to ask whether or not any of these hinged structures have been actually installed and if so, whether there has been any experience with them through different weather conditions in varying temperatures, etc.

In thinking of the problem of expansion and contraction it has occurred to me that there might be some unsatisfactory results due to the fact that the guy rods would slack off in the summer time, and tighten up in the winter time. It would seem very impractical to adjust the turnbuckles seasonally and I am wondering if it was contemplated that this would be done. On page 1124, Mr. Thomas speaks of the analysis showing a series of more than three successive unguyed towers not being desirable. I should like to know the basis for determining the number of three rather than some other figure. Mr. Thomas can probably answer that question.

**W. H. Colburn:** Consideration of the capital cost of delivering power at the point of use shows that cost to be somewhat staggering. Figures which I have roughly in mind for a certain short line are in the neighborhood of $45 per mile per kv-a. delivered. The modern trend is toward the maximum simplification possible consistent with the maintaining of service. Hence, any construction which will lessen this cost of line construction without sacrifice of line safety should be welcome. Mr. Thomas' proposed construction seems to offer such a possibility and deserves serious study in contrast with more conventional types of construction.

**R. D. Coombs:** (communicated after adjournment) The "post type tower" is a guyed-mast-H frame and while it should be economical in cost, the question arises as to whether it is quite fair to compare it to a wide base tower design if the designer of the latter is held to the usual specifications. This same general idea is being used in some recent railroad electrification structures, around Philadelphia. It would be interesting to know just how far the designers of either kind of structure have permitted themselves to vary from the detail requirements of the usual wide base tower specifications.

The writer is not at all concerned over the fact that a wide base tower foundation may have alternate compression and tension, and doubts that such a tower ever failed from this cause. Undoubtedly the fine record of wide base towers is as the author says because they have never received their maximum theoretical loading. On the other hand it is also a fact that many such towers have not fallen even after wildly excessive loads or outrageous incidents. The writer refers to such cases as the three following:

(a) The conductors were doubled in size, perhaps 5 ft. pulled out of the sag, and the stubs were very badly set.

(b) A tangent tower was used at a large angle corner.

(c) The foundation under one corner descended 2 or 3 ft. from a cause unrelated to the tower.

Of course in each case the tower was partly injured, but the point is it did not fall down.

The proposed construction must of course depend for stability on the various guys. The longitudinal or ground wire guys must have a very much better clamp than any known type other than a heavy strain conductor clamp. The guys to ground depend on the guy anchorage and this seems a good occasion to inquire what relationship, if any, exists between the assumptions used to determine the strength of such anchorages and the assumptions demanded of a designer for wide base tower anchorages. The writer has claimed for many years that the foundation assumptions were all wrong or else the guy anchor figures were wrong.

What values will be permitted for the $1/r$ of the posts as a whole, the length being from crossarm to ground?

While the total weight of steel per structure may be less than for a wide base tower, its cost classification may be higher on account of the latticed masts, hinges, turnbuckles, and clevises.

The writer is inclined to think that the author has given the flat spacing a little the best of it compared to most of the horizontal separations for long span construction. In other words would a horizontal separation of 10 or 12 ft. be considered acceptable by the designers of the existing long span 110-kv. lines?

**P. H. Thomas:** Evidently Mr. Andrews has been thinking about this new type of tower. I am sorry we haven't more time for there are many interesting problems which have been pretty carefully studied but not touched upon. In regard to the first question as to how much we have to sacrifice in the strength of ground wires, when we omit individual longitudinal guys between anchored towers. That is more or less a matter of design within the control of the engineer. I have made about three very careful detailed designs of these towers for actual profiles and on the basis on which those have been worked out, I have assumed that the structure would have to stand one broken conductor on a six wire circuit with the maximum sleet and maximum wind, or maximum ground wire tension.

I made allowance of ten per cent in the stress on the conductor and the ground wire needs more strength which is secured by

using extra high strength strand. I should like to point out that the limiting stress was taken at the condition of maximum sleet and wind. I think if a census was taken it would be found that broken conductors occur nine-tenths of the time under other conditions and less than one-tenth of the time under these maximum loading conditions, so that in nearly every actual case additional reserve strength will be available. The set-up is this, the bridge which is held only by cables in the intermediate bridge is a very flexible structure. It adjusts its position without stress to the mean position of the various cables. It should be noted that if the bridge is allowed to pass excessively in one direction from neutral, the footing being fixed in position, there is an effect from the overhanging weight which causes a horizontal thrust on the footing.

The horizontal deflection of the crossarms when a break in a cable occurs produces a higher tension in cables on one side of the arm and a lower one on the other and it is the difference in these tensions which balances the stress due to the broken cable.

Answering the last question of Mr. Andrews as to why I have suggested that three consecutive unguyed towers is as many as is likely to be suitable, I will point out that the tightening up of cables which comes from the physical movement of the crossarms due to a broken conductor is divided between the spans between the break and the next stabilizer towers, that is between the moving crossarm and the first fixed point, and the more spans there are the less tightening is there in any one of them. Again the more the crossarms overhang the neutral position the greater is the tendency to accumulate additional cable stress due to its weight. I presume two unguyed towers in succession are more conservative than three but three is the maximum limit.

The question of the temperature is a very interesting one. After giving it a good deal of thought I believe it is not a matter which will cause practical difficulty. My suggestion is that when a stabilizer tower is set up the guys should be tightened until there is a very considerable stress in the guy. This does not weaken the power of the tower to resist the pull of a broken conductor unless this stress is more than one-half the elastic limit of the guy. In this case one guy is pulling against the other very tightly. When a broken conductor occurs it produces stress on the guy on the other side and the effect is to tighten up the far guy, that loosens the near guy and if the stress of the broken cable reaches the elastic limit of the guy on the far side the stress is substantially slacked off on the near guy and the full strength of the strained member in holding the broken conductor.

As to a convenient method of using solid rods for guys, my suggestion is to use a 25-foot unit rod with a butt-on forged on each end and some kind of open-sided socket in which the ends of two rods can be slipped, thus making a coupling between them. That type of construction is now in use on some of the Pennsylvania Railroad electrification and it seems a very feasible thing. In setting up a tower there may be specified for use an appropriate number of these 25-foot lengths and 12½-foot lengths for each guy, these guys being finally completed in the ground with a lot of assorted short lengths carried around by the erecting crew, the turnbuckle giving the final adjustment.

With such a construction and a U-bolt connection at the tower there is considerable flexibility and it will be found that the total elongation due to the flexibility of the connection and the stretch of the rod is considerably more than any effect due to the contraction by cold. Presumably there will be no change of length in the ground. The only effect of temperature would be the differential effect of the expansion of the steel in the post and of the steel in the guys. If the guys are longer there will of course be proportionately more expansion. While it is thus true that there will be a variation in the lengths of members due to temperature, I believe it will turn out they will not be taken into account practically.

In reply to Mr. Coombs, the paper is not intended to offer any criticism of the usual narrow base tower, merely to show that a material advantage can be obtained by the use of the new construction where the conditions do not require the other construction.

It should be noted that the duty on the cable clamps, either conductor or ground wire clamps, as the result of a broken cable is not very severe, since the stress on the clamp is only the difference in stress between the tight side and the loose side and further since the stress due to a broken ground wire is divided between two conductor clamps.

An examination of design detail shows that no special material is required for hinges or devices other than the usual plates and bolts. All the latticing of the posts can be done with two or at most three lengths of latticing, throwing these members into quantity production. A real cost advantage comes from the use of round rods for these have a lower base price than angles.

The matter of horizontal spacing has been fully discussed in the previous paper referred to and the spacings recommended are believed to be entirely conservative for these services.

# The Calculation of Alternator Swing Curves

## The Step-by-Step Method

BY F. R. LONGLEY*
Associate, A. I. E. E.

*Synopsis.—The paper is intended to give a thorough explanation of step-by-step calculations of the synchronous rotor oscillations and other transients, which occur in electrical power systems when faults or other sudden changes take place. It is divided essentially into two parts. In Part I a descriptive illustration of the phenomena is given in order that the reader may visualize the conditions. In Part II general formulas are developed for calculations where any number of salient or non-salient pole machines are operating at various points on an impedance network. In Appendix I a special and simplified example is set up and analyzed. In Appendices II and III the numerical calculations of the swing curve for the special example in Appendix I are given, and a brief discussion is offered on the accuracy of this step-by-step method of calculation.*

* * * * *

### Introduction

THIS paper is based on the method suggested in the paper *System Stability as a Design Problem*, by R. H. Park and E. H. Bancker.[2] Its purpose is to develop further the methods of making step-by-step calculations of the angular swings and other transient phenomena of synchronous machines in a power system following disturbances. Additional material from the paper *Progress in the Study of System Stability*, by I. H. Summers and J. B. McClure,[3] has been incorporated and the resulting methods have been worked out in great detail. The object of doing this is to make the theory and the practical procedure clear even to a novice, so that any engineer who finds it desirable will have at hand rules for making the calculations.

The synchronous machine formulas are based on the vector diagrams developed by Messrs. Doherty and Nickle in their series of papers[4] on synchronous machines and also as given by R. H. Park in his paper[5] on *Two-Reaction Theory*.

The need for this paper is indicated by the following review of the subject:

The two stability papers mentioned above are the only ones which, to the author's knowledge, give details of the procedure of making step-by-step stability calculations. The first mentioned paper covers a great deal of ground and suggests much of the material here presented, including the general procedure, but the information is given without much detail so that it is practically impossible for an engineer who does not have some additional information to use it. The second paper considers a special case which is often encountered and simplifies the work considerably. It gives instructions in precise detail for making calculations under the assumptions involved, and makes it possible for any interested engineer to make calculations, based on the assumption of constant rotor linkages, and equality of reactances in the direct and quadrature axes.

There are some cases, however, which do not fall into the class amenable to calculation by this method. In practise these are primarily the cases which involve variation of field excitation. It is to furnish detailed instructions for making these additional calculations that this paper is presented.

A careful descriptive illustration of the phenomena involved will be given first. This is followed by the development of general swing curve formulas for any number of salient pole machines having varying excitations and connected to an impedance network (resistances included). A special case is then taken and it is shown how the general formulas adapt themselves to it. Finally the numerical calculations of the swing curves for the special case are given. It will be seen later that this example represents a condition commonly encountered when problems of transient instability are found to exist in electrical power systems.

## Part I

### A Descriptive Illustration of the Phenomena Involved

A physical understanding of the manner in which the electrical quantities and rotor position of a synchronous alternator vary during and after a transient disturbance should add to the interest of the subject and aid readers to follow the mathematical analysis. These illustrations are descriptive only and form no part of the development of the swing curve formulas.

Two or more pieces of synchronous apparatus are stable as long as they remain in synchronism. When power is exchanged between a synchronous generator and motor an electrical angle $\delta$, exists between their rotors. Any transient disturbance will cause the rotors of rotating synchronous apparatus to oscillate or swing with respect to each other. Whether or not they remain in synchronism will depend upon the severity of the swings. The swings can be calculated by the step-by-step process, and are usually plotted to show the angle $\delta$ between rotors as a function of time.

This angle $\delta$ will depend among other things upon the excitation system used, the impedances of the system,

*Western Massachusetts Companies, Springfield, Mass. Formerly of the General Electric Co., Schenectady, N. Y.

2. For references see Bibliography.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

the character of the disturbance, the initial load, and the governor characteristics.

All quantities in this paper will be expressed in per units[8] unless otherwise stated. Per units are decimal percentages. They are percentages without the multiplier of 100 and are used in place of percentages because they make it unnecessary to watch for, and correct for, coefficients of 100 when calculations are being made.

Let us consider two large salient pole alternators synchronized through a reactive tie over which a steady

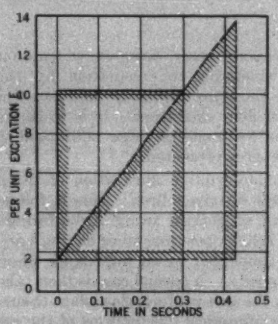


Fig. 1—Two Types of Super Excitation

Case I in solid lines. Case II in broken lines

power flows from one to the other, and let this tie be suddenly weakened by a single-phase fault.

The effect of excitation will be demonstrated on a magnified scale by applying the type often referred to as "super-excitation."[10]

In order to illustrate the effect of the *rate* of excitation rise, two types of "super-excitation" are used, and the effect of each of these two types is shown separately. Upon application of the fault the excitation in one case rises instantly from 156 volts to a ceiling (maximum value) of 1000 volts, or in per units from 1.59 to 10.2; while in the other case it rises from 156 volts to 1350 volts at a rate of 2810 volts per sec., or in per units from 1.59 to 13.77.

The rise in volt-seconds* is the same in each case and is that shown by the shaded areas in Fig. 1. The curves resulting from the instantaneous rise in excitation are in solid lines, and will be referred to as Case I, while those resulting from the excitation rise at the rate of 2810 volts per second are in dotted lines, and will be referred to as Case II.

As explained in Appendix I of Bibliography 1, a given rise in volt seconds will produce very closely a proportional rise in the field flux of large alternators during the first half second, no matter how applied.

The more quickly the volt-seconds are applied, the greater the stability. The stability, during a fault, is not a function of the rate of excitation rise alone, nor of the excitation ceiling, alone. It is a function of both these conditions, expressed together as volt-seconds.

If, at the instant the fault is applied, the alternator field flux linkages $\Psi_d$ could rise instantly to the proper value, there would be no swing of the rotors whatsoever. This required rise in flux, for the example used here is shown by the dashed curve in Fig. 2.

An instantaneous rise in alternator flux is impossible but the nearer it is approached the greater will be the stability. Fig. 2 shows that the solid curve approaches this condition more nearly than the dotted line. Both finally arrive at the same flux when their volt-seconds become the same, at 0.3 sec. and 0.425 sec., respectively, as shown by Fig. 1, but the dotted line gives the rotor more time to swing before it is stiffened by the rise in flux.

The electrical torque $T_e$ is proportional to the field

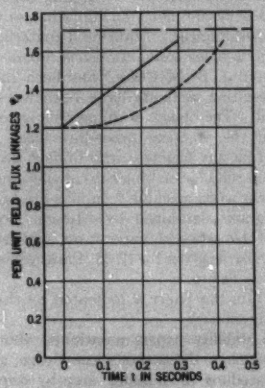


Fig. 2—Field Flux Linkages Produced by Excitation in Fig. 1

Case I in solid lines. Case II in broken lines. Curve in long dashes shows field flux linkages required for perfect stability

flux, and is a function of the rotor angle $\delta$. If this flux remains constant, the relation between $T_e$ and $\delta$ is shown in Fig. 3, by Curve $A$ when there is no fault, and by Curve $B$ during the fault. Both Curves $A$ and $B$ will change when the field flux linkages $\Psi_d$ change.

Before the fault occurs the electrical torque is $T_1$, Fig. 3, and neglecting resistance and machine losses, it is also the torque applied to the generator shaft. The prime mover torque may often be considered constant during the transient, as shown by the horizontal line $T_1$ in Fig. 3. This is especially true of waterwheel units with their large sluggish governors.

Before the fault occurs, the torque-angle characteristic is Curve $A$, the torque is 2.38, and the generator

*Appendix I of Bibliography 1.

is operating at point $a$, a rotor angle of 35.7 deg. The moment the fault is applied, the torque angle characteristic drops to curve $B$ and the electrical torque drops to point $b$. The difference between input and output torque $(T_1 - T_e) = T_a$ is $a\,b$. The excess torque, $a\,b$, is applied to the generator rotor and moves it toward a new angle of 56 deg. at point $c$ where $T_e$ becomes again equal to $T_1$.

A magnified view of the curves within the dotted rectangle, Fig. 3, is shown in Fig. 4.

If there is no change in field flux, the rotor will move along Curve $B$. In swinging from $b$ to $c$, the rotor

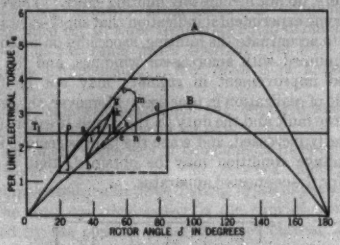


FIG. 3—ELECTRICAL TORQUE BETWEEN GENERATOR AND MOTOR, SHOWN AS A FUNCTION OF THE ELECTRICAL ANGLE BETWEEN THE ROTOR AXES

receives an acceleration which forces it to swing past $c$ to the position $d$, an angle of 80 deg. This limit, $d$, of the rotor swing is determined by the areas $a\,b\,c$ and $c\,d\,e$, which must be equal.[2] An area in Figs. 3 or 4, is the product of $T_e$ and $\delta$, and is therefore energy. The area $a\,b\,c$ is the energy input to the rotor, produced by the excess of input over output torque. If the machine is to remain in step, this same energy must be given up by the rotor, and this is done when the rotor swings from $c$ to $d$, giving to the system the energy represented by the area $c\,d\,e$.

Neglecting losses and possible hunting of the governor, the rotor will continue to oscillate between positions $b$ and $d$ until some new transient, such as a removal of the fault, takes place.

If the excitation for case I is applied when the fault occurs, the section $b\,d$ of Curve $B$ changes to $b\,g$. The energy input to the rotor is $a\,b\,f$, while the equal energy given up by the rotor is $f\,g\,h$.

The maximum swing of the rotor is at $g$, an angle of 53 deg. There appears to be no need to increase the field current after the maximum angle has been reached. It is assumed that the regulating equipment planned for this type of excitation would hold this maximum field current constant until the fault has been removed or other conditions warrant its reduction, except that the average field current held after the point $g$ has been reached would be about 5 per cent less than that which would actually exist at point $g$.

Under these conditions, the rotor will swing back along the smooth Curve $g\,i\,j$ where area $i\,j\,p$ is equal to area $i\,g\,h$. In the next forward swing, since the field current is slightly lower than that which existed at $g$, the rotor will move along the curve $j\,i\,k$, where area $i\,k\,h$ is equal to area $i\,j\,p$. The rotor will then continue to oscillate between positions $j$ and $k$ in the same manner as previously described under constant flux conditions for the oscillation between $b$ and $d$.

For the excitation described in Case II, the rotor will swing along curve $b\,l\,m$ where area $l\,m\,n$ is equal to area $a\,b\,l$. The maximum angle in this case is seen to be 66 deg., but since the excitation is permitted to continue rising as shown by the dotted curve, Fig. 1, the field current and, therefore, the field flux is permitted to continue rising after the maximum angle has been reached, and the motor starts its return swing along $m\,o$ instead of along a curve similar to $g\,i\,j$.

Figs. 3 and 4 give the angular swings as functions of the torque but not as functions of time. It is interesting to see how these quantities vary with time.

In Fig. 5, the difference between input and output torques is plotted as a function of time. Its initial value is $a\,b = 0.773$, the same as $a\,b$ in Figs. 3 and 4. An area in Fig. 5, is the product of torque and time and

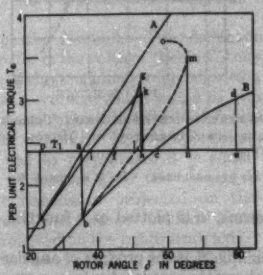


FIG. 4—ELECTRICAL TORQUE BETWEEN GENERATOR AND MOTOR, SHOWN AS A FUNCTION OF THE ELECTRICAL ANGLE BETWEEN THE ROTOR AXES

is, therefore, an impulse. But impulse is equal to momentum and:

$$M\,w = \int T_a\,d\,t \tag{1}$$

where

$t$ = time.
$w$ = departure from synchronous speed.
$M$ = inertia.
$T_a$ = accelerating torque = $a\,b$.

From (1)

$$w = \frac{1}{M} \int T_a\,d\,t \tag{2}$$

The integral term $\int T_a\,d\,t$ is the area shown shaded in Fig. 5. When the positive and negative areas become equal, the total area is zero and $w$ is zero. At the

moment when $w$ is zero, the rotor has come to rest and is ready for its return swing. The rotor comes to rest on its outward swing at its maximum angular position, which from Fig. 5, occurs at 0.295 sec. and 0.3625 sec. for Cases I and II respectively.

Integrating the shaded areas in Fig. 5, gives the departure from synchronous speed as shown by (2).

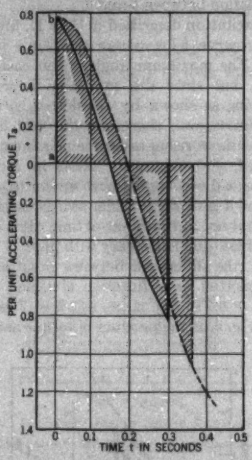


FIG. 5—DIFFERENCE BETWEEN SHAFT TORQUE AND ELECTRICAL TORQUE ON GENERATOR OR MOTOR, SHOWN AS A FUNCTION OF TIME

Case I in solid lines. Case II in broken lines

By this means, $w$ is plotted as a function of time in Fig. 6.

An area in Fig. 6 is the product of angular speed and time and is therefore angular displacement, or

$$\delta = \int w \, d t \qquad (3)$$

where

$\delta$ = angular displacement of the generator rotor from its initial position.

The maximum values of $\delta$ occur when the shaded areas in Fig. 6 are positive maximums, and this is seen to occur when $w$ crosses the zero axis at 0.295 sec. and 0.3625 sec. for Cases I and II, respectively.

Performing the integration of (3) by taking the shaded areas in Fig. 6, the angular swings of the rotor are obtained as a function of time, and adding to these angles the initial angle of 35.7 deg. gives the total rotor displacement as a function of time.

The angular swing curves thus obtained are plotted in Fig. 7, where it is seen again that the maximum swings of 53 deg. and 66 deg. occur at 0.295 sec. and 0.3625 sec. for Cases I and II, respectively. It is readily seen that the rotor displacement is greater in Case II than in Case I, and that the excitation for Case I provides the greater stability during the first swing.

The "super-excitation" used in this illustration produces a large and rapid increase in the alternator field flux, and stiffens the machine so that both the magnitude of the rotor swings and the oscillation period are smaller than that which results when less drastic forms of excitation are used.

From the standpoint of system operation and stability after the fault has been removed, the actual use of super-excitation on generators is a mooted question. These calculations include only the first swing and, therefore, do not include any hunting effect. There has been some experimental indication that super-excitation tends to accentuate the hunting, especially on machines not equipped with amortisseur windings, and the calculated improvement in stability may not be fully capable of realization in practise. Moreover, the severity of the fault and the duty on the circuit breakers may be greatly increased, and when the fault is removed, an overvoltage condition may be obtained, that is too great for the connected apparatus.

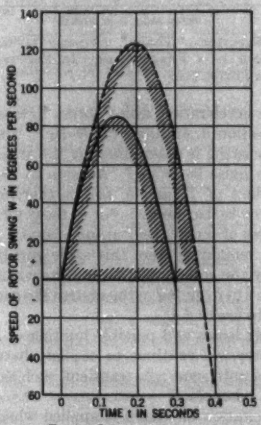


FIG. 6—SPEED OF ROTOR OSCILLATIONS, SHOWN AS A FUNCTION OF TIME

Case I in solid lines. Case II in broken lines

On the other hand, these considerations may not be found sufficiently important to outweigh the advantages of the scheme, especially when the machine having "super-excitation" is also provided with low resistance amortisseur windings.

## Part II

### DEVELOPMENT OF GENERAL SWING CURVE FORMULAS

*The Impedance Network of the System.* A balanced three-phase shunt impedance may be switched across

a three-phase circuit at any point where a fault is considered to occur, producing a flow of balanced three-phase power which is exactly equal in magnitude to the flow of power, balanced or unbalanced, resulting from a balanced or unbalanced fault. By the method of "Symmetrical Components"[3,4] any set of three-phase currents, or voltages, balanced or unbalanced, can be divided into three sets of three-phase symmetrical components. One set is balanced and revolves in a positive direction (the positive phase sequence components). The second is balanced and revolves in a positive direction with the sequence of the phases reversed (the negative phase sequence components). In the third set all three vectors are equal in magnitude and lie in the same phase position (the zero phase sequence components). They revolve in a positive direction.

Under balanced conditions the negative and zero phase sequence components are zero.

Each of the three sets of components meets its own particular impedances in the network joining the machines resulting in three distinct types of networks.

The total electrical power is the sum of that produced by the positive phase sequence current flowing

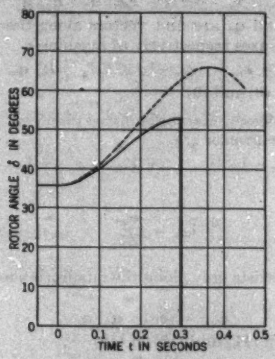


Fig. 7—Electrical Angle between Rotor Axes of Generator and Motor, shown as a Function of Time

Case I in solid lines. Case II in broken lines

in the positive phase sequence network, the negative phase sequence current flowing in the negative phase sequence network, and the zero phase sequence current flowing in the zero phase sequence network.

The balanced network which gives a flow of power equal in magnitude to that resulting from a fault, balanced or unbalanced, is obtained by placing a balanced three-phase impedance **Z** at the point of fault. Where

$$\mathbf{Z} = \mathbf{Z}_n + \mathbf{Z}_z \tag{4}$$

if the fault is from one conductor to ground.

$$\mathbf{Z} = \mathbf{Z}_n \tag{5}$$

if the fault is between two conductors.

$$\mathbf{Z} = \frac{\mathbf{Z}_n\,\mathbf{Z}_z}{\mathbf{Z}_n + \mathbf{Z}_z} \tag{6}$$

if the fault is from two conductors to ground.

$$\mathbf{Z} = 0 \tag{7}$$

if the fault is between all three conductors.

$\mathbf{Z}_n$ = Total negative phase sequence impedance of the system, viewed from the point of fault.

$\mathbf{Z}_z$ = Total zero phase sequence impedance of the system viewed from the point of fault.

*The Relations between the Electrical Quantities of All*

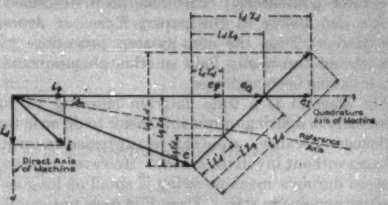


Fig. 8—Vector Diagram of Stator Voltages and Current of a Synchronous Alternator

*Machines on the Network.* The excitation voltage $\mathbf{e}_i$ of an alternator is the voltage "behind" the synchronous impedance of the machine projected on the quadrature axis. It is the voltage which would be generated at no load and no saturation when the load field current flows in the rotor winding. It is proportional to the field current $I$ and in percentages it is equal to the field current $I$. Likewise $\mathbf{e}_Q$ is the voltage "behind" the quadrature impedance projected on the quadrature axis, and $\mathbf{e}_\psi$ is the voltage "behind" the transient impedance projected on the quadrature axis.

The direct component $\Psi_d$ of the field flux linkages is proportional to $\mathbf{e}_\psi$.

The slip ring voltage is $E$.

The stator terminal voltage is $\mathbf{e}$.

The stator current is $\mathbf{i}$. Its projection on the quadrature axis is the quadrature component $\mathbf{i}_q$ and its projection on the direct axis is the direct component $\mathbf{i}_d$.

Unit terminal voltage may be any value decided on but is usually taken as the rated voltage of the machine.

Unit field current is the field current which will produce unit stator voltage at unit speed (taken here as rated speed of the machine) at no saturation and at no load.

Unit field flux linkage is the field flux linkage which will produce unit stator voltage at rated speed and at no load.

Unit slip ring voltage is the slip ring voltage required to give unit field current under steady state conditions.

Unit power is the base power selected.

Fig. 8 is a vector diagram showing voltages and currents for any one machine. Its quadrature axis is

designated by $q$ and its direct axis is designated by $d$. The diagram is a true time diagram of stator voltages and currents, and is sufficient to calculate the flow of power into or out of any of the machines on the network.

The machines are assumed to have zero time constants in their quadrature axes.

It will be seen that this diagram is the same as that derived by Park in his paper on *Two-Reaction Theory*[9] except that resistance in the machine has been neglected, and voltage due to the rate of change of linkages $\Psi$ has been neglected. Practically these quantities are negligible in most cases. A notable example is that of "negative damping," a phenomenon involving cumulative rotor oscillations. This has been described by Nickle and Pierce in the paper, *Effect of Armature Resistance*.[13] Thus the step-by-step procedure given here cannot throw any light on this phenomenon, its causes having been neglected.

The diagram is a time diagram showing voltages. Practically in figuring torque it is easier to do so in terms of linkages, because torque can be expressed in terms of linkages without involving speed. However, the change in speed during a machine swing is small as long as the machine remains in step. Even if it were not small the correct torque could be obtained by using linkages instead of voltages. For purposes of making the formulas consistent with the usual conception of flow of current due to voltages, they are expressed in terms of voltage with the understanding that the magnitude of the voltages used is taken proportional to linkages in order to minimize the errors. When this is done there would be no error due to change in speed if there were no resistance involved. Practically the error due to the presence of resistance is very small. An illustration of this is the familiar phenomenon of the steady short circuit current of an alternator remaining constant as the speed drops to a low value, though the generated voltage is proportional to speed. The linkages are constant, so the current is constant, because the resistance is negligible.

Consider any $s$ number of synchronous machines connected to an impedance network and let the machines be designated by the numbers 1, 2, 3, 4 . . . $s$.

Currents flowing from a machine will be taken as positive while currents flowing into a machine will be taken as negative.

The subscripts have the following significances:

When one subscript only occurs it designates the machine to which the quantity having the subscript applies.

For stator currents $\mathbf{i}$ the first subscript designates the machine from which the current is flowing while the second subscript designates the machine into which the current is flowing. For impedances $\mathbf{Z}$ two duplicate subscripts designate the driving point impedance of the machine designated by the subscripts, while two unlike subscripts designate the transfer impedance between the machines designated by subscripts.

The driving point impedance is the total impedance of the system from the point taken. The transfer impedance is the impedance between any two machines. Thus $\mathbf{Z}_{11}$ is the driving point impedance of machine No. 1, while $\mathbf{Z}_{21}$ is the transfer impedance between machines 1 and 2.

A rotor angle $\delta$ having only one subscript is the angle between the rotor axis of the machine designated by the subscript, and the reference vector. A rotor angle $\delta$ having two subscripts is the angle between the rotor axes of the two machines designated by the two subscripts and is mathematically equal to the angle between the rotor of the machine designated by the first subscript and the reference vector, minus the angle between the rotor of the machine designated by the second subscript and the reference vector.

The angle $\theta$ is an impedance angle and the subscripts of $\theta$ are the same as those of the impedance $\mathbf{Z}$ to which $\theta$ applies.

The movement of the rotor of each machine will be measured from some arbitrary reference vector.

Formulas will be written for the $n$th machine.

From Fig. 8 the following relations may be obtained.

$$\mathbf{e}_{Qn} = \mathbf{e}_{1n} - (x_{dn} - x_{qn})\,(\mathbf{i}_n \cdot \mathbf{d}_n)\,\mathbf{q}_n \tag{8}$$

where $\mathbf{d}_n$ and $\mathbf{q}_n$ are unit vectors along the direct and quadrature axes respectively of machine $n$.

$$\mathbf{e}_{\Psi n} = \mathbf{e}_{1n} - (x_{dn} - x_{dn}')\,(\mathbf{i}_n \cdot \mathbf{d}_n)\,\mathbf{q}_n \tag{9}$$

Combining (8) and (9)

$$\mathbf{e}_{\Psi n} = \mathbf{e}_{Qn} - (x_{qn} - x_{dn}')\,(\mathbf{i}_n \cdot \mathbf{d}_n)\,\mathbf{q}_n \tag{10}$$

The stator currents[8] are

$$\mathbf{i}_n = -\,\mathbf{i}_{1n} - \mathbf{i}_{2n} \;.\;.\;.\; + \mathbf{i}_{nn} \;.\;.\;.\; - \mathbf{i}_{sn} \tag{11}$$

where

$$\mathbf{i}_{mn} = \frac{\mathbf{e}_{Qm}}{\mathbf{Z}_{mn}} \tag{12}$$

Since $\mathbf{e}_Q$ exists only along the quadrature axis we may also write

$$\mathbf{e}_{Qn} = (\mathbf{e}_{Qn} \cdot \mathbf{q}_n)\,\mathbf{q}_n \tag{13}$$

Substituting (11) and (12) in (10)

$$\mathbf{e}_{\Psi n} = \mathbf{e}_{Qn} - \left[ (x_{qn} - x_{dn}') \left( \frac{\mathbf{e}_{Qn}}{\mathbf{Z}_{nn}} \;.\;.\;.\; - \frac{\mathbf{e}_{Q1}}{\mathbf{Z}_{1n}} \;.\;.\;.\; - \frac{\mathbf{e}_{Qs}}{\mathbf{Z}_{sn}} \right) \cdot \mathbf{d}_n \right] \mathbf{q}_n \tag{14}$$

Let

$$\theta_{mn} = \text{impedance angle of } \mathbf{Z}_{mn} \tag{15}$$

$$\alpha_{mn} = 90^\circ - \theta_{mn} \tag{16}$$

$$\delta_m = \text{angle of } e_{Qm} \text{ with the reference axis} \tag{17}$$

$$\delta_{mn} = \delta_m - \delta_n \tag{18}$$

Then

$$\left[ \left( \frac{\mathbf{e}_{Qm}}{\mathbf{Z}_{mn}} \cdot \mathbf{d}_n \right) \mathbf{q}_n \right] \cdot \mathbf{q}_n$$

$$= \frac{e_{Qm}}{Z_{mn}} \operatorname{Cos}(\delta_{mn} + 90^\circ - \theta_{mn})$$

$$= \frac{e_{Qm}}{Z_{mn}} \operatorname{Cos}(\delta_{mn} + \alpha_{mn}) \tag{19}$$

Therefore we may write:

$$\frac{e_{\varphi n}}{x_{qn} - x_{dn}'} = \left[ \frac{1}{x_{qn} - x_{dn}'} - \frac{\operatorname{Cos}\alpha_{nn}}{Z_{nn}} \right] e_{Qn}$$

$$+ \sum_{m=1}^{m=n-1} \frac{e_{Qm}}{Z_{mn}} \operatorname{Cos}(\delta_{mn} + \alpha_{mn})$$

$$+ \sum_{m=n+1}^{m=s} \frac{e_{Qm}}{Z_{nm}} \operatorname{Cos}(\delta_{nm} - \alpha_{nm}) \tag{20}$$

This is the equation for the $n$th machine out of $s$, with $m$ representing all the other machines. There is a total of $s$ equations like this, one for each machine.

Now the torque may be taken

$$T_{en} = \mathbf{e}_{Qn} \cdot \mathbf{i}_n \tag{21}$$

Substituting

$$T_{en} = \frac{e_{Qn}^2}{Z_{nn}} \operatorname{Sin}\alpha_{nn} - \sum_{m=1}^{m=n-1} \frac{e_{Qm}\, e_{Qn}}{Z_{mn}} \operatorname{Sin}(\delta_{mn} + \alpha_{mn})$$

$$+ \sum_{m=n+1}^{m=s} \frac{e_{Qn}\, e_{Qm}}{Z_{nm}} \operatorname{Sin}(\delta_{nm} - \alpha_{nm}) \tag{22}$$

In order to simplify writing the equations let

$$\frac{e_{\varphi n}}{x_{qn} - x_{dn}'} = W_n \tag{23}$$

$$\frac{1}{x_{qn} - x_{dn}'} - \frac{\operatorname{Cos}\alpha_{nn}}{Z_{nn}} = \mu_n \tag{24}$$

$$\frac{\operatorname{Cos}(\delta_{mn} - \alpha_{mn})}{Z_{mn}} = A_{mn} \tag{25}$$

$$\frac{\operatorname{Cos}(\delta_{mn} + \alpha_{mn})}{Z_{mn}} = B_{mn} \tag{26}$$

Then Equations (27) may be written

$$\left.\begin{aligned} W_1 &= \mu_1 e_{Q1} + A_{12} e_{Q2} + \ldots A_{1s} e_{Qs} \\ W_2 &= B_{12} e_{Q1} + \mu_2 e_{Q2} + \ldots A_{2s} e_{Qs} \\ &\ldots\ldots\ldots\ldots\ldots\ldots \\ W_s &= B_{1s} e_{Q1} + B_{2s} e_{Q2} + \ldots \mu_s e_{Qs} \end{aligned}\right\} \tag{27}$$

and solved

$$e_{Qn} = \frac{\begin{vmatrix} \mu_1 & \ldots & W_1 & \ldots & A_{1s} \\ B_{12} & \ldots & W_2 & \ldots & A_{2s} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ B_{1s} & \ldots & W_s & \ldots & \mu_s \end{vmatrix}}{\begin{vmatrix} \mu_1 & A_{12} & A_{13} & \ldots & A_{1s} \\ B_{12} & \mu_2 & A_{23} & \ldots & A_{2s} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ B_{1s} & B_{2s} & B_{3s} & \ldots & \mu_s \end{vmatrix}} \tag{28}$$

where the $W$ column replaces the $n$th column in the numerator.

*The Open Circuit Time Constant of a Synchronous Alternator.* This time constant $T_o$ may be calculated from the design constants of the machine, or it may be obtained experimentally by a number of methods. The following is suggested.

With the machine running at normal speed, and with its stator open circuited, build up the stator voltage to about half the rated voltage of the alternator. Let this voltage be $e_1$.

When $e_1$ becomes constant, suddenly short circuit the slip rings (a resistance should be placed between the slip rings and exciter armature to prevent short circuiting the exciter) and take an oscillograph record of the change in the stator voltage. This voltage will be:

$$e = e_1 \epsilon^{-\frac{t}{T_o}} + e_o \tag{29}$$

where $e_o$ is the residual stator voltage.

When $t = T_o$

$$e = \frac{e_1}{\epsilon} + e_o = 0.368\, e_1 + e_o \tag{30}$$

The time in seconds required for $e$ to drop from $e_1$ to the value given by (30) is $T_o$.

*The Per Unit Inertia Constant.* The swing of the rotors is a function of their $W R^2$ s. In the per unit system the $W R^2$ must be converted to an inertia constant $M$.

Apply unit torque $T_u$ to the rotor when it is at rest, until the machine reaches unit speed.

$$T_u = M \frac{d\,W}{d\,t} \tag{31}$$

where

$W$ is per unit angular speed of the rotor, $t$ is time, and $M$ is a constant.

Integrating

$$t = \frac{M}{T_u} \int_0^1 d\,W = \frac{M}{T_u} \tag{32}$$

but $T_u$ is unity and therefore

$$t = M \tag{33}$$

Therefore $M$ is the time in seconds required to bring the machine from rest to unit speed when unit torque is applied to the shaft. With this definition the value of $M$ in terms of the $W R^2$ may be obtained.

Let

$\mathfrak{T}$ = rotor torque in ft-lb.
$\omega$ = rotor speed in radians per second
$t$ = time in seconds
$g$ = acceleration of gravity

$$\mathfrak{T}_u = \frac{W R^2}{g} \frac{d\,\omega}{d\,t} \tag{34}$$

$$t = \frac{W R^2}{\mathfrak{I}_u g} \int_0^{\omega_u} d\,\omega \tag{35}$$

where $\mathfrak{I}_u$ is the torque required to give unit or base power at rated or unit speed, and $\omega_u$ is the speed of the rotor in radians per second at rated speed. Under these conditions $t = M$ and integrating (35)

$$M = \frac{W R^2\ \omega_u}{\mathfrak{I}_u g} = \frac{W R^2 (\omega_u)^2}{g P_u} \tag{36}$$

where $P_u$ is unit or base power in ft-lb. per sec. It is convenient to change $P_u$ to base $K W$ and substituting the proper constants (36) becomes

$$M = \frac{(W R^2)\left(\frac{2\pi n}{60}\right)^2}{(32.2)\ (\text{Base } K W)\ (737.6)}$$

$$= \frac{0.462\ (W R^2)\left(\frac{n}{1000}\right)^2}{\text{Base } K W} \tag{37}$$

where $n$ is the rated speed of the machine in rev. per min. and $W R^2$ is the weight in pounds of the rotating part times the square of its radius of gyration.

Where two or more machines are assumed to swing together and thus behave as a single unit, the inertia constant $M$ of this fictitious unit is the sum of the inertia constants of the individual units which it represents.

*Calculation of the Change in Rotor Angle during Any One of the Step-by-Step[2] Intervals of Time.* Let the electrical torque $T_{en}$ change suddenly at the instant $n$ from $T_{en}'$ to $T_{en}''$. It is assumed that $T_{en}'$ is constant from the instant $n - 1/2$ to $n$, a total time of $\frac{\Delta t}{2}$, and that $T_{en}''$ is constant from $n$ to $n + 1/2$, a total time of $\frac{\Delta t}{2}$. Thus $T_{en}'$ produces an average change $\Delta S_{(n-1/4)}$ in speed during a time $\frac{\Delta t}{2}$, and $T_{en}''$ produces an average change $\Delta S_{(n+1/4)}$ in speed during a time $\frac{\Delta t}{2}$.

Remembering that the increment of time during which $T_{en}'$ or $T_{en}''$ is applied is $\frac{\Delta t}{2}$ we have

$$\Delta S_{(n-1/4)} = \frac{\Delta t}{2\,M}(T_1 - T_{en}') \tag{38}$$

and

$$\Delta S_{(n+1/4)} = \frac{\Delta t}{2\,M}(T_1 - T_{en}'') \tag{39}$$

where $T_1$ is the mechanical torque applied to the shaft at the instant $n$.

At the instant $(n + 1/2)$ the speed is:

$$S_{(n+1/2)} = S_{(n-1/2)} + \Delta S_{(n-1/4)} + \Delta S_{(n+1/4)} \tag{40}$$

Substituting (38) and (39) in (40)

$$S_{(n+1/2)} = S_{(n-1/2)} + \frac{\Delta t}{M}\left(T_1 - \frac{T_{en}' + T_{en}''}{2}\right) \tag{41}$$

The rotor angle $\delta$ at the instant $n + 1$ is:

$$\delta_{(n+1)} = \delta_n + \Delta\,\delta_{(n+1)} \tag{42}$$

Where $\Delta\,\delta_{(n+1)}$ is the increase in $\delta$ at the instant $(n + 1)$

The average speed between the instants $n$ and $(n + 1)$ is:

$$S_{(n+1/2)} = \frac{\Delta\,\delta_{(n+1)}}{\Delta t} \tag{43}$$

which is the slope of the angle time curve between the instants $n$ and $(n + 1)$.

Rearranging (43)

$$\Delta\,\delta_{(n+1)} = (\Delta t)\,S_{(n+1/2)} \tag{44}$$

Substituting (41) in (44)

$$\Delta\,\delta_{(n+1)} = (\Delta t)\,S_{(n-1/2)} + \frac{(\Delta t)^2}{M}\left(T_1 - \frac{T_{en}' + T_{en}''}{2}\right) \tag{45}$$

From (44)

$$\Delta\,\delta_n = (\Delta t)\,S_{(n-1/2)} \tag{35}$$

Substituting (46) in (45)

$$\Delta\,\delta_{(n+1)} = \Delta\,\delta_n + \frac{(\Delta t)^2}{M}\left(T_1 - \frac{T_{en}' + T_{en}''}{2}\right) \tag{47}$$

Since all terms in (47) are per unit quantities the term $\frac{(\Delta t)^2}{M}\left(T_1 - \frac{T_{en}' + T_{en}''}{2}\right)$ is a per unit angle. Unit angle is the electrical angle through which the rotor moves at normal or unit speed in unit time or one second. Hence:

$$\text{Unit angle} = 360\,f \text{ degrees} \tag{48}$$

where $f$ = normal frequency.

If (47) is to be in degrees we have from (48),

$$\Delta\,\delta_{(n+1)} = \Delta\,\delta_n + \frac{360\,f\,(\Delta t)^2}{M}\left(T_1 - \frac{T_{en}' + T_{en}''}{2}\right) \tag{49}$$

Letting

$$\frac{360\,f\,(\Delta t)^2}{M} = k \tag{50}$$

(49) becomes:

$$\Delta\,\delta_{(n+1)} = \Delta\,\delta_n + k\left(T_1 - \frac{T_{en}' + T_{en}''}{2}\right) \tag{51}$$

It is convenient to let the accelerating torque $\left(T_1 - \frac{T_{en}' + T_{en}''}{2}\right)$ in (51) be

$$\left( T_1 - \frac{T_{en}' + T_{en}''}{2} \right) = T_{en} \tag{52}$$

and (51) becomes:

$$\Delta \delta_{(n+1)} = \Delta \delta_n + k\, T_{en} \tag{53}$$

When there is no discontinuous change in $T_{en}$ we have $T_{en} = T_{en}' = T_{en}''$ and (52) becomes $(T_1 - T_{en})$; whence (51) becomes:

$$\Delta \delta_{(n+1)} = \Delta \delta_n + k\, (T_1 - T_{en}) \tag{54}$$

The swing starts as the result of a discontinuous change in $T_{en}$. Under these conditions $\Delta \delta_n = \Delta \delta_o = 0$, $T_{en}' = T_1$, $T_{en}'' = T_{en}$, and $\Delta \delta_{(n+1)} = \Delta \delta_1$, whence (51) becomes

$$\Delta \delta_1 = \frac{k}{2}\, (T_1 - T_{en}) \tag{55}$$

Any change in the governor position changes $T_1$ and $T_1$ may be altered accordingly if the governor characteristics are known. If electrical damping occurs, such as would be produced by an amortisseur winding, it may be included as shown by R. H. Park and E. H. Bancker in Appendix XII of Bibliography 2. The derivations of (54) and (55), which are special forms of (51), are also given in Appendix XII of Bibliography 2.

In calculating the swing curve (55) is used for the first step, (54) is used for subsequent steps until switching or the removal of the fault, or both take place, when (51) is used for the first step following the change in $T_{en}$, after which (54) is used again in the subsequent steps until another discontinuous change takes place in $T_{en}$ when (51) is again used as described above, and so on.

*Procedure for the Calculation of the Swing Curves.* The procedure for making a step-by-step calculation may be summed up as follows:

I. Determine $e_{Q1}\, e_{Q2} \ldots e_{Qs}$ and $\delta_1\, \delta_2 \ldots \delta_s$ from steady state conditions before the fault is applied in the same manner that steady state voltages are usually found, considering that $e_Q$ is the voltage existing behind the quadrature reactance of the machine.

II. Find $e_{\varphi n}$ before the fault is applied from Equation (20).

III. Apply fault and determine new driving point and transfer impedances.

IV. Determine new value of $e_{Qn}$ from (28), letting $e_{\varphi n}$ remain constant and using new values of impedances. Later when this step is repeated after an angle change the new angles are used instead of the new impedances.

V. Find $T_{en}$ from (22) using $e_{Qn}$ just obtained.

VI. Determine $e_{in}$ from

$$e_{in} = e_{Qn} \left( \frac{x_{dn} - x_{dn}'}{x_{qn} - x_{dn}'} \right) - e_{\varphi n} \left( \frac{x_{dn} - x_{qn}}{x_{qn} - x_{dn}'} \right) \tag{56}$$

This formula is obtained by combining (8) and (9)

VII. Calculate change in $e_{\varphi n}$ from

$$\Delta e_{\varphi n} = \frac{(E_n - e_{in})\, \Delta t}{T_{en}} \tag{57}$$

where $\Delta t$ is the increment of time used for one step; $E_n$ is the average slip ring volts, during the $\Delta t$ considered; $e_{in}$ is the value of the synchronous stator voltage at the beginning of the $\Delta t$ considered; $T_{en}$ is the open circuit time constant of the machine; and $\Delta e_{\varphi n}$ is the change which takes place in $e_{\varphi n}$ during the $\Delta t$ considered.

This formula[8] comes directly from the well known relation that the applied voltage is equal to the resistance drop plus the inductive drop, the quantities being all in per unit values.

VIII. Calculate new value of $e_{\varphi n}$ from $e_{\varphi n}$ found in II and $\Delta e_{\varphi n}$ found in VII.

$$e_{\varphi n} = e_{\varphi n} + \Delta e_{\varphi n} \tag{58}$$

new II. VII.

IX. Calculate change in angle from (55). The other angular changes are to be calculated as explained in the discussion of (55), (54), and (51).

X. Allow the angle to shift and repeat IV to X.

Appendices I and II of the paper will be devoted to illustrating the procedure by means of a special example. The general procedure is modified in this special case for convenience in illustrating fully each step.

ACKNOWLEDGMENT

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## Appendix I

### THE ANALYSIS OF A SIMPLIFIED CASE

*The Arrangement of the System to be Studied.* The system to be studied usually consists of a network of transmission lines with step-up and step-down transformers at various points where power is supplied to the system or delivered to load centers. While practically all contributing factors affecting the swings of alternator rotors can be included in the step-by-step method, certain reasonable assumptions will greatly simplify and reduce the amount of work required in the calculations.

When the stability of a given generating plant is being considered, it is often possible to reduce the power system to a single generator feeding power through an impedance to a single equivalent motor. These generators may be waterwheel units with quick response excitation. Their salient pole characteristics and the effect of changes in their excitation will be included in the calculations. The single equivalent motor represents the system that is fed by the generating station

and may be condensed to one equivalent round rotor machine whose transient reactance is equal to that of the system as viewed from the point of fault and having a constant voltage behind its reactance. When the machines in the generating plant are similar in characteristics they will all behave in a similar manner and the entire generating station may be treated as a single machine.

It is assumed that a hydroelectric generating station feeds power to a system over two paralleled transmission lines. At the terminals of the transmission lines are transformer banks with the neutrals of their high-voltage windings solidly grounded. A single conductor to ground fault is taken on one of the lines and near the high-voltage bus of the generating station. The generators are essentially duplicates and are treated as a single equivalent machine. It is assumed that the resistances are small enough to neglect, and reactances only are considered.

It is not probable that the gate opening of the water-wheels will be able to change much in one or two seconds and the driving torque applied to the shaft of the generators is, therefore, assumed constant for this length of time. The load on the equivalent motor is likewise assumed constant.

The reactances of the "set up" with the shunt $x$ which represents the fault condition, are shown in Fig. 9.

The value of $x$ is obtained from (4).

The voltage (assumed constant) of the motor is $e_{\psi b}$.

There is no generated voltage in the negative or zero phase sequence networks and since there is no resistance, there is no power in these two networks. The only electrical power, then, is that produced by the positive

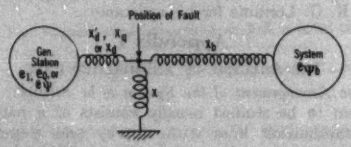


Fig. 9—Simulation of Fault on Line between Generator and Motor by Placing a Balanced Three-Phase Shunt at the Position of the Fault

phase sequence current flowing in the positive phase sequence network in Fig. 9.

The currents and voltages in Fig. 9 are perfectly balanced and the resulting balanced three-phase power flow is equal in magnitude to the actual unbalanced power exchange between the generator and motor.

*The Vector Diagram*[2, 5, 9] *Showing the Electrical Quantities and Angles to be Studied.* The vector diagram of the quantities to be considered is shown in Fig. 10, where $V$ is the voltage at any point between the generator and the motor. For convenience it is taken here at the point where the fault is to be applied.

The generator current $i$ is divided into two components, the direct component $i_d$ in phase with the generator rotor direct axis and the quadrature component $i_q$ at right angles to the generator rotor direct axis.

The angle between the rotors of the generator and motor is $\delta$. The power factor angle is $\alpha$ where $V$ is measured.

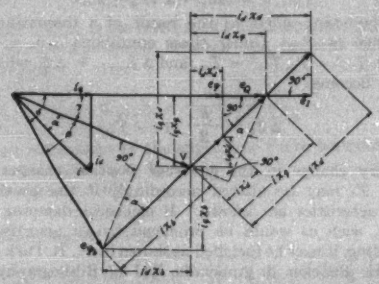

Fig. 10—Vector Diagram of Voltages and Current When a Salient Pole Generator Feeds a Non-Salient Pole Motor

*The Flow of Power Between the Generating Station and the System Which it Feeds.* Since there are only 2 machines $s = 2$ and from (28)

$$e_Q = \frac{\begin{vmatrix} W_1 & A_{12} \\ W_2 & \mu_2 \end{vmatrix}}{\begin{vmatrix} \mu_1 & A_{12} \\ B_{12} & \mu_2 \end{vmatrix}} = \frac{W_1\ \mu_2 - W_2\ A_{12}}{\mu_1\ \mu_2 - A_{12}\ B_{12}} \tag{59}$$

From (23), (24), (25), and (26) we have before the fault is applied (Fig. 9 without the shunt $x$)

$$W_1 = \frac{e_\varphi}{(x_q - x_d')} \tag{60}$$

$$\mu_1 = \left[\frac{1}{(x_q - x_d')} - \frac{1}{(x_q + x_b)}\right] \tag{61}$$

since $\alpha_{11} = 90 - \theta_{11} = 0$; $\cos \alpha_{11} = 1$; and $Z_{11} = x_q + x_b$.

$$A_{12} = \frac{\cos \delta}{(x_q + x_b)} = B_{12} \tag{62}$$

$$W_2 = \frac{e_{\psi b}}{(x_{qb} - x_{db}')} \tag{63}$$

$$\mu_2 = \left[\frac{1}{(x_{qb} - x_{db}')} - \frac{1}{(x_q + x_b)}\right] \tag{64}$$

In (63) and (64) the subscript $b$ designates quantities which belong to the motor. Since the motor has non-salient poles $x_{qb} = x_{db}$ and $e_{1b} = e_{Qb}$. Since the flux linkages behind the transient reactance of the motor

are constant $x_{qb} = x_{db}' = x_{db}$ and $e_{Qb} = e_{\varphi b} =$ a constant.

Substituting (60) . . (64) in (59)

$$e_Q = \frac{\left[\frac{e_\varphi}{(x_q - x_d')}\right]\left[\frac{1}{(x_{qb} - x_{db}')} - \frac{1}{(x_q + x_b)}\right] - \left[\frac{e_{\varphi b}}{(x_{qb} - x_{db}')}\right]\left[\frac{\cos\delta}{(x_q + x_b)}\right]}{\left[\frac{1}{(x_q - x_d')} - \frac{1}{(x_q + x_b)}\right]\left[\frac{1}{(x_{qb} - x_{db}')} - \frac{1}{(x_q + x_b)}\right] - \left[\frac{\cos\delta}{(x_q + x_b)}\right]^2} \tag{65}$$

Multiplying numerator and denominator of (65) by $(x_{qb} - x_{db}')$, letting this term be zero since $x_{qb} = x_{db}'$, and simplifying.

$$e_Q = e_\varphi \frac{(x_q + x_b)}{(x_d' + x_b)} - e_{\varphi b} \frac{(x_q - x_d')}{(x_d' + x_b)} \cos\delta \tag{66}$$

Formula (66) was developed to demonstrate the application of the general formulas in Part II to any swing curve calculation. It is seen that (66) is exactly the same as (84).

It happens that the simplifications possible in the particular example that has been selected make it easier to develop the necessary formulas directly from the vector diagram, Fig. 10, and from this point on the formulas will therefore be developed from this diagram. Any one of them, however, can be obtained from the general method given in Part II. The additional method also gives an additional point of view and aids in visualizing the various phenomena.

The power flow in Fig. 10 is the product of $V$ and the projection of $i$ on $V$. Since there is no resistance, the power is the same at any place along the line and is equal to the product of the voltage at the point taken and the projection of the current on that voltage. Therefore, if the power $P_e$ be measured at $e_Q$ it will be:

$$P_e = e_Q\, i_q \tag{67}$$

From Fig. 10 we have before the fault is applied

$$e_Q = e_t - i_d\,(x_d - x_q) \tag{68}$$

$$e_t = e_{\varphi b} \cos\delta + i_d\,(x_d + x_b) \tag{69}$$

$$i_d = \frac{e_t - e_{\varphi b}\cos\delta}{(x_d + x_b)} \tag{70}$$

$$e_{\varphi b} \sin\delta = i_q\,(x_q + x_b) \tag{71}$$

$$i_q = \frac{e_{\varphi b}\sin\delta}{(x_q + x_b)} \tag{72}$$

Substituting (70) in (68),

$$e_Q = e_t - \frac{(x_d - x_q)}{(x_d + x_b)}\,(e_t - e_{\varphi b}\cos\delta) \tag{73}$$

$$e_Q = e_t \frac{(x_q + x_b)}{(x_d + x_b)} + \frac{e_{\varphi b}\,(x_d - x_q)\cos\delta}{(x_d + x_b)} \tag{74}$$

Substituting (72) and (74) in (67),

$$P_e = \frac{e_t\, e_{\varphi b}}{(x_d + x_b)} \sin\delta + \frac{e_{\varphi b}^2\,(x_d - x_q)\cos\delta\sin\delta}{(x_d + x_b)\,(x_q + x_b)} \tag{75}$$

$$P_e = \frac{e_t\, e_{\varphi b}}{(x_d + x_b)} \sin\delta + \frac{e_{\varphi b}^2\,(x_d - x_q)}{2\,(x_d + x_b)\,(x_q + x_b)} \sin 2\,\delta \tag{76}$$

In (76) the power flow is given in terms of the generator synchronous voltage $e_t$, the system voltage, the rotor angle, and some of the network reactances.

We may conveniently write (76) as

$$P_e = e_t\, H + N \tag{77}$$

where

$$H = \frac{e_{\varphi b}}{(x_d + x_b)} \sin\delta \tag{78}$$

$$N = \frac{e_{\varphi b}^2\,(x_d - x_q)}{2\,(x_d + x_b)\,(x_q + x_b)} \sin 2\,\delta \tag{79}$$

$H$ and $N$ may be plotted against $\delta$ and their values used in (14) to obtain the power inasmuch as $e_t$ and $\delta$ are calculated in the step-by-step process (see Figs. 15 and 16, curves II). A more detailed explanation is given later.

The power may be also expressed in terms of the $e_\varphi$ in place of the $e_t$.

From Fig. 10,

$$e_Q = e_\varphi + i_d\,(x_q - x_d') \tag{80}$$

$$e_\varphi = e_{\varphi b}\cos\delta + i_d\,(x_d' + x_b) \tag{81}$$

$$i_d = \frac{e_\varphi - e_{\varphi b}\cos\delta}{(x_d' + x_b)} \tag{82}$$

Substituting (82) in (80),

$$e_Q = e_\varphi + \frac{(x_q - x_d')}{(x_d' + x_b)}\,(e_\varphi - e_{\varphi b}\cos\delta) \tag{83}$$

$$e_Q = e_\varphi \frac{(x_q + x_b)}{(x_d' + x_b)} - e_{\varphi b} \frac{(x_q - x_d')}{(x_d' + x_b)} \cos\delta \tag{84}$$

Substituting (72) and (84) in (67),

$$P_e = \frac{e_\varphi\, e_{\varphi b}}{(x_d' + x_b)} \sin\delta - \frac{e_{\varphi b}^2\,(x_q - x_d')}{2\,(x_q + x_b)\,(x_d' + x_b)} \sin 2\,\delta \tag{85}$$

Curve $A$, Figs. 3 and 4, are plotted from (85),

To determine $\delta$ we have from Fig. 10,

$$\delta = \beta + \gamma \tag{86}$$

$$\beta = \tan^{-1} \frac{i\, x_b \cos\alpha}{V - i\, x_b \sin\alpha} \tag{87}$$

$$\gamma = \tan^{-1} \frac{i\, x_q \cos\alpha}{V + i\, x_q \sin\alpha} \tag{88}$$

$$\delta = \tan^{-1} \frac{i\, x_b \cos\alpha}{V - i\, x_b \sin\alpha} + \tan^{-1} \frac{i\, x_q \cos\alpha}{V + i\, x_q \sin\alpha} \tag{89}$$

When the shunt $x$ is applied in Fig. 9, the generator current may be found by superposition.

Without the shunt, the current is that produced by the vector difference between $\mathbf{e}_Q$ and $\mathbf{e}_{\psi b}$ applied to $(\mathbf{x}_q + \mathbf{x}_b)$.

With the shunt

$$\mathbf{i} = \mathbf{i}_{QQ} - \mathbf{i}_{\psi_b Q} \tag{90}$$

where $\mathbf{i}_{QQ}$ is the generator current produced by $\mathbf{e}_Q$ only and $\mathbf{i}_{\psi_b Q}$ is the generator current produced by $\mathbf{e}_{\psi b}$ only.

Let the current flowing from the generator be positive.

Letting $\mathbf{e}_{\psi b}$ be zero:

$$\mathbf{i}_{QQ} = \frac{\mathbf{e}_Q}{\mathbf{x}_q + \dfrac{\mathbf{x}\,\mathbf{x}_b}{\mathbf{x} + \mathbf{x}_b}} = \frac{\mathbf{e}_Q\,(\mathbf{x} + \mathbf{x}_b)}{\mathbf{x}\,\mathbf{x}_q + \mathbf{x}_q\,\mathbf{x}_b + \mathbf{x}\,\mathbf{x}_b} \tag{91}$$

Letting $\mathbf{e}_Q$ be zero

$$\mathbf{i}_{\psi_b \psi_b} = \frac{\mathbf{e}_{\psi b}}{\mathbf{x}_b + \dfrac{\mathbf{x}\,\mathbf{x}_q}{\mathbf{x} + \mathbf{x}_q}} \tag{92}$$

Where $\mathbf{i}_{\psi_b \psi_b}$ is the motor current produced by $\mathbf{e}_{\psi b}$ only.

$$\mathbf{i}_{\psi_b Q} = \mathbf{i}_{\psi_b \psi_b} \frac{\mathbf{x}}{\mathbf{x} + \mathbf{x}_q} \tag{93}$$

Substitute (92) in (93),

$$\mathbf{i}_{\psi_b Q} = \frac{\mathbf{e}_{\psi b}\,\mathbf{x}}{\mathbf{x}_b\,\mathbf{x} + \mathbf{x}_b\,\mathbf{x}_q + \mathbf{x}\,\mathbf{x}_q} \tag{94}$$

Substituting (91) and (94) in (90),

$$\mathbf{i} = \frac{\mathbf{e}_Q\,(\mathbf{x} + \mathbf{x}_b) - \mathbf{e}_{\psi b}\,\mathbf{x}}{\mathbf{x}_q\,(\mathbf{x} + \mathbf{x}_b) + \mathbf{x}\,\mathbf{x}_b} \tag{95}$$

$$\mathbf{i} = \frac{\mathbf{e}_Q - \mathbf{e}_{\psi b}\left[\dfrac{\mathbf{x}}{\mathbf{x} + \mathbf{x}_b}\right]}{\mathbf{x}_q + \dfrac{\mathbf{x}\,\mathbf{x}_b}{(\mathbf{x} + \mathbf{x}_b)}} \tag{96}$$

Let the paralleled value of $\mathbf{x}$ and $\mathbf{x}_b$ be $\mathbf{x}_e$ and

$$\mathbf{x}_e = \frac{\mathbf{x}\,\mathbf{x}_b}{\mathbf{x} + \mathbf{x}_b} \tag{97}$$

Substituting (97) in (96),

$$\mathbf{i} = \frac{\mathbf{e}_Q - \mathbf{e}_{\psi b}\,(\mathbf{x}_e/\mathbf{x}_b)}{\mathbf{x}_q + \mathbf{x}_e} \tag{98}$$

Let

$$\mathbf{e}_{\psi b}\,(\mathbf{x}_e/\mathbf{x}_b) = \mathbf{e}_{\psi e} \tag{99}$$

and (98) becomes:

$$\mathbf{i} = \frac{\mathbf{e}_Q - \mathbf{e}_{\psi e}}{\mathbf{x}_q + \mathbf{x}_e} \tag{100}$$

Now when there is no shunt it may be seen from Fig. 10 that

$$\mathbf{i} = \frac{\mathbf{e}_Q - \mathbf{e}_{\psi b}}{\mathbf{x}_q + \mathbf{x}_b} \tag{101}$$

Comparing (101) with (100) and noting the values of $\mathbf{x}_e$ and $\mathbf{e}_{\psi e}$ in (97) and (99) it is seen that if the shunt $\mathbf{x}$ in Fig. 9, be disconnected from ground and paralleled with the system transient reactance $\mathbf{x}_b$ and the system excitation $\mathbf{e}_{\psi b}$ be reduced by the ratio $\mathbf{x}_e/\mathbf{x}_b$, the resulting setup shown in Fig. 11 will give exactly the same generator current as that in Fig. 9, and since reactances only are used, the angle between $\mathbf{e}_1$ and $\mathbf{e}_{\psi e}$ Fig. 11, is the same as the angle between $\mathbf{e}_1$ and $\mathbf{e}_{\psi b}$ Fig. 9.[7]

It is convenient to let

$$X_d' = x_d' + x_e \tag{102}$$

$$X_q = x_q + x_e \tag{103}$$

$$X_d = x_d + x_e \tag{104}$$

and (100) may be written

$$i = \frac{e_Q - e_{\psi e}\,(\cos\delta - j\sin\delta)}{j\,X_q} \tag{105}$$

$$i = \frac{e_{\psi e}\sin\delta}{X_q} - j\left(\frac{e_Q - e_{\psi e}\cos\delta}{X_q}\right) \tag{106}$$

From (106) we take

$$i_q = \frac{e_{\psi e}\sin\delta}{X_q} \tag{107}$$

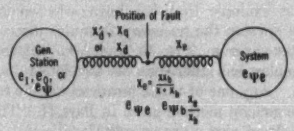


FIG. 11—SIMPLIFICATION OF CIRCUIT IN FIG. 9, BY ELIMINATION OF THE SHUNT

$$i_d = \frac{e_Q - e_{\psi e}\cos\delta}{X_q} \tag{108}$$

and from (70) we have during the fault

$$i_d = \frac{e_1 - e_{\psi e}\cos\delta}{X_d} \tag{109}$$

Fig. 10, is the vector diagram for Fig. 11, when $x_e$ and $e_{\psi e}$ replace $x_b$ and $e_{\psi b}$ respectively, and from Fig. 10:

$$e_Q = e_1 - i_d\,(x_d - x_q)$$

or

$$e_Q = e_1 - i_d\,(X_d - X_q) \tag{110}$$

Substitute (108) in (110)

$$e_Q = e_1 - \frac{(X_d - X_q)}{X_q}\,(e_Q - e_{\psi e}\cos\delta) \tag{111}$$

$$e_Q = e_1\,\frac{X_q}{X_d} + \frac{(X_d - X_q)}{X_d}\,e_{\psi e}\cos\delta \tag{112}$$

Substitute (107) and (112) in (67).

$$P_e = \frac{e_1\,e_{\psi e}}{X_d}\sin\delta + \frac{(X_d - X_q)}{X_d\,X_q}\,e_{\psi e}^2\sin\delta\cos\delta \tag{113}$$

$$P_s = \frac{e_t\, e_{\psi_s}}{X_d} \sin\delta + \frac{e_{\psi_s}^2 (X_d - X_q)}{2\, X_d X_q} \sin 2\,\delta \qquad (114)$$

Compare (114) with (76).

In the same manner that (85) was obtained it can be shown that:

$$P_s = \frac{e_\psi\, e_{\psi_s}}{X_d'} \sin\delta - \frac{e_{\psi_s}^2 (X_q - X_d')}{2\, X_q X_d'} \sin 2\,\delta \qquad (115)$$

Both (114) and (115) are balanced three-phase powers equal in magnitude to the actual unbalanced electrical power on the generator when the short circuit is applied. We thus obtain the power by means of a balanced three-phase calculation.

But the power is a function of the synchronous voltage $e_t$ and it remains to see how $e_t$ is affected by the unbalanced fault. A transient stator current will change the rotor current by armature reaction. The negative phase sequence current has a frequency of 120 cycles with respect to the rotor and induces a 120-cycle harmonic in the rotor current but has no effect upon its d-c. component. The zero phase sequence current produces no armature reaction, for the sum of its three vectors is zero inside the stator winding. The positive phase sequence current $i$ revolves with the rotor, it produces a continuous armature reaction upon the rotor, and it alone produces a net change in the rotor current.

In the per unit system (114) may be written:

$$T_e = e_t H + N \qquad (116)$$

where $T_e$ is the per unit electrical torque and

$$H = \frac{e_{\psi_s}}{X_d} \sin\delta \qquad (117)$$

$$N = \frac{e_{\psi_s}^2 (X_d - X_q)}{2\, X_d X_q} \sin 2\,\delta \qquad (118)$$

All quantities in (117) and (118) are in per units.

Equations (117) and (118) may be plotted separately as functions of $\delta$, and if at any instant $\delta$ and $e_t$ are known, $H$ and $N$ may be read from their curves and $T_e$ obtained conveniently from (116). See Curves $I$, Figs. 15 and 16.

In the same manner (115) may be written in the per unit system as:

$$T_e = \frac{e_\psi\, e_{\psi_s}}{X_d'} \sin\delta - \frac{e_{\psi_s}^2 (X_q - X_d')}{2\, X_q X_d'} \sin 2\,\delta \qquad (119)$$

Curve $B$, Figs. 3 and 4 were plotted from (119).

If the per unit generator field flux linkages is assumed constant, $T_e$ and $\delta$ are the only variables in (119) and $T_e$ may be plotted as a function of $\delta$ only. For large generators with moderate excitation systems, it has been found that the field flux linkages do not change much during the first 1½ seconds of a single line to ground or a line to line fault and under such conditions, the assumption that $e_\psi$ is constant introduces only a small error.

*The Relation Between the Generator Field Current and the Generator Field Flux Linkages.* Let the per unit field current of the generator be $I$ and the direct component of the per unit generator field flux linkages be $\Psi_d$. In the per unit system the generator synchronous voltage $e_t$ is equal to $I$ and the per unit generator transient voltage $e_\psi$ is equal to $\Psi_d$.

The difference between the input and output torques $(T_1 - T_e) = T_a$, will accelerate the generator rotor.

In the step-by-step method it is assumed that $T_a$ remains constant during small and equal increments of time $\Delta t$. It has been found that if $\Delta t$ be not greater than about one-tenth of the time required for one complete oscillation of the alternator rotor the accuracy of the calculations is very good. This oscillation usually requires from one to two seconds and in nearly all cases we have used a value of $\Delta t = 0.05$ second.

At the end of each $\Delta t$ it is necessary to find a new $T_a$ for the next increment of time. $T_a$ is a function of the variables $e_t$ and $\delta$, so $e_t$ and $\delta$ must be known at the beginning of each $\Delta t$. The rotor angle $\delta$ is known from calculations made during the preceding $\Delta t$. $I$ is a function of the slip ring volts and the angular movement of the rotor. It is assumed that the slip ring volts and rotor position are constant during each $\Delta t$, and $I$ approaches, along its exponential curve, the steady state value that the existing slip ring voltage would produce, as determined by the time constant $T$.

The applied excitation, such as that shown in Fig. 12, is broken up into a number of constant values, each of which is applied during the proper $\Delta t$. This gives the change of $I$ due to the slip ring volts $E$. To this must be added the effect of the change in rotor position during $\Delta t$. The way in which these components add is shown in Figs. 13 and 14. The initial value of $I$ at time zero is obtained by the vector diagram, and is shown in Figs. 13 and 14 as $I_{01}$. It follows its exponential curve to $I_{11}$, assuming no motion of the rotor until the end of the time $\Delta t$ when the rotor suddenly moves to its new position, causing $I$ to change from $I_{11}$ to $I_{12}$. Knowing $I_{12}$ and $\delta$ at the end of $\Delta t$, $T_a$ can be found and the movement of the rotor during the next $\Delta t$ can be calculated.

Prior to the fault, the load conditions of voltage $V$, current $i$, and power factor angle $\alpha$ must be known at some point along the line. Let this position be at $V$ in Fig. 10. Then $x'_d$, $x_q$, and $x_d$ are the generator reactances plus the intervening reactances up to this point, and $x_b$ is the reactance from this point into the system.

To obtain $I$ before the fault occurs, the component of $V$ along $e_t$ in Fig. 10 is,

$$V_d = \sqrt{V^2 - (i_q x_q)^2} \qquad (120)$$

and

$$e_t = \sqrt{V^2 - (i_q x_q)^2} + i_d x_d \qquad (121)$$

Substitute (72) and (70) in (121),

$$e_t = \sqrt{V^2 - \left[\left(\frac{x_q}{x_q + x_b}\right) e_{\psi b} \sin\delta\right]^2} + \left(\frac{x_d}{x_d + x_b}\right)(e_t - e_{\psi b}\cos\delta) \quad (122)$$

$$e_t = \left(1 + \frac{x_d}{x_b}\right)\sqrt{V^2 - \left[\left(\frac{1}{1 + x_b/x_q}\right) e_{\psi b}\sin\delta\right]^2} - \frac{x_d}{x_b} e_{\psi b}\cos\delta \quad (123)$$

To obtain $e_\psi$ in terms of known load conditions prior to the short circuit, we have from Fig. 10,

$$e_\psi = V_d + i_d x_d' \quad (124)$$

Substitute (120) in (124),

$$e_\psi = \sqrt{V^2 - (x_q i_q)^2} + i_d x_d' \quad (125)$$

From Fig. 10

$$e_\psi = e_{\psi b}\cos\delta + i_d(x_d' + x_b) \quad (126)$$

$$i_d = \frac{e_\psi - e_{\psi b}\cos\delta}{(x_d' + x_b)} \quad (127)$$

Substitute (72) and (127) in (125),

$$e_\psi = \sqrt{V^2 - \left[\left(\frac{x_q}{x_q + x_b}\right) e_{\psi b}\sin\delta\right]^2} + \left(\frac{x_d'}{x_d' + x_b}\right)(e_\psi - e_{\psi b}\cos\delta) \quad (128)$$

$$e_\psi = \left(1 + \frac{x_d'}{x_b}\right)\sqrt{V^2 - \left[\left(\frac{1}{1 + x_b/x_q}\right) e_{\psi b}\sin\delta\right]^2} - \frac{x_d'}{x_b} e_{\psi b}\cos\delta \quad (129)$$

To obtain $e_t$ in terms of $e_\psi$ we have from Fig. 10

$$e_t = e_\psi + i_d(x_d - x_d') \quad (130)$$

Substitute (127) in (130)

$$e_t = e_\psi + \frac{(x_d - x_d')}{(x_b + x_d')}(e_\psi - e_{\psi b}\cos\delta) \quad (131)$$

$$e_t = e_\psi \frac{(x_d + x_b)}{(x_d' + x_b)} - e_{\psi b}\frac{(x_d - x_d')}{(x_d' + x_b)}\cos\delta \quad (132)$$

and conversely

$$e_\psi = e_t \frac{(x_d' + x_b)}{(x_d + x_b)} + e_{\psi b}\frac{(x_d - x_d')}{(x_d + x_b)}\cos\delta \quad (133)$$

During the fault $x_b$ becomes $x_s$ and $e_{\psi b}$ becomes $e_{\psi s}$, whence (132) and (133) become,

$$e_t = e_\psi \frac{X_d}{X_d'} - e_{\psi s}\frac{(X_d - X_d')}{X_d'}\cos\delta \quad (134)$$

$$e_t = e_\psi \frac{X_d}{X_d'} - e_{\psi s}\left(\frac{X_d}{X_d'} - 1\right)\cos\delta \quad (135)$$

$$e_\psi = e_t \frac{X_d'}{X_d} + e_{\psi s}\left(1 - \frac{X_d'}{X_d}\right)\cos\delta \quad (136)$$

*The Short Circuit Time Constant of the Generator and Its Effect upon the Rotor Current.* In the per unit system, slip ring volts $E$ are equal to field current $I$ under steady state conditions.

If in any circuit the flow of current $i$, is controlled by a time constant $T$, the force which is changing $i$ remains constant and the initial current $i_0$ and the final current $i_\infty$ are known, the current $i$ at any instant is,

$$i = i_\infty + (i_0 - i_\infty)\,\epsilon^{-\frac{t}{T}} \quad (137)$$

For the small intervals of time $\Delta t$ we may use with very good accuracy, the first two terms of the exponential series so that,

$$\epsilon^{-\frac{\Delta t}{T}} = 1 - \frac{\Delta t}{T} \quad (138)$$

and (137) becomes,

$$i = i_0 - (i_0 - i_\infty)\frac{\Delta t}{T} \quad (139)$$

As seen in Fig. 13, the value of $I$ at the beginning of

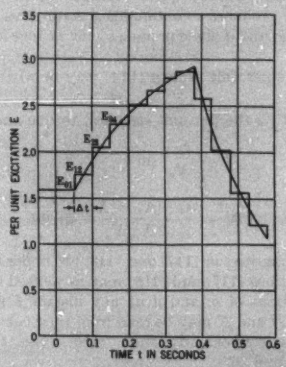


FIG. 12—SLIP RING VOLTAGE OF THE GENERATOR, PRODUCED BY A QUICK RESPONSE EXCITATION SYSTEM, SHOWN AS A FUNCTION OF TIME

the first $\Delta t$ is $I_{02}$. During this $\Delta t$, Fig. 12 shows that the excitation is $E_{01}$.

Therefore from (137) $I_{11}$ in per units is,

$$I_{11} = I_{02} - (I_{02} - E_{01})\frac{\Delta t}{T} \quad (140)$$

Since $I$ and $e_t$ are equal in per unit magnitudes, the value of $e_t$ due to the effect of $E$ during $\Delta t$ is,

$$e_{t(n1)} = e_{t\,(n-1)2} - (e_{t\,(n-1)2} - E_{(n-1)n})\frac{\Delta t}{T} \quad (141)$$

The time constant $T$ is a function of the open circuit time constant $T_0$ and the reactances to which the machine is connected. $T_0$ is the time constant of the rotor circuit when the stator is open circuited.

The relation[4] is,

$$T = T_0 \frac{(x_d' + x_b)}{(x_d + x_b)} \tag{142}$$

or during the fault

$$T = T_0 \frac{(x_d' + x_e)}{(x_d + x_e)} = T_0 \frac{X_d'}{X_d} \tag{143}$$

*The Effect of the Rotor Swings Upon the Generator*

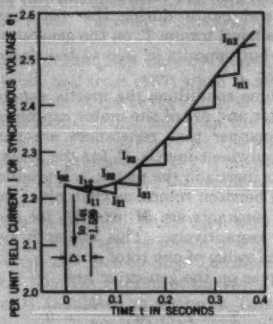


FIG. 13—GENERATOR FIELD CURRENT PRODUCED BY THE EXCITATION IN FIG. 12, SHOWN AS A FUNCTION OF TIME, AND SHOWING THE STEP-BY-STEP CALCULATIONS BY WHICH IT IS OBTAINED

*Field Currents.* To determine the change in $I$ due to the change $\Delta\delta$ in the rotor angle during the time $\Delta t$ it is assumed that the change in angle takes place instantly at the end of $\Delta t$, changing $I$ from $I_{11}$ to $I_{12}$ in Figs. 13 and 14, or at the instant $n$, $I$ changes from $I_{n1}$ to $I_{n2}$ when the angle changes by $\Delta\delta_n$.

In Figs. 13 and 14, and Equations (140) and (141), the first subscript to $I$ (or $e_1$) is the instant at which $I$ (or $e_1$) is taken, the second subscript 1 is for $I$ (or $e_1$) before the rotor changes its angle, and the second subscript 2 is for $I$ (or $e_1$) after the rotor changes its angle.

In Fig. 12 and Equations (140) and (141) the first subscript to $E$ is the instant at which $E$ begins and the second subscript is the instant that $E$ ends. Thus, in Fig. 12, $E_{01}$ is the value of $E$ from instant 0 to instant 1 and $E_{12}$ is the value of $E$ from instant 1 to instant 2. In (141) $E_{(n-1)n}$ is the value of $E$ from instant $(n-1)$ to instant $n$.

The subscript to $\Delta\delta$ gives the instant at which the change $\Delta\delta$ takes place in the angle. The subscript to $\delta$ in the following equations gives the instant at which the angle is $\delta$.

The change $(e_{1(n2)} - e_{1(n1)})$ in $e_1$ due to the change $\Delta\delta_n$ in the angle at the instant $n$ is obtained as follows:

From Fig. 10,

$$e_\varphi = e_1 - i_d (x_d - x_d') \tag{144}$$

and before the instantaneous change $\Delta\delta_n$ takes place,

$$e_{\varphi(n)} = e_{1(n1)} - i_{dn1} (x_d - x_d') \tag{145}$$

From (70)

$$i_{dn1} = \frac{e_{1(n1)} - e_{\varphi b} \cos\delta_{(n-1)}}{(x_d + x_b)} \tag{146}$$

Substituting (146) in (145)

$$e_{\varphi(n)} = e_{1(n1)} - \frac{(x_d - x_d')}{(x_d + x_b)} (e_{1(n1)} - e_{\varphi b} \cos\delta_{(n-1)}) \tag{147}$$

$e_\varphi$ is produced by the flux linkages of the rotor and cannot change instantly, so that immediately before and immediately after the change $\Delta\delta_n$ occurs, $e_\varphi$ has the same value. From (82):

$$i_{dn2} = \frac{e_{\varphi(n)} - e_{\varphi b} \cos\delta_n}{(x_d' + x_b)} \tag{148}$$

Substituting (147) in (148)

$$i_{dn2} = \frac{e_{1(n1)}}{(x_d' + x_b)} - \frac{(x_d - x_d')}{(x_d' + x_b)(x_d + x_b)} (e_{1(n1)} - e_{\varphi b} \cos\delta_{(n-1)}) - \frac{e_{\varphi b}}{(x_d' + x_b)} \cos\delta_n \tag{149}$$

From (145)

$$e_{1(n1)} = e_{\varphi(n)} + i_{dn1} (x_d - x_d') \tag{150}$$

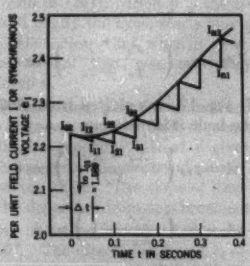


FIG. 14—GENERATOR FIELD CURRENT WHEN THE SLIP RING VOLTS REMAIN CONSTANT, SHOWN AS A FUNCTION OF TIME, AND SHOWING THE STEP-BY-STEP CALCULATIONS BY WHICH IT IS OBTAINED

And since $e_\varphi$ does not change during the instantaneous change $\Delta\delta$ in the angle $\delta$,

$$e_{1(n2)} = e_{\varphi(n)} + i_{dn2} (x_d - x_d') \tag{151}$$

Subtracting (150) from (151)

$$e_{1(n2)} - e_{1(n1)} = (i_{dn2} - i_{dn1}) (x_d - x_d') \tag{152}$$

Substituting (149) and (146) in (152)

$$e_{1(n2)} - e_{1(n1)} = (x_d - x_d') \left[ \frac{e_{1(n1)}}{(x_d' + x_b)} \right.$$

$$- \frac{(x_d - x_d')}{(x_d' + x_b)(x_d + x_b)} (e_{1(n1)} - e_{\varphi b} \cos \delta_{(n-1)})$$

$$- \frac{e_{\varphi b}}{(x_d' + x_b)} \cos \delta_n - \left( \frac{e_{1(n1)} - e_{\varphi b}}{(x_d + x_b)} \cos \delta_{(n-1)} \right) \Bigg]$$

$$= (x_d - x_d') \left[ \left( \frac{e_{1(n1)} - e_{\varphi b} \cos \delta_n}{(x_d' + x_b)} \right) \right.$$

$$\left. - \left( 1 + \frac{x_d - x_d'}{x_d' + x_b} \right) \left( \frac{e_{1(n1)} - e_{\varphi b} \cos \delta_{(n-1)}}{(x_d + x_b)} \right) \right]$$

$$= \frac{(x_d - x_d')}{(x_d' + x_b)} [e_{1(n1)} - e_{\varphi b} \cos \delta_n - e_{1(n1)} + e_{\varphi b} \cos \delta_{(n-1)}]$$

$$= e_{\varphi b} \left[ \frac{(x_d - x_d')}{(x_d' + x_b)} \right] (\cos \delta_{(n-1)} - \cos \delta_n)$$

or

$$e_{1(n2)} = e_{1(n1)} + e_{\varphi b} \left[ \frac{x_d - x_d'}{x_d' + x_b} \right] [\cos \delta_{(n-1)} - \cos \delta_n] \tag{153}$$

$$e_{1(n2)} = e_{1(n1)} + (A_{(n-1)} - A_n) \tag{154}$$

where

$$A_{(n-1)} = e_{\varphi b} \left( \frac{x_d - x_d'}{x_d' + x_b} \right) \cos \delta_{(n-1)}$$

$$A_n = e_{\varphi b} \left( \frac{x_d - x_d'}{x_d' + x_b} \right) \cos \delta_n$$

or

$$A = e_{\varphi b} \left( \frac{x_d - x_d'}{x_d' + x_b} \right) \cos \delta \tag{155}$$

Curve *II*, Fig. 17, was plotted from (**102**).

During the fault (**155**) becomes:

$$A = e_{\varphi e} \left( \frac{X_d - X_d'}{X_d'} \right) \cos \delta$$

$$A = e_{\varphi e} \left( \frac{X_d}{X_d'} - 1 \right) \cos \delta \tag{156}$$

Curve *I*, Fig. 17, was plotted from (**156**).

Substituting (**156**) in (**135**) we have during the fault:

$$e_1 = e_\varphi \frac{X_d}{X_d'} - A \tag{157}$$

Rearranging (**157**)

$$e_\varphi = \frac{X_d'}{X_d} (e_1 + A) \tag{158}$$

Substituting (**155**) in (**132**) we have when the fault is not applied:

$$e_1 = e_\varphi \frac{(x_d + x_b)}{(x_d' + x_b)} - A \tag{159}$$

Rearranging (**159**)

$$e_\varphi = \frac{(x_d' + x_b)}{(x_d + x_b)} (e_1 + A) \tag{160}$$

Note that $A$ is obtained from (**155**) when there is no fault, and from (**156**) when there is a fault.

*Modification of the Inertia Constants where Resistances are Neglected and Only Two Machines are Considered.* When resistances and machine losses are neglected, the mechanical torque $T_1$ applied to the shaft of the generator before the disturbance is equal in magnitude but opposite in sign to the mechanical load torque on the shaft of the equivalent motor before the disturbance. The shaft torques are assumed constant on both the generator and motor during the disturbance. Likewise the electrical torque $T_e$ on the generator is equal in magnitude but opposite in sign to the electrical torque on the motor.

Under these conditions the inertia constants $M_1$ of the generator and $M_2$ of the motor can be combined in the same manner that resistances are paralleled, to given an equivalent inertia $M$ for the generator which with infinite inertia in the motor, will produce the same total swing between rotors, as that which occurs when the inertia constants are $M_1$ and $M_2$ for the generator and motor respectively. This makes it necessary to calculate the swing of one rotor only.

The torques on the generator are:

$$T_1 - T_e - M_1 \frac{d^2 \delta_1}{d t^2} = 0 \tag{161}$$

The torques on the motor are:

$$- T_1 + T_e - M_2 \frac{d^2 \delta_2}{d t^2} = 0 \tag{162}$$

where $\delta_1$ and $\delta_2$ are the increase in the angles of the generator and motor respectively, in per units.

Equating (**161**) and (**162**)

$$M_1 \frac{d^2 \delta_1}{d t^2} = - M_2 \frac{d^2 \delta_2}{d t^2} \tag{163}$$

Integrating (**163**)

$$M_1 \delta_1 = - M_2 \delta_2 \tag{164}$$

The total angular increase $\delta$ between rotors is:

$$\delta = \delta_1 - \delta_2 \tag{165}$$

From (**164**)

$$\delta_2 = - \delta_1 \frac{M_1}{M_2} \tag{166}$$

Substituting (**166**) in (**165**)

$$\delta_1 = \left( \frac{M_2}{M_1 + M_2} \right) \delta \tag{167}$$

Substituting (**167**) in (**161**)

$$T_1 - T_e = \frac{M_1 M_2}{M_1 + M_2} \frac{d^2 \delta}{d t^2} = T_a \tag{168}$$

or

$$T_a = M \frac{d^2 \delta}{d t^2} \tag{169}$$

where

$$M = \frac{M_1 M_2}{M_1 + M_2} \tag{170}$$

*The Manner in which a Quick Response Voltage Regulator Responds when Rapid Changes in A-C. Voltage Take Place.* The manner in which the slip ring volts change is a function of the regulator characteristics as well as of the exciter voltage speed.

If the field flux linkages are to be held constant, the field current $I$ will vary as a function of the rotor angle $\delta$.

This relation is obtained directly from (159) when there is no fault, and from (157) when there is a fault.

In the calculation of the swing curve, $e_i = I$ is determined at each step. If $I$ is less than the value given by (159) or (157) as the case may be, the voltage regulator will raise the excitation. If $I$ is greater than the value given by (159) or (157), the regulator will lower the excitation.

The manner in which $I$ must vary with $\delta$ to hold constant field flux linkages is shown in Fig. 18.

*Tabulation of the Step-by-Step Calculations of the Swing Curve.* The calculations of the swing curve may be conveniently tabulated as shown in Table I.

TABLE I

TABULATION OF THE SWING CURVE CALCULATIONS

| | Item | | | |
|---|---|---|---|---|
| $n$ = number of time instant | | 0 | 1 | 2 |
| $n\ (\Delta t)$ = seconds | | 0 | $1(\Delta t)$ | $2(\Delta t)$ |
| $e_{1(n1)} = e_{1(n-1)2} - [e_{1(n-1)2} - E_{(n-1)n}]\dfrac{\Delta t}{T} = n_{(n-1)n} + p_{(n-1)}$ | $a$ | | † | |
| $A_{(n-1)}$ from curve when $\delta = \delta_{(n-1)}$ | $b_{(n-1)}$ | | † | |
| $A_n$ from curve when $\delta = \delta_n$ | $c_n$ | | † | |
| $A_{(n-1)} - A_n = b_{(n-1)} - c_n$ | $d_n$ | | † | |
| $e_{1(n2)} = a_n + d_n$ | $e_n$ | * | † | |
| $H_n$ from curve when $\delta = \delta_n$ | $f_n$ | * | † | |
| $e_{1(n2)}\ H_n = (e_n)\ (f_n)$ | $g_n$ | * | † | |
| $N_n$ from curve when $\delta = \delta_n$ | $h_n$ | * | † | |
| $T_{en} = g_n + h_n$ | $i_n$ | * | † | |
| $T_{an} = (T_1 - T_{en}) = T_1 - i_n$ | $j_n$ | * | † | |
| $k\ T_{an} = \dfrac{360 f\ (\Delta t)^2}{M}\ T_{an} = k\ j_n$ except 1st step switching, etc. | $k_n$ | * | † | |
| $\Delta\ \delta_{(n+1)} = \Delta\ \delta_n + k_n = l_n + k_n$ | $l_{(n+1)}$ | 0 | * | † |
| $\delta_{(n+1)} = \delta_n + \Delta\ \delta_{(n+1)} = m_n + l_{(n+1)}$ | $m_{(n+1)}$ | $\delta$ | * | † |
| $E_{n(n+1)}$ from excitation curve | $n_{n(n+1)}$ | $n_{01}$ | $n_{12}$ | $n_{23}$ |
| $e_{1(n2)} - E_{n(n+1)} = e_n - n_{n(n+1)}$ | $o_n$ | * | † | |
| $e_{1(n2)} - E_{n(n+1)}]\dfrac{\Delta t}{T} = o_n \dfrac{\Delta t}{T}$ | $p_n$ | * | † | |

It is a condensed tabulation of the information derived thus far, with the instants at which the various items apply shown by the subscripts $n$. The preliminary calculations marked ‡ are obtained from (89), (129), and (157). The initial angle $\delta_0$ calculated from (89) cannot change the first instant of the disturbance. Before the disturbance $e_\psi$ is given by (129) but like $\delta_0$, $e_\psi$ cannot change instantly and (129), therefore, gives $e_\psi$ at the first instant of the disturbance. The value of $e_i$ or $I$ at the first instant of the disturbance is obtained from (157).

The first step calculations are marked *, and the second step marked †. Subsequent steps are done in in the same manner as that marked †. It will be noted that $\delta$, and $e_{1(n1)}$ in column 1 are obtained from calculations in column 0. The same conditions holds for all subsequent columns.

Before starting the swing curve, auxiliary curves for $A$, $H$, and $N$ should be plotted as functions of $\delta$ from (156), (155), (117), (78), (118), and (79). These curves give items $b$, $c$, $d$, $f$, and $h$ in Table I. Curve $H$ is a fundamental sine wave and when multiplied by $e_i$ it gives the electrical torque that the generator would deliver if it were of non-salient pole construction. Curve $N$ adds the reluctance torque, which is that due to the salient pole construction, and is a second harmonic with reference to the fundamental Curve $H$. From (118) it will be seen that the excitation for $N$ comes from the system.

Item $n$ is simply filled in from the known step-by-step excitation curve, Fig. 12.

Item $a$ is (141); Item $e$ is (154). Item $g$ is the first term in (116). Item $i$ is (116). Item $j$ is part of a term in (51), (54), or (55). Item $k$ is a term in (51), (54), or (55). Item $l$ is (51), (54), or (55) depending upon conditions. Item $m$ is (42). Item $o$ is part of the second term in (141). Item $p$ is the second term in (141). And finally the cycle starts over again with item $a$ as (141). Note that when a new column is started, the column that was previously $(n + 1)$ becomes column $n$.

Table I gives, either directly or indirectly, practically all the transient positive phase sequence electrical quantities in the generator. Item $e$ gives the field current. Item $i$ gives the electrical power or torque. Item $m$ gives the angle. The slope of item $m$ against time gives the departure from synchronous speed.

From item $c$ and $e$ the field flux linkages are given by (158) or (160). The direct component $i_d$ of the stator current $i$ is given by (70) or (109). The quadrature component $i_q$ of the stator current $i$ is given by (72) or (107). The stator current is:

$$i = \sqrt{i_d^2 + i_q^2} \tag{171}$$

These values can be plotted not only against time but against each other, such as electrical power against angle.

If the field flux linkages are assumed constant, and this can usually be done during the first swing with only a small error, only items $i$, $j$, $k$, $l$, and $m$ of Table I are required for the angle time curve. The electrical torque or power is given in per unit values by (85) or (119) in which $T$, and $\delta$ are the only variables. The second harmonic is added directly in the equations.

$T_i$ should be plotted against $\delta$, giving item $i$. The other items are as previously described in Table I.

After the "per unit" quantities have been obtained, they can be expressed in terms of kv., kw., and kv-a., etc., by multiplying by the number of such electrical units in the particular unit used as standard. This was done when (**48**) was used to convert per unit angles in (**47**) to degrees in (**49**).

In other quantities such as kw., if unit kw. is chosen to equal 100,000 kw. and a calculated per unit figure of 0.5 is obtained, then the calculated kw. are 100,000 × 0.5 = 50,000 kw.

## Appendix II

### Example of a Swing Curve Calculation

*Where a Fault is Applied and Removed by Switching Out the Faulty Line in 0.33 Second*

The positive phase sequence reactance diagram during the fault is shown in Figs. 9 and 11. Before the fault it is Fig. 9, without the shunt $x$.

The base chosen is 100,000 kv-a.

The units chosen are:

unit kv-a. = 100,000 kv-a.
unit kw. = 100,000 kw.
unit kv. = 220 kv.

A generating plant is feeding a system over a pair of duplicate paralleled 220-kv. transmission lines at each end of which are solidly grounded $\Delta$ $Y$ transformers, with the high-tension windings connected in $Y$ and the low-tension windings connected in $\Delta$.

A single conductor to ground short circuit on one of the lines will be taken near the high-tension generator bus, and the faulty line will be removed in 0.33 second.

Measured at the high-tension terminals of the generating station transformers the load is 238,000 kw. at 0.93 power factor and at a potential of 231 kv.

In per units

$$T_1 = \frac{238{,}000}{100{,}000} = 2.38$$

$$V = \frac{231}{220} = 1.05$$

The speed of the generators is 81.8 rev. per min. All the generators are practically duplicates and have duplicate excitation systems. The total $W R^2$ of the generators is 512,654,800 lb. ft.$^2$ Adding 12.5 per cent for the waterwheels and their content of water, the total $W R^2$ is 577,000,000 lb. ft.$^2$

From (**37**)

$$M_1 = \frac{0.462 \times 577 \times 10^6 \times (0.0818)^2}{105} = 17.85$$

From the paragraph following (**37**), the inertia constant of the equivalent motor representing the system is:

$M_2 = 272$

From (**170**)

$$M = \frac{(17.85)\ (272)}{289.85} = 16.75$$

The frequency is 60 cycles, and $\Delta t$ will be taken as 0.05 sec. Therefore from (**50**)

$$k = \frac{360 \times 60\ (0.05)^2}{16.75} = 3.222$$

From the system network

$x_b = 0.0954$ before the fault occurs.
$x_b = 0.1464$ after removing the faulty line.

From the generator reactances the system network and (**4**)

$x = x_s + z_n = 0.0859$

From (**97**)

$$x_s = \frac{(0.0859)\ (0.0954)}{0.1813} = 0.0452$$

The generator reactances are:

transient reactance = 0.1035
quadrature reactance = 0.2070
synchronous reactance = 0.3290

The reactance between the generator and the fault is that of the transformer. It is 0.031.

Hence:

$x_d' = 0.1035 + 0.0310 = 0.1345$
$x_q = 0.2070 + 0.0310 = 0.2380$
$x_d = 0.3290 + 0.0310 = 0.3600$

From (**102**), (**103**), and (**104**)

$X_d' = 0.1345 + 0.0452 = 0.1797$
$X_q = 0.2380 + 0.0452 = 0.2832$
$X_d = 0.3600 + 0.0452 = 0.4052$

Before the fault occurs

$x_d' + x_b = 0.1345 + 0.0954 = 0.2299$
$x_q + x_b = 0.2380 + 0.0954 = 0.3334$
$x_d + x_b = 0.3600 + 0.0954 = 0.4554$

After removing the faulty line

$x_d' + x_b = 0.1345 + 0.1464 = 0.2809$
$x_q + x_b = 0.2380 + 0.1464 = 0.3844$
$x_d + x_b = 0.3600 + 0.1461 = 0.5064$

Before the fault occurs the total a-c. current is

$$i = \frac{\text{Kw.}^*}{\text{Kv.} \cos \alpha} = \frac{2.38}{1.05 \times 0.93} = 2.435$$

and using $V$ as the reference vector

$\mathbf{i} = 2.435 \angle \cos^{-1} 0.93$
$\mathbf{i} = 2.435 \angle 21.6° = 2.265 - j\,0.896$
$\mathbf{e_{v_b}} = \mathbf{V} - \mathbf{i}\,\mathbf{x_b} = 1.05 - j\,0.0954\ (2.265 - j\,0.896)$
$= 1.05 - j\,0.216 - 0.0855$
$\mathbf{e_{v_b}} = 0.9645 - j\,0.216 = 0.988 \angle 12.6°$

*The use of per units or percentages eliminates the factor $\sqrt{3}$ in three-phase calculations.

The initial angle (before the fault occurs) is obtained from (**89**). It is,

$$\delta_e = \tan^{-1} \frac{(2.435)\,(0.0954)\,(\cos 21.6°)}{1.05 - (2.435)\,(0.0954)\,(\sin 21.6°)}$$

$$+ \tan^{-1} \frac{(2.435)\,(0.2380)\,(\cos 21.6°)}{1.05 + (2.435)\,(0.2380)\,(\sin 21.6°)}$$

$$= \tan^{-1} 0.224 + \tan^{-1} 0.426 = 12.6° + 23.1°$$

$$\delta_e = 35.7°$$

From (**99**)

$$e_\psi = 0.988 \frac{(0.0452)}{(0.0954)} = 0.468$$

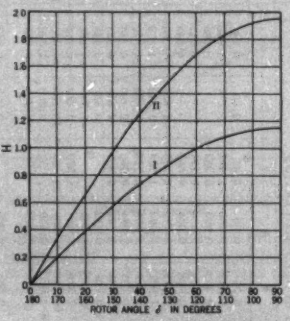


FIG. 15—THE QUANTITY $H$ USED IN CALCULATING THE ELECTRICAL TORQUE BETWEEN THE GENERATOR AND MOTOR, SHOWN AS A FUNCTION OF THE ELECTRICAL ANGLE BETWEEN THE ROTOR AXES

Curve I applies during the fault
Curve II applies after the faulty line has been removed

From (**129**) the initial transient voltage (before the fault occurs) is,

$$e_\psi = \left(1 + \frac{0.1345}{0.0954}\right)$$

$$\sqrt{(1.05)^2 - \left[\left(\frac{1}{1 + 0.0954/0.2380}\right)(0.988)(0.5835)\right]^2}$$

$$- \frac{1.345}{0.0954}\,(0.988)\,(0.8121)$$

$$e_\psi = 1.195$$

After the fault is applied, the $H$, $N$, and $A$ curves must be plotted.

The $H$ curves are obtained from (**117**) and (**78**).

During the fault

$$H = \frac{0.468}{0.4052} \sin \delta$$

$$H = 1.154 \sin \delta$$

After the faulty line has been switched out

$$H = \frac{0.988}{0.5064} \sin \delta$$

$$H = 1.95 \sin \delta$$

The $H$ curves are plotted in Fig. 15.

The $N$ curves are obtained from (**118**) and (**79**).

During the fault

$$N = \frac{0.468^2\,(0.4052 - 0.2832)}{2\,(0.4052)\,(0.2832)} \sin 2\,\delta$$

$$N = 0.1164 \sin 2\,\delta$$

After the fault

$$N = \frac{0.988^2\,(0.3600 - 0.2380)}{2\,(0.5064)\,(0.3844)} \sin 2\,\delta$$

$$N = 0.3056 \sin 2\,\delta$$

The $N$ curves are plotted in Fig. 16.

From (**156**) we have during the fault:

$$A = 0.468 \left(\frac{0.4052}{0.1797} - 1\right) \cos \delta$$

$$A = 0.588 \cos \delta$$

After the fault, from (**155**)

$$A = 0.988 \left(\frac{0.3600 - 0.1345}{0.2809}\right) \cos \delta$$

$$A = 0.793 \cos \delta$$

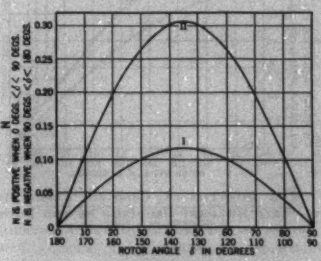


FIG. 16—THE QUANTITY $N$ USED IN CALCULATING THE ELECTRICAL TORQUE BETWEEN THE GENERATOR AND MOTOR, SHOWN AS A FUNCTION OF THE ELECTRICAL ANGLE BETWEEN THE ROTOR AXES

Curve I applies during the fault
Curve II applies after the faulty line has been removed.

The $A$ curves are plotted in Fig. 17.

From (**157**) the synchronous voltage immediately after the fault occurs is,

$$e_{1(02)} = (1.159) \left(\frac{0.4052}{0.1797}\right) - A$$

$A$ is obtained from Curve $I$ of the $A$ Curves when $\delta = \delta_0 = 35.7$ deg. and,

$$e_{1(02)} = 2.695 - 0.478 = 2.217$$

The open circuit time constant was found to be,

$$T_o = 4.8 \text{ seconds}$$

and from (**143**) we have during the fault,

$$T = (4.8)\frac{(0.1797)}{(0.4052)} = 2.13 \text{ sec.}$$

From (**142**) we have after the fault,

$$T = (4.8)\frac{(0.2809)}{(0.5064)} = 2.66 \text{ sec.}$$

The term $\frac{\Delta t}{T}$ in (**141**) is,

During the fault

$$\frac{\Delta}{T}t = \frac{0.05}{2.13} = 0.0235$$

and after the fault

$$\frac{\Delta t}{T} = \frac{0.05}{2.66} = 0.0188$$

The step-by-step calculations can now be made on the swing curve. Table I can be filled in as shown in

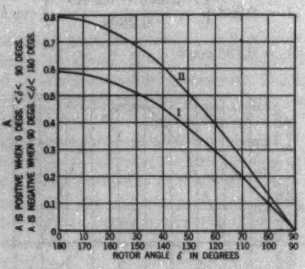


FIG. 17—THE QUANTITY *A* USED IN CALCULATING THE CHANGE IN FIELD CURRENT PRODUCED BY THE ROTOR OSCILLATIONS, SHOWN AS A FUNCTION OF THE ELECTRICAL ANGLE BETWEEN THE ROTOR AXES

Curve I applies during the fault
Curve II applies after the faulty line has been removed.

Table II. The various values for item *n* are filled in from Fig. 12. Like all other values Fig. 12 is plotted in per units. From the generator saturation curve it was found that unit *I* is 363 amperes. The resistance of the field winding is 0.27 ohm, and unit slip ring volts is 363 × 0.27 = 98 volts. To obtain Fig. 12, the ordinates of the curve of excitation volts versus time were divided by 98.

A small time of 0.05 second was allowed for the regulator contacts to operate before the excitation began to rise. It will be seen that the steady state excitations before the disturbance was 1.59, giving 1.59 × 98 = 156 slip ring volts and 1.59 × 363 = 577 field amperes per generator.

TABLE II

SAMPLE SWING CURVE CALCULATION

| *n* | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *n* (0.05) | 0 | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 | 0.33 | 0.38 | 0.43 | 0.48 | 0.53 | 0.58 | 0.63 |
| $e_{a(n)}$ | | 2.203 | 2.198 | 2.218 | 2.259 | 2.319 | 2.398 | 2.457 | | 1.905 | 1.905 | 1.953 | 1.874 | 1.746 | |
| $A_{(n-1)}$ | | 0.478 | 0.472 | 0.448 | 0.408 | 0.353 | 0.293 | 0.220 | | 0.260 | 0.212 | 0.226 | 0.298 | 0.416 | |
| $A_n$ | | 0.472 | 0.448 | 0.408 | 0.353 | 0.293 | 0.230 | 0.174 | | 0.212 | 0.235 | 0.298 | 0.416 | 0.540 | |
| $A_{(n-1)} - A_n$ | | 0.006 | 0.024 | 0.040 | 0.055 | 0.060 | 0.063 | 0.056 | | 0.048 | −0.013 | −0.073 | −0.118 | −0.133 | |
| $e_{i(n)}$ | 2.217 | 2.209 | 2.222 | 5.258 | 2.314 | 2.379 | 2.449 | 2.513 | 1.856 | 1.953 | 1.932 | 1.880 | 1.766 | 1.613 | |
| $H_n$ | 0.672 | 0.693 | 0.751 | 0.832 | 0.922 | 1.001 | 1.063 | 1.103 | 1.842 | 1.879 | 1.870 | 1.804 | 1.663 | 1.407 | |
| $e_{(n)}$ $H_n$ | 1.490 | 1.531 | 1.670 | 1.880 | 2.133 | 2.383 | 2.608 | 2.770 | 3.475 | 3.670 | 3.650 | 3.394 | 2.920 | 2.272 | |
| $N_n$ | 0.111 | 0.113 | 0.112 | 0.117 | 0.112 | 0.101 | 0.084 | 0.065 | 0.190 | 0.158 | 0.106 | 0.213 | 0.272 | 0.305 | |
| $T_m$ | 1.661 | 1.643 | 1.785 | 1.997 | 2.245 | 2.484 | 2.692 | 2.841 | 3.665 | 3.828 | 3.816 | 3.607 | 3.192 | 2.677 | |
| $2.38 - T_m$ | 0.779 | 0.737 | 0.595 | 0.383 | 0.135 | −0.104 | −0.312 | | −0.85 | −1.448 | −1.436 | −1.227 | −0.812 | −0.197 | |
| $3.222\ (2.38 - T_m)$ | 1.254 | 2.375 | 1.918 | 1.234 | 0.435 | −0.335 | −1.005 | | −2.740 | −4.665 | −4.627 | −3.953 | −2.620 | −0.635 | |
| $\Delta\ \delta_{(n+1)}$ degrees | 0 | 1.254 | 3.629 | 5.547 | 6.781 | 7.216 | 6.881 | 5.876 | 6.450 | 3.710 | −0.905 | −5.583 | −9.535 | −12.155 | −12.790 |
| $\delta_{(n+1)}$ degrees | 35.700° | 36.954° | 40.583° | 46.130° | 52.911° | 60.127° | 67.008° | 72.884° | 70.750° | 74.460° | 73.505° | 67.922° | 58.386° | 46.233° | 33.443° |
| $E_{a(n+1)}$ | 1.590 | 1.700 | 2.060 | 2.310 | 2.520 | 2.675 | 2.810 | | 2.880 | 2.580 | 2.020 | 1.560 | 1.215 | | |
| $e_{(n)} - E_{a(n+1)}$ | 0.627 | 0.449 | 0.162 | −0.052 | −0.206 | −0.296 | −0.361 | | −0.904 | −0.627 | −0.008 | 0.320 | 0.541 | | |
| $\left[E_{i(n)} - E_{a(n+1)}\right]\frac{0.05}{T}$ | 0.014 | 0.011 | 0.004 | −0.001 | −0.005 | −0.007 | −0.008 | | −0.019 | −0.012 | −0.001 | 0.006 | 0.010 | | |

To make the transition in the calculations at 0.33 sec. when the fault and faulty line are removed, the calculations are carried on with the fault up to 0.35 sec.

Plotting $\delta$ and $e_{1(n2)}$ against time it is seen that at 0.33 sec. $\delta = 70.75$ deg. and $e_{1(n2)} = 2.49$ (the true value of the synchronous voltage or the field current at an instant is $e_{1(n2)}$ and not $e_{1(n1)}$). Immediately before switching the value of $A$ at 70.75 deg. is 0.195 and from (158) the transient voltage at this instant is,

$$e_\Phi = \frac{0.1797}{0.4052}(2.49 + 0.195) = 1.19$$

After removing the fault, the number II Curves must

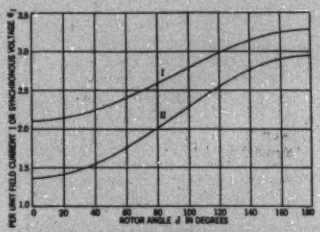


FIG. 18—GENERATOR FIELD CURRENT, OR SYNCHRONOUS VOLTAGE, REQUIRED TO MAINTAIN CONSTANT GENERATOR FIELD FLUX LINKAGES, OR TRANSIENT VOLTAGE, SHOWN AS A FUNCTION OF THE ELECTRICAL ANGLE BETWEEN THE ROTOR AXES

Curve I applies during the fault
Curve II applies after the faulty line has been removed

be used for $A$, $H$, and $N$. Neither $\delta$ nor $e_\Phi$ can change instantly and immediately after removing the fault the value of $A$ at 70.75 deg. is 0.260, the value of $e_\Phi$ is still 1.19, and from (159),

$$e_1 = 1.19\frac{(0.5064)}{(0.2809)} - 0.260 = 1.886$$

From the curve of $\delta$ versus time, the increment $\Delta\delta_n$ of $\delta$ from 0.28 sec. to 0.33 sec., (the regular $\Delta t$ internal of 0.05 sec.) is $70.75° - 64.30° = 6.45°$.

These new values of $e_1$, $\Delta\delta$, and $\delta$ are tabulated in column 8 of Table II.

Assuming that the voltage regulator is the quick response type, the regulator will endeavor to hold constant the initial transient voltage of 1.195. To maintain this value of transient voltage during the fault the field current $I$ = the synchronous voltage $e_1$ must be that given by (157) which becomes,

$$e_1 = 1.195\frac{(.4052)}{(.1797)} - A^*$$

$$e_1 = 2.695 - A^*$$

At the moment the fault line is switched out, the field current required to hold the field flux linkages constant at the per unit value of 1.195 is from (159):

$$e_1 = 1.195\frac{(0.5064)}{(0.2809)} - A^*$$

$$e_1 = 2.155 - A^*$$

These values of $e_1$ are plotted in Fig. 18.

By comparing the values of $e_{1(n2)}$ in Table II, which are the per unit synchronous voltages, with the values of the per unit synchronous voltages plotted in Fig. 18, it will be seen that $e_1$ is less than the amount required to hold constant transient voltages until the rotor has swung to an angle of 74.460 deg., which occurs at 0.38 second. Up until this time the voltage regulator forces the excitation voltage to continue to rise, as shown by Fig. 12, in an effort to hold a constant transient voltage, but at the rotor angle of 74.460 deg. the synchronous voltage exceeds the required value as shown by Curve II, Fig. 18, and the voltage regulator reduces the excitation in order to bring the synchronous voltage back down to Curve II. The decrement in

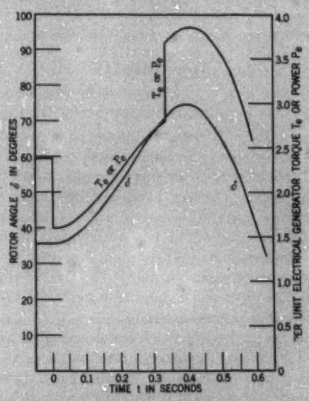


FIG. 19—ELECTRICAL TORQUE OR POWER BETWEEN GENERATOR AND MOTOR, AND ELECTRICAL ANGLE BETWEEN ROTOR AXES OF GENERATOR AND MOTOR, EACH SHOWN AS A FUNCTION OF TIME

slip ring voltage, therefore, starts at 0.38 second, as shown by Fig. 12, and continues until $e_1$ is brought back to Curve II, Fig. 18, at some later time not shown on the curve sheets, and at which time the excitation will rise again in the same manner as it did in the first 0.38 second. This process will continue with the excitation rising and falling as the voltage regulator attempts to hold constant field flux linkages.

By plotting $T_e$ against time it is seen that at 0.33 sec. $T_{en}' = 2.795$. From the calculations in column 8, Table II $T_{en}'' = 3.665$. The average value of $T_{en}$

*The values of $A$, as previously explained, are different during the fault and after the fault.

at 0.33 sec. is $\frac{T_{an}' + T_{an}''}{2} = \frac{2.795 + 3.665}{2} = 3.230$,

see (51), and item $j$ becomes $2.38 - 3.23 = -0.85$.

The term $\frac{0.05}{T}$ becomes 0.0188

The swing curves of angle between rotors, and of generator electrical power, as calculated in the above example and tabulated in Table II are plotted in Fig. 19.

The angle is in degrees. The torque or power is plotted in per units. To convert to kilowatts multiply the ordinates of the curve by the number of kilowatts in one unit of power. This, as previously stated, is 100,000 kw. Thus from Fig. 19, the initial power is $2.38 \times 100{,}000 = 238{,}000$ kw. before the fault. When the fault is applied, the power drops instantly to $1.601 \times 100{,}000 = 160{,}100$ kw. and rises during the swing to $2.79 \times 100{,}000 = 279{,}000$ kw. at 0.33 second, when the short circuit and fault line is relayed out and it jumps instantly to $3.665 \times 100{,}000 = 366{,}500$ kw., after which the swing continues as shown.

## Appendix III

### Accuracy of the Step-by-Step Method of Calculating Alternator Swing Curves

The accuracy of the step-by-step method of calculating the transient phenomena produced in alternators by disturbances such as short circuits, and often referred to as swing curves, is remarkably good.

A high degree of accuracy can be obtained by mechanically integrating the differential equation of the alternator swing. When this is done and the answer compared with that obtained by the step-by-step method, the error will usually be found to come within the limits of slide rule accuracy.

While no method of calculations can give an exact check of test results unless the exact value of all circuit and machine constants are known, good agreements can usually be obtained. This is true of the step-by-step method which was employed to calculate the curves shown in Figs. 10, 11, and 12 of Bibliography 1. The reader can judge for himself the degree of agreement between these calculated and test curves.

In cases where the field flux linkages, the prime mover torque, and the mechanical motor load torque are considered constant, and the damping and resistance losses are neglected, the step-by-step method of calculating the rotor swing gives, as it properly should, practically the same peak value for the second swing as for the first, showing practically no cumulative error between peaks. As an example, in a particular case the rotor angle rose from an initial value of 35.7 deg. to a peak of 80 deg. on the first swing and 80.6 deg. on the second swing. The step-by-step method presented here is a refinement of an earlier step-by-step method which contained a cumulative error. The degree of refinement now attained may be judged by comparing the old and new method. Using the old method on the example described in this paragraph, the rotor angle rose from its initial value of 35.7 deg. to a peak of 85.9 deg. on the first swing and a peak of 119 deg. on the second swing.

In some special cases, such as a three-phase short circuit on the generator bus with a constant prime mover input torque and no losses in the fault or in the machine, there is no error in the step-by-step method of calculating the rotor displacement. The differential equation of the rotor position can be easily integrated for such a condition and it can be shown mathematically that the results thus obtained are a perfect duplicate of those obtained by the step-by-step process.

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## Discussion

**I. H. Summers:** I should like to point out what Mr. Longley has not brought out very clearly perhaps, and that is that the essential contribution of his paper is that he has given a complete outline of a method of calculation, for not only the angular swing of the alternators under transient conditions but also all the other variables in the alternators, such as field current, flux, etc., where any number of alternators is connected to a system network.

In my discussion yesterday of the paper on the network analyzer by Messrs. Hazen and Schurig and Gardner, I mentioned the advantages of using the network analyzer to help in the solution of problems in transient stability when a large number of machines is connected to the network. In fairness to the analytical method, I should like to try to describe some features of the method as described by Mr. Longley.

In the first place, any solution on the network analyzer depends on the analytical solution for the equations on which it is based and

for the procedure used. The equations are used in the solution on the network analyzer to make certain auxiliary calculations in carrying out the method. In the second place there is a large class of problems in which a synchronous machine swinging against a bus or two machines swinging against each other are all that are necessary to be investigated. Examples of this are problems relating to high-speed excitation effect of varying field currents, damping, etc. In these cases, it may be that the solution by analytical methods is sufficiently simplified so that it becomes unnecessary to resort to the analyzer, and it may even be that time will be saved by going through the analytical solution rather than making the set-up and going through the checking processes necessary to the analyzer. What I am trying to bring out is that both methods have their place. The analytical method is of great importance because it furnishes a tool available to everyone who wishes to use it, whereas a miniature system such as the network analyzer may not be so readily available to those situated a distance away from places where this kind of apparatus exists.

**F. R. Longley:** There is just one point I want to bring out in the use of the step-by-step method of calculation. If you will adhere to that method, no matter what you are calculating you will usually eliminate the step-by-step cumulative error. Take for instance an excitation voltage rise curve plotted as a function of time. It may be considered constant for small intervals of time and broken up into small step-by-step intervals accordingly, but the total area under the step-by-step curve must be equal to the area under the actual curve. If you do not keep these areas equal the amount of your cumulated error will be the difference in the areas that you have not taken into account.

Here are a few curves which will demonstrate that there is a real difference in the effect of different types of excitation. These curves (Fig. 1) show the angle between the rotor axes of a synchronous generator and motor during a line to ground fault. The abscissa is in seconds, the ordinate in degrees. Each curve is for a different type of excitation. Otherwise the conditions are the same. Curve *A* is for constant slip ring volts. Curve *B* is for an excitation rise of about 300 volts per second. Curve *C* is for constant rotor flux linkages. Curve *D* is for super-excitation. Curve *A* rides through the first and second swing but appears to be headed for loss of synchronism during the third or fourth swing. Curve *B* has a smaller amplitude in the second swing than in the first, showing that the rise in excitation is slowly getting in its

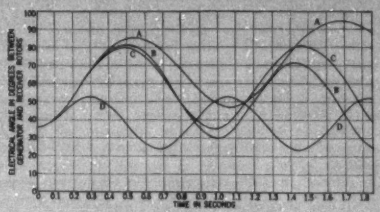


Fig. 1—Swing Curves Between Generating Station and System for Various Types of Excitation Following One Conductor to Ground Fault on Transmission Line. Transformer Neutrals Solidly Grounded

Curve *A*—Constant slip ring volts
Curve *B*—Excitation speed of about 300 volts per second
Curve *C*—Constant rotor flux linkages
Curve *D*—Super-excitation

work. Curve *C* has the same amplitudes in each swing, as it properly should, since the flux linkages are held constant. Curve *D* has much smaller amplitudes than *A*, *B*, or *C*, and a higher frequency of oscillation. It can therefore be seen from these curves that the effect of excitation may, in some cases, be an important factor in stability calculations.

# Radio Telephone Service to Ships at Sea

BY WILLIAM WILSON[1] and LLOYD ESPENSCHIED[2]
Member, A. I. E. E. Member, A. I. E. E.

*Synopsis.—The paper discusses the American end of the ship-to-shore radio telephone system and the connecting equipment on board the Leviathan. The most suitable wavelengths for this service are in the short-wave range, but the use of these wavelengths complicates the problem, since different wavelengths are required according to the distance of the ship from shore, the time of day, season of year, etc. The problem on shipboard is further complicated by the fact that the transmitting and receiving systems are necessarily near together and special precautions are necessary to take care of interference from the radio telephone transmitter and the radio telegraphic services. In addition to interference from these sources, there is a background of interference in the ship's electrical equipment, all of which necessitates a much more powerful land station than is necessary on shipboard.*

*In the present system, the shore transmitter has a power rating of 15 kw. and the ship transmitter of 500 watts. The shore transmitting station is located at Ocean Gate, N. J., and the receiving station at Forked River, N. J. At both of these locations, directive antennas are employed which cover the ship's lanes. The stations are connected by wire to the Long Lines toll office in New York, and the over-all control of the circuit is carried out from this point. Both the ship and shore transmitters are crystal controlled. The ship's receiver is highly selective and is of the double-detection type. Communication between the ship and the shore is carried out by use of a pair of frequencies, one for transmission in each of the two directions, separated from each other by about three per cent. Ships of a number of nations are being equipped with wireless telephone apparatus and as the service expands, it will undoubtedly be necessary to formulate a plan in which international agreement is reached on the allocations of frequencies for ship-to-shore telephony and telegraphy, in order that undue interference within the services themselves or between the two services shall not ensue.*

IN view of the developments which have recently taken place in the field of ship-to-shore radio telephony, it would appear appropriate to review the state of the science and to discuss the problems which have arisen, the facilities which have been installed, and the general results obtained.

The ship-to-shore radio telephone system, which is here described, was opened for public service between the *Leviathan* and the United States on December 8, 1929. This was the first extension of the public telephone service to a ship at sea and enabled calls to be made between the vessel and any Bell System subscriber. The system as set up is intended primarily for giving telephone service to the larger passenger-carrying vessels as an extension to the wire network, and should be distinguished from the more simple uses which have been made of radio telephony in the marine field, such as that of enabling a coastal station operator to talk with coast guard vessels, fishing trawlers, etc.

This paper is concerned with the developments which have been carried out in the United States, including the establishment of transmitting and receiving stations on the New Jersey coast, the equipping of the *Leviathan* and the establishment of service to that ship.

It is significant of the wide-spread interest in this type of service that developments have also gone forward rapidly on the European side where the British, Germans, and French are preparing coastal stations and equipping some of the larger ships for public telephone service. The British have already initiated service to two of the White Star Liners, the *Olympic* and the *Majestic*, and before the summer is over it is likely that half a dozen of the larger transatlantic vessels will be undertaking this service, connecting with both the American and the European networks.

## Early Developments

Attempts to apply telephony in the maritime field date back to the pioneer work on radiotelephony itself, but it was not until the application of the vacuum tube were developed that radio telephony for any service became finally practicable.

Following the long distance, point-to-point radio telephone experiments of 1915, there was carried out in the following year what is believed to have been the first trial of two-way radio telephony from the wire telephone system to a vessel at sea. This trial was conducted by Bell System engineers in cooperation with the Navy Department. On that occasion the Secretary of the Navy, in his office in Washington, carried on two-way conversations with the captain of the *U. S. S. New Hampshire* off Hampton Roads.

Following the further development of radio telephony during the War, there was undertaken, in the years 1920-1922, an extensive development of ship-to-shore radio telephony, looking toward the linking of ships at sea with the land line telephone network.[3] At that time there was built a coastal radio telephone station at Deal Beach, N. J., and several ships were equipped on a trial basis. Extensive engineering tests were made and a number of demonstrations carried out which proved the physical feasibility of establishing such connections. While the trials were successful from the technical standpoint, the development was not carried into commercial use because the adverse economic conditions existing in the post-War period did not appear to justify the initiation of the new service at that time. Furthermore, the waves in the range of 300-500 meters, which

1. Bell Telephone Laboratories, New York, N. Y.
2. American Telephone and Telegraph Company, New York, N. Y.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

3. "Radio Extension of the Telephone System to Ships at Sea," by H. W. Nichols and Lloyd Espenschied, *I. R. E. Proceedings*, Vol. 11, No. 3, 1923.

had been used in these early trials, were soon thereafter assigned for broadcasting.

In the last few years the whole outlook has changed considerably. The development of short-wave radio systems has greatly increased the message carrying capacity of the radio spectrum and has made it feasible to maintain communication over a greater range of distances than was previously practicable for ships. Transoceanic radio telephone services have been inaugurated, and with the large increase in steamship travel there has arisen a renewed interest in the extension of telephone service to ships at sea.

When it became evident that short-wave transmission

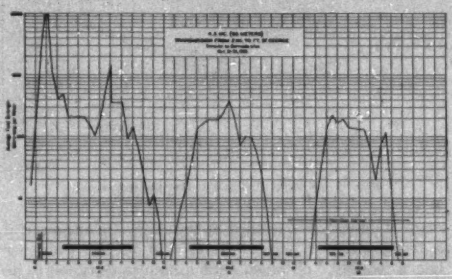

Fig. 1—Received Fields, New York-Bermuda Run 1925

might be desirable for ship-to-shore telephone service, there was undertaken a program involving the measurement of the strength of the electric fields received aboard ship from a shore transmitter. This work was part of a general program intended to obtain fundamental data upon short-wave transmission, for purposes of point-to-point, as well as for ship-to-shore telephone services. The tests were first made in 1925 on vessels running between New York and Bermuda. Further measurements were made on other ships in subsequent years.

Fig. 1 is an example of the result of these earlier tests. Transmission was from Deal Beach on 4.5 megacycles, (66 meters). The curve shows the relatively weak field which was received as the vessel left dock, due to the considerable stretch of land which intervened in the transmission path, the rise of the field to high values as the ship passed out of the harbor, and the gradual diminution as the vessel continued on her course. It will be observed that transmission on this frequency was effective at night all the way to Bermuda, but that during the daytime the transmission failed for distances greater than a few hundred miles. Corresponding measurements showed that daylight transmission could be secured by means of a higher frequency, such as 9 megacycles (33 meters). Measurements of this kind, supplemented by data obtained for a wide range of distances over land, and for transatlantic distances, have built up a fairly complete set of quantitative data on short-wave transmission over different distances and for various times of the day and year.

Along with this study of transmission conditions, there was carried on the development of short-wave apparatus technique for telephony. The first application was in the field of point-to-point transatlantic operation and the considerable art built up there, including the design of transmitters, receivers, directive antennas, and the working out of two-way operating methods, served as a very useful basis from which to develop the coastal and ship stations for the maritime system.

With this background of development, preparations were made to set up a two-way, short-wave radio telephone system for commercial service. This service was centered upon New York because of the large concentration of ocean-going traffic at that port.

## The Technical Problem

One of the most important problems to be solved in the design of a short-wave system is that of determining the frequencies necessary for giving the service involved. The frequencies which are best suited to the different distances, time of day, and season of the year for transmission over the North Atlantic are indicated in the curves of Fig. 2. The curves for the greater distances refer to the transmission which appears to take place in the upper regions of the earth's atmosphere and is usually referred to as sky-wave transmission. Each of the sky-wave curves traces the optimum frequency-distance relation for the time of day and season of the

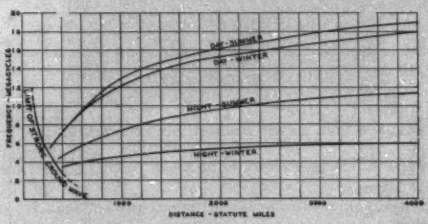


Fig. 2—Distance-Frequency Characteristic

year indicated. The curves merely give a general picture of the frequency relation and do not take account of other effects, such as fading, magnetic storms, etc.

The figure brings out very clearly the necessity for using a variety of wavelengths if the ship lanes are to be adequately covered. Fortunately, there is a considerable band on each side of the curves shown, in which good transmission can be obtained, and this enables one to choose a small number of frequencies in the short-wave range which are adequate to cover the conditions. Actually, it is found that a set of about four frequencies

will suffice to cover the North Atlantic. For distances greater than a few hundred miles this characteristic obtains irrespective of whether the transmission is over water or over land, by reason of the fact that the transmission appears to take place in the upper regions of the earth's atmosphere.

Closer in to the transmitting station, however, there is the so-called surface component, the attenuation of which is much less over sea water than over land. It will be seen that the surface wave may be relied upon for distances of the order of 200-300 miles, for frequencies of about 4 megacycles. The transmission of this component is much more stable and reliable than is the transmission of the sky wave. It seemed important, therefore, to utilize the surface wave to the maximum extent possible.

With this in mind, a series of transmission measurements was made over a stretch of water between New Jersey, Long Island, and Nantucket for the purpose of more accurately evaluating the effectiveness of the surface wave component, particularly in so far as it bears upon the question of how close to the water front the coastal station need be placed. Transportable transmitting and receiving stations were used in these tests. It was found that as the transmitting or the receiving station was moved away from the water front, the attenuation increased materially. For example, moving either terminal a mile back from the coast line increases the attenuation some 8 db. at 4.5 megacycles. On the other hand, a narrow stretch of land, such as a sand bar, out a few miles from the coast, introduces relatively little loss. These results indicate that if full advantage is to be obtained from the more reliable

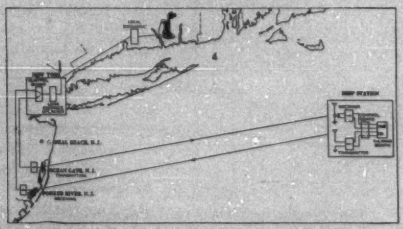


Fig. 3—U. S. Coastal Station Circuit Between New York and Ship

surface-wave component, the coastal station should be immediately upon the seacoast or a salt-water bay.

An important factor in connection with radio reception on shipboard is that of electrical interference. The modern steamship requires for its operation and its service a large amount of electrical machinery. In addition to this, it is equipped with various radio telegraphic services. The operation of all of this electrical equipment produces interference in a receiver which is much in excess of that normally encountered in a shore receiving station which can be so located as to be reasonably free from electrical disturbances. Furthermore, there is on the ship another source of disturbance which is due to charging and discharging of various parts of the rigging in the strong electromagnetic fields of the various radio transmitters. These various sources of disturbance were found in the earlier shipboard experiments and the high noise levels are, in general, the predominant factor in limiting the communication range. These factors

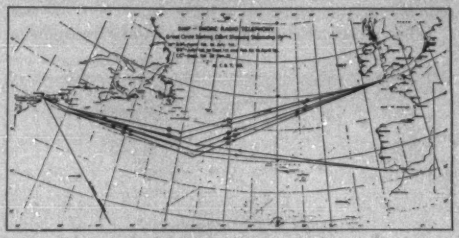

Fig. 4—North Atlantic Steamship Lanes

made it desirable to employ at the shore end as powerful a transmitter as was available and to use whatever benefit could be obtained from antennas designed to be roughly directive along the transatlantic ship lanes. A transmitting set of the type used in transatlantic communication, but adapted for the ship-to-shore wavelengths, was therefore employed.

Since the shore receiver can be located in a comparatively quiet situation and since use can also be made of roughly directive receiving antennas, there is no advantage in transmitting as large an amount of power from the ship as from the shore. The actual power radiated by the *Leviathan's* transmitter is of the order of 500 watts. The shore receiver is of the type used on the transatlantic radio telephone circuits, working with a directive antenna. The arrangement provides a fairly well proportioned system, the channels being substantially equally effective in the two directions.

## The Shore System

The general setup of the system is illustrated in Fig. 3. The coastal stations, sending and receiving, are located about 60 miles south of New York on the New Jersey shore, at Ocean Gate and Forked River. The course followed by the transatlantic ships is indicated on the map of Fig. 4. The directional bearing of this course and the directivity characteristic of the New Jersey shore station antennas are illustrated in Fig. 5. It will be observed that the breadth of the transmitted beam is adequate to take care of the variation of the directional bearing of the course. For steamship routes other than the transatlantic, as for example the coastal route to the South, other antenna arrangements will be required.

In general, the whole coastal station, including the transmitting and receiving units, taken together with the wire line connections and control position in New York, is similar to one end of a transatlantic point-to-point circuit. The transatlantic facilities have been described in previous papers[4] and reference should be made to them for more detail than is given below. The transmitting set has been adapted to cover the frequency range used in the service. It has a power of 15 kw. output of unmodulated carrier and is capable of

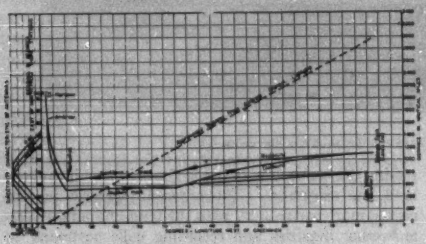

Fig. 5—Directional Bearings

delivering 60 kw. peak power. A photograph of a similar transmitter at Deal Beach, which is being used for this service pending the completion of the transmitting station at Ocean Gate, is shown in Fig. 6. The

Fig. 6—Illustration Deal Beach Transmitting Set

antennas are simpler and less directional than those employed in the transatlantic circuit, and give a transmission gain of 8 to 10 db. as compared with a single half-wave antenna.

The receiving station at Forked River has been in operation since the opening of commercial service last December. A photograph of the receiving set is shown in Fig. 7. The receiver is of the double-detection type, of high gain and selectivity, and employs screen-grid tubes. It is provided with automatic gain control. The apparatus shown includes not only the receiving set proper but also the equipment which is required for monitoring the circuit and for connecting with the wire line into New York. The receiving antennas are of the same general type as those used in the transatlantic system, which consist of a row of quarter-wavelength verticals connected alternately top and bottom by quarter-wavelength conductors. In the case of the longer wavelengths used in the ship-to-shore service, the vertical conductors are reduced in height and the horizontal links correspondingly elongated. A photograph of the

Fig. 7—Illustration Forked River Receiving Set

station at Forked River and two of the antennas is shown in Fig. 8.

The control and operating terminal equipment in New York is identical with that in use on the transoceanic radio telephone circuits. The control positions, as they exist in the New York long-distance telephone building for both transatlantic and ship-to-shore circuits, are pictured in Fig. 9. These control positions have associated with them such things as voice-frequency repeaters, indicators of the volume being transmitted and received over the circuit, gain controls, monitoring and testing facilities, and voice-current operated switching devices. The latter prevent the speech received from the ship from being reradiated from the shore transmitting station and permit independent adjustment of amplification in the circuits leading to the transmitting and receiving stations. Thus, the volume

4. Papers on Transatlantic Telephone Service by Messrs. Miller, Bown, Oswald, and Cowan, A. I. E. E. Quarterly Trans., Vol. 49, April 1930, p. 621.

sent to the transmitting station may be kept substantially constant, despite variations in speech volume received from different land line subscribers and full modulation of the transmitter may be obtained for over-riding noise on the ship. The function of the technical control operator is that of maintaining the circuit in the correct technical condition for talking. In general, it is the intention that the shore transmitting and receiving stations should function, as far as possible, merely as repeater stations, with the control of the over-all circuit from New York to the ship resting in the New York technical operator.

Fig. 8—Illustration Forked River Station with Antenna

Fig. 9—New York Technical Control Positions

The circuit terminates as an operating facility before a traffic operator at one of the long-distance telephone boards. In Fig. 10 is shown an illustration of the traffic positions for the transatlantic radio telephone circuits, including, at the right, two positions devoted to the ship-to-shore service. The duty of one of these two girls is confined to the radio circuit itself in that she talks to the ship operator, passes and receives information as to calls, and is generally responsible for completing the connection between the ship circuit and the land line subscriber. The adjacent operator is concerned more particularly with the land line subscribers, answering inquiries and recording calls outbound to ships and, in turn, getting in touch with and holding land line subscribers for inbound calls.

## The Ship Station

The Leviathan's radio transmitter was designed to supply about 500 watts, 80 per cent modulated radio frequency power to an antenna at frequencies from 3 to 17 megacycles. To insure satisfactory operating conditions, the carrier frequency stability was made as good as that required for point-to-point service and the transmitter has been designed with the object of holding the frequency within 0.01 per cent. This facilitates the establishment of contact between the ship and shore and obviates the necessity for frequent retuning of the shore receiver. The background noise on the unmodulated carrier, due to commutator ripple, etc., is inappreciable and the audio-frequency characteristics from 200 to 2750 cycles is flat to within $\pm$ 2 db.

Fig. 10—New York Traffic Positions

In addition to these electrical requirements, the mechanical design must be such as to withstand ship's vibration, permit easy access to the interior so as to facilitate wave change, and at the same time protect the operators from electrical shock.

The transmitter consists of a crystal oscillator and associated amplifiers. The crystal provides the necessary carrier frequency accuracy and stability and the amplifiers step up the power of the carrier to the desired level. Audio-frequency filters are placed in all voltage supply circuits to eliminate background noise. The modulation system with its associated transformers is designed to produce the requisite audio-frequency quality. A diagram of the circuit is shown in Fig. 11.

Very thorough electrical shielding is necessary between amplifier stages to prevent singing. This shielding makes the changing of coils, which is necessary for the changing of wavelengths, very unhandy, and hence the crystal control and amplifier system, except the last stage, is provided in duplicate, one side being used for the longer and the other for the two shorter waves. Wave changing, except for the output circuit

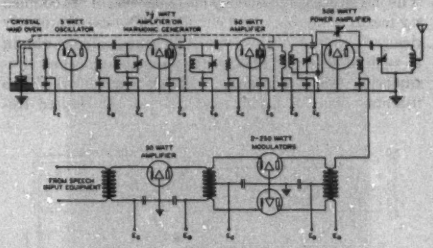


Fig. 11—Ship Transmitter's Schematic Diagram

of the power stage, is then accomplished by connecting the proper amplifier to the power stage.

The quartz plates used in the crystal control system are circular, being approximately one inch in diameter, and are clamped rigidly in the holder. This clamping serves to prevent any change of frequency with mechanical vibration. The holder with its crystal is mounted in a small oven, the temperature of which is held constant at 50 deg. cent. to better than ± 0.1 deg. cent. The thermal system of this oven is so designed that the change of internal oven temperature with temperature changes of the surrounding air is negligible.

As shown in the figure, the crystal is connected between the grid and filament of a 5-watt vacuum tube which, together with the parallel resonant circuit connected to the output of this tube, forms the crystal oscillator. The radio-frequency voltage developed by the crystal oscillator is applied directly to the grid of a 7½-watt screen-grid tube which can be used either as an amplifier or a frequency doubler. The output of this tube, except in the case of the higher frequencies, is applied directly to the grid of a 50-watt screen-grid amplifier. For the higher frequencies a second frequency doubler can be switched into the circuit. The output of the 50-watt tube is coupled through a balanced transformer to the final amplifier stage. The amplifier or frequency doubler stages are separately shielded and radio-frequency filters are provided in all power supply leads.

The power amplifier consists of an air-cooled, three-element, one-kilowatt tube. Neutralization is accomplished by the familiar balancing arrangement shown in the figure. The output circuit of this stage consists of a parallel resonant circuit with provision for tapping in the connection to the antenna.

Modulation takes place in the plate circuit of the final amplifier stage, the plate current supply being fed

Fig. 12—Illustration Leviathan Transmitter

through a special transformer, the secondary of which is connected to two 250-watt tubes connected push-pull and fed by a 50-watt amplifier.

The power supply is obtained from motor-generator sets operated from the 110-volt, d-c. ship supply. Protection of the operators and apparatus is provided by means of relays and contactors in the high-voltage supply circuits which prevent the high voltages from being applied if the filament or grid circuits are not closed or if the doors of the transmitter are open.

An illustration of the ship's transmitter is shown in Fig. 12. The picture is somewhat out of perspective owing to difficulty in taking the photograph in the limited space available on shipboard.

The receiving problem on shipboard is complicated by a number of factors. The transmitting and receiving

frequencies must be within a few per cent of each other, if the best transmission conditions for the time and place are to be utilized and if the frequencies are to remain in the bands assigned internationally to the mobile services. This requirement, as well as the noise conditions on shipboard, calls for a receiver of high selectivity, which is obtained, in the present instance, by the use of a double-detection set. The over-all selectivity is accomplished both by having a number of

Fig. 13—Receiver on SS. Leviathan

highly selective circuits ahead of the first detector and by using tuned circuits in the intermediate frequency stages, the high-frequency selectivity being used primarily to prevent overloading of the first tube and the intermediate frequency circuits being used to obtain the final selectivity required.

A reduction of the disturbances due to stay noises and better discrimination against the transmitted carrier is obtained if the transmitting and receiving antennas are widely spaced. On the other hand, for operating reasons, it is desirable to have the transmitter and receiver located in the same room. In the case of the *Leviathan* installation, the transmitting antenna is located directly above the radio room, between the second and third stacks, and the receiving antenna is placed as far as possible behind the third stack. The receiving antenna is connected through a suitable step-down circuit to a shielded transmission line, the other end of which is connected to the receiver, the receiver itself being very thoroughly shielded to avoid direct interference from the transmitter. On account of limited space, only two antennas are provided to handle the four frequencies, each antenna representing a compromise between the most efficient antennas which could be put up to handle the separate wavelengths.

As stated above, the receiver itself is of the double-detection type, using heater type tubes throughout. Screen-grid tubes are used for the first detector and intermediate frequency amplifiers and three-element tubes in the remaining positions. A photograph of the receiver and associated voice-frequency equipment, as it is installed on the *Leviathan*, is shown in Fig. 13, and a diagrammatic representation of the receiver is shown in Fig. 14. The high-frequency selective system consists of four separately shielded tuned circuits, coupled by small capacities. The use of a screen-grid tube in the detector circuit gives a twofold advantage over the use of a three-element tube in that a higher input impedance is maintained at the higher frequencies and the necessity for neutralizing against the reaction of the beating oscillator on the input circuit is eliminated. The beating voltage is made of the order of 75 to 100 volts for the purpose of reducing the effective tube noise in the detector plate circuit. With this arrangement no d-c. plate voltage is ordinarily required The screen voltage is 22 volts. The output circuit is tuned to the intermediate frequency of 300,000 cycles and connection with the first intermediate amplifier is effected by means of a low impedance transmission line. The intermediate frequency amplifier stages are coupled by means of double tuned circuits. The use of properly designed circuits of this type makes it possible to obtain a high degree of selectivity against undesired frequencies while obtaining sufficient band width to maintain ease of tuning and to pass the desired fre-

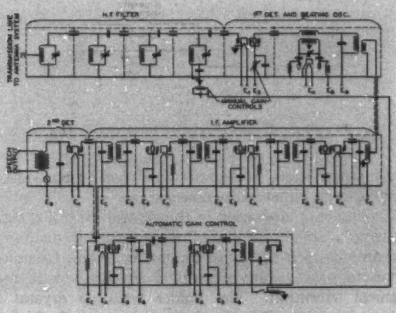


Fig. 14—Ship Receiver Schematic Diagram

quencies. The second detector is of the conventional grid bias type. Automatic gain control is provided in which a certain amount of the carrier is taken at the end of the intermediate frequency stages, amplified and rectified. The resulting d-c. current produces a voltage drop across a resistance, which is applied to the grid of the first detector in such a manner that an increase in the intermediate frequency output brings about a reduction in the total set gain and vice versa. Manual gain control for following wide changes in the received fields is accomplished by variation of the

voltages applied to the grid and the screen of the first detector.

The voice-frequency equipment, in addition to the desk telephone set located in the subscriber's booth, comprises a technical operator's position located adjacent to the ship's receiver, and an attendant's desk located on a lower deck in a room adjacent to the subscriber's booth. The control equipment consists of repeaters, volume control devices, and volume indicators, by means of which the levels of the incoming and outgoing signals can be properly adjusted. Keys are provided which enable the technical operator to talk either over the radio circuit or to the ship subscriber. The booth attendant has facilities by which he can talk either to the subscriber or to the control operator and has a connection with the ship's telephone system for the purpose of locating persons on the ship and calling

Fig. 15—Subscriber's Booth on Leviathan

them to the radio telephone booth. The subscriber's booth is provided with a desk telephone set having a high-grade transmitter. The outgoing and incoming circuits are shielded from each other and brought separately to the transmitter and receiver of the subscriber's set. An illustration of the subscriber's booth on the *Leviathan* is shown in Fig. 15.

## The Wavelength Situation and Simultaneous Telephone and Telegraph Operation

Communication between ship and shore is carried out by the use of a pair of frequencies, one for transmission in each of the two directions, separated from each other by about 3 per cent. The specific frequencies which were first assigned by the Federal Radio Commission to the shore station and the *Leviathan* were necessarily chosen on more or less of a makeshift basis, in the absence of any comprehensive wavelength plan for this new service. The Commission has recently had under study the setting up of more adequate provisions for ship-to-shore telephone channels, whereby it is hoped a series of frequencies may be designated for telephone service exclusively and whereby there may be established the relation between the telephone and the telegraph frequencies necessary for the avoidance of interference between the two services. Especially is coordination of the two sets of frequencies necessary on the larger vessels, in order that simultaneous telegraph and telephone service may be given without mutual

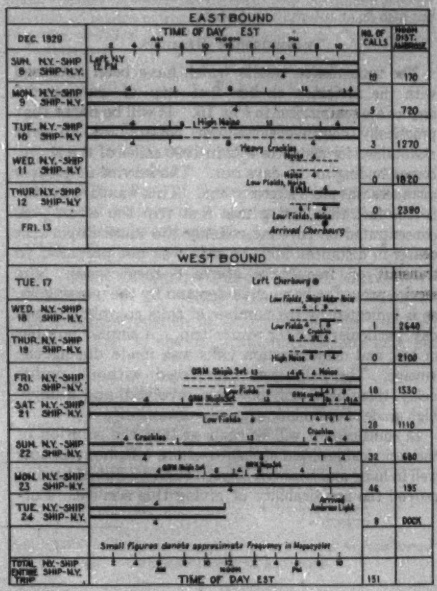


Fig. 16—Transmission Results between SS. Leviathan and New York

interference. On the larger liners simultaneous use of the radiotelephone and radiotelegraph service must be provided for. This means that the transmitters of both services must keep accurately on their frequencies and be free of spurious components, and that the receivers must be highly selective. It further entails that the transmitting and receiving frequencies in each of the two cases be so coordinated that the transmission frequency of one service does not lie too near the receiving frequency of the other, and bespeaks a considerable amount of mutual cooperation between the operating agencies involved. Difficulties of fitting in the two services were encountered in the early work on the

*Leviathan* and, although the problem has not been worked out to final solution, sufficient progress has been made, in cooperation with the engineers of the Radio Corporation of America, to enable the telegraph and telephone services to be conducted simultaneously without undue interference.

In view of the fact that ships of a number of nations are already preparing to give radio telephone service on the transatlantic routes and with the probability of this service also extending to other parts of the world, it would appear to be a matter of importance that the whole question of marine frequency allocations be worked out in the near future not merely on a national but also on an international basis.

### Transmission Results

The transmission results which have been obtained with the *Leviathan* on her first trip of commercial service are summarized in Fig. 16. It will be noted that practically continuous 24-hour communication was maintained for distances within 1000 miles of the shore, corresponding to two days out. The service at greater distances was more intermittent. This was largely due to the fact that during this first trip the effort was concentrated on covering reliably the more important nearer-in distances, and the ship was not prepared to transmit on frequencies above 8 megacycles. The service proved to be much in demand by the passengers, as is indicated by the number of calls completed each day, particularly on the return trip. A similar number of test and demonstration calls was made during the voyage. The calls were completed without undue delay, there being only one ship involved, and a fairly high grade of communication was obtained.

In conclusion it will be realized that the solution of the technical problem of ship-to-shore telephony is now well in hand and has been carried to the point of having proved the practicability of giving this service. Further problems are naturally arising in carrying the development into more general effect, particularly operating problems and those concerned with the international coordination of the service. The indications are that the larger transoceanic ships will be rather generally equipped for telephony and that the service will become one of permanent value in the maritime field.

## Discussion

**W. B. Kirke:** I should like to ask the authors if there are other insulations beside the *Leviathan* installed?

**Lloyd Espenschied:** Yes, in addition to the *Leviathan* there are the *Majestic* and *Olympic* which have been equipped in England. All three ships are now giving service to both the English and the American sides of the Atlantic.

In reference to the suggestion which was just made, that a record be kept of the radio transmission effects for the purpose of establishing a possible correlation with natural phenomena, such as solar activity and magnetic storms, I might say that we do keep quite a careful record of quantitative measurements of radio transmission, made from day to day, and that we attempt to correlate these results with the occurrence of sunspots and magnetic storms. In general, there appears to be quite a definite correlation between variations in radio transmission and the 11-year cycle of solar activity. There is as yet no very consistent correlation between the individual sunspots and radio transmission. However, we do find that magnetic storms, *i. e.*, at abnormal conditions in the earth's magnetic field, are accompanied almost invariably by a reduced effectiveness of short-wave transmission across the North Atlantic. It may be of interest to know this: As a convenient means for quickly detecting the occurrence of a magnetic storm, we maintain a pair of wires, grounded at each end and each one hundred miles or so long, one wire running north and south, the other, east and west. We have current recorders continually in operation on these two circuits and find that the failure of short-wave transmission is almost invariably accompanied by abnormal fluctuations in ground current. This whole matter of the relationship between solar disturbances, magnetic storms, and radio transmission is, of course, a large and interesting field for exploration, and is being studied by a number of people. It is hoped that radio will prove to be a useful tool in helping to disclose the natural phenomena which are at work.

# Shunt Resistors for Reactors

BY F. H. KIERSTEAD,* H. L. RORDEN,* and L. V. BEWLEY*
Member, A. I. E. E. Associate, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—The object of this paper is to present the results of an investigation to determine the effect of resistors shunting current limiting reactors, on the impulse behavior of the typical system employing them. The typical system is reduced, without loss of essential generality, to a comparatively simple analytic network; and the impulse behavior of this network is then calculated mathematically. These calculations are adequately supported by test results with impulse generator and cathode ray oscillograph, both in the field and in the laboratory, and accurate agreement established. Methods are developed and illustrated for taking into account incident waves, such as those due to lightning, of arbitrary shape. Under the most unfavorable condition of wave shape and circuit conditions, voltages approaching four times that of the incident wave may be built up at the bus by reflections and oscillations. In general, through the use of a shunting resistor, of proper value, three beneficial results are obtained: (a) Oscillations are completely eliminated, thereby limiting the maximum voltage which can occur on the bus to never more than twice that of the incident wave. (b) The initial rise in voltage on the line side of the reactor, due to positive reflections, is reduced and can be held down to the final value corresponding to the tail of an infinite rectangular incident wave. (c) The internal oscillations in the reactor itself can be eliminated, and the voltage distribution improved. The extent to which these improvements can be realized, under a wide range of possible operating conditions, is discussed and illustrated in this paper. With some combinations, the improvements are very great, while for others, there is no appreciable gain. The criterion for utilization of shunt resistors is,—will the elimination of oscillations and the reduction of positive reflections, under the most unfavorable possible operating condition which can be experienced on a given system, be worth the cost?*

* * * * *

## Introduction

THIS paper is part of an extensive investigation of lightning waves on transmission lines, which has been under way for a number of years under the general direction of Mr. F. W. Peek, Jr.

There has been a wide divergence in the opinion of engineers as to the relative merits of resistors shunting current limiting reactors. Some have ascribed to them the property of reducing transient voltages, which apparatus has to stand, while others have felt they do not reduce these transients and, in some cases, may actually increase the voltage stresses in connected apparatus. The purpose of the investigation described in this paper was to determine by an analytical treatment of the apparatus and circuits involved, what benefits or detriments should be expected from the use of resistors.

The presentation of this investigation takes the following form:

I. The typical system using current limiting reactors is considered.

II. The general analytic network of the typical system is resolved into its generalized impedances and the progress of an incoming or incident wave through these impedances is outlined.

III. The equivalent circuit of the network is described.

IV. The shape of the incident waves used in the calculations is defined and the mathematical methods of dealing with them are described.

V. Formulas for calculating the effects of the incident wave on the typical system are given, together with the results of calculations on this system.

VI. Experimental results are given which show that the effect of waves upon such systems may be accurately calculated.

VII. The effect of a resistor on the internal distribution of voltage in a reactor is discussed and experimental results are shown.

VIII. General conclusions are drawn.

## I. Typical Circuit Using Current Limiting Reactors

In a typical system in which reactors are used, as shown in Fig. 1, the apparatus and circuits may be

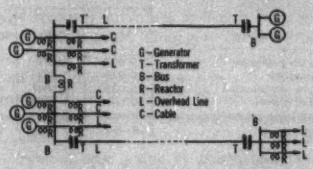


Fig. 1—Single Line Diagram of a Typical System using Current Limiting Reactors

represented for mathematical treatment of impulse voltages as follows:

1. Overhead lines by surge impedances of 300 to 600 ohms.
2. Underground cables by surge impedances of 30 to 90 ohms.
3. Station busses by capacitances to ground.
4. Terminal equipment by the equivalent circuits shown in Fig. 2. The use of a capacitance as the equivalent circuit of a transformer, has been established theoretically and experimentally.[1-7-10] The equivalent circuit for a generator was determined by Mr. E. W. Boehne and will be discussed in a paper by

*General Transformer Engg. Dept., General Electric Company, Pittsfield, Mass.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*

1. For references see Bibliography.



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him to be presented at the summer convention. Reactors behave practically as pure inductances in their external effect on traveling waves, as will be shown by

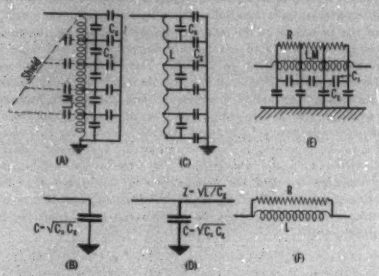


FIG. 2—EQUIVALENT CIRCUITS OF TERMINAL APPARATUS TO LIGHTNING SURGES

A. Transformer, ideal.
B. Transformer, approx.
C. Rotating machine, ideal.
D. Rotating machine, approx.
E. Reactor with shunt resistor, ideal.
F. Reactor with shunt resistor, approx.

the experimental results recorded in this paper. They range in value from 0.0002 to 0.010 henries.

The following table gives the range of effective capacitance to ground of apparatus and station busses.

| Apparatus | Capacitance in m. f. | | |
|---|---|---|---|
| | Max. | Min. | Ave. for all apparatus |
| Generators (salient poles) | 0.003 | 0.001 | 0.002 |
| Turbo alternators | 0.010 | 0.002 | 0.005 |
| Transformers (distribution) | 0.0020 | 0.0004 | 0.0010 |
| Transformers (power) | 0.0010 | 0.0002 | 0.0005 |
| Transformers (non-resonating) | 0.0050 | 0.002 | 0.003 |
| Bus systems | 0.015 | 0.002 | 0.005 |

## II. THE GENERAL ANALYTIC NETWORK OF A TYPICAL SYSTEM

The general analytic network of a typical system is shown in Fig. 3. It consists of the following generalized impedances:

1. Surge impedances of lines and cables—$z_1$, $z_2$ . . . . . $z_n$.
2. Series impedance (reactors, choke coils, series capacitors, etc.) $Z_1(p)$, $Z_2(p)$ . . . . . $Z_n(p)$.
3. Shunt impedances to ground (transformers, generators, busses, etc.) $Z_e(p)$.
4. Impedances $Z_e(p)$ and $Z(p)$ which consist of several impedances in series and in parallel, included together to simplify mathematical treatment.

An incident wave $e_1$ traveling along line $z_1$ and striking impedance $Z_e(p)$ causes:

1. A reflected wave $e_1'$ which combines with $e_1$ to give a total potential $e_1''$ at the transition point.
2. Refracted waves transmitted to the other lines, $e_2''$, $e_3''$ . . . . . $e_n''$.
3. A potential $e$ across the shunt impedance $Z_e(p)$ to ground.
4. Potentials $E_1$, $E_2$ . . . . . $E_n$ across the series impedances $Z_1(p)$, $Z_2(p)$ . . . . . $Z_n(p)$.

The general mathematical solution of this circuit is given in Appendix I.

## III. EQUIVALENT CIRCUIT OF THE NETWORK

The circuit that has been used (as the equivalent of the network of a typical system in which reactors are placed) in the calculations of this investigation

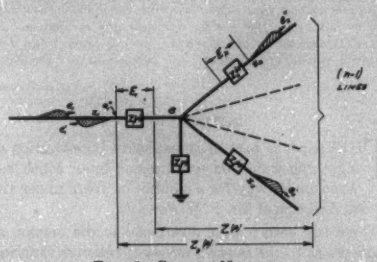


FIG. 3—GENERAL NETWORK

is shown in Fig. 4 and its complete solution is given in Appendix II. In this figure, the surge impedance $z_1$ is the feeder (either overhead line or underground cable) which carries the oncoming incident wave $e_1$. This feeder terminates at the bus in a reactor unit of inductance $L$, shunt resistance $R$, and an effective series resistance $r$ (due primarily to the transient skin effect of the lightning wave). Tests with a typical impulse on a reactor of 0.002 henrys inductance indicated an effective series resistance of about 100 ohms. The total equivalent capacitance to ground, due to all terminal equipment (including transformers, generators, and busses) has been lumped as a single capacitance $C$. All outgoing feeders as well as the effective surge impedances of rotating apparatus, have been lumped as a single outgoing feeder of surge impedance $z_2$. Atten-

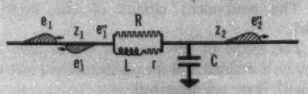


FIG. 4—EQUIVALENT CIRCUIT OF LINES, REACTOR AND TERMINAL APPARATUS

tion is called to the fact that in a typical power system, there would also be reactors in the outgoing feeders, but including them in the analysis increases the order of the differential equations so that their explicit solution becomes too involved. The error introduced by omitting these inductances is not great, and will be

discussed later on. When the incident wave $e_1$, strikes the junction, a part $e_1'$ is reflected back, and a part $e_2''$ passes on to the outgoing feeders as a transmitted wave.

## IV. Shapes of the Incident Wave Used in Calculations and Mathematical Method of Dealing with Them

There are usually three ways in which the effect of wave shape may be computed:

(a) Substitute in the circuit equations of the variable, the operational equivalent for the analytical expression of the wave and solve the resultant operational equations. This practise raises the degree of the differential equation and may therefore complicate it too much to allow of a rational solution.

(b) Find the solution for an infinite rectangular wave, and then through the application of Duhamel's theorem, find the solution corresponding to the time function of the applied wave. This practise necessitates making a complicated integration which may prove impossible except in very simple cases.

(c) By means of Heaviside's shifting theorem, find

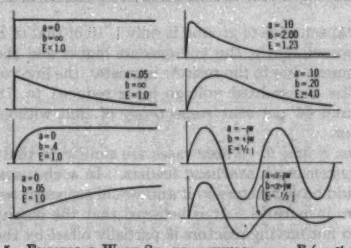


Fig. 5—Empirical Wave Shapes given by $e = E\,(\epsilon^{-at} - \epsilon^{-bt})$

solutions for simple exponential applied waves. Then the solution corresponding to more complicated waves, which are compounded of exponentials, is found by superposition of solutions.

The computations in this paper have been based on this third method which is more fully described in Appendix I.

Examples of waves which may be built up out of a pair of exponential waves are shown in Fig. 5. These also may be compounded. For instance, if it is required to find the solution corresponding to a "typical lightning surge" having a damped high-frequency oscillation, a superposition of the 6th and 8th waves of Fig. 5 (with the constants adjusted, of course, to give the proper wave-fronts, crests, tails, frequencies, and damping) will prove quite satisfactory.

The formulas and methods given in this paper for the calculation of reflected and transmitted voltages apply for an incident wave having any of the shapes given in Fig. 5. The computations of reflected and transmitted waves have been based on incident waves of shapes similar to the 1st, 2nd, and 6th waves in Fig. 5.

## V. Formulas for Calculating the Effects of an Incident Wave on the Typical System, and Results of Calculations

In this section are given the calculated effects of impulses on a network having an equivalent circuit as shown in Fig. 4.

The derivation of the equations which were used in making these calculations is given in Appendix II. It is based on an incident wave of the shape given by the equation $e_1 = E_1\,\epsilon^{-at}$.

The equation of the reflected wave is:

$$\begin{aligned} e_1' &= x\,E_1\epsilon^{-at} + y\,E_1\,\epsilon^{-at}\sin(\omega t + \phi) \\ &= x\,E_1\,\epsilon^{-at} + Y\,E_1\,\epsilon^{-at}\sinh(\Omega t + \Phi) \\ &= x\,E_1\,\epsilon^{-at} + E_1\,\epsilon^{-at}\,(W_1\,\epsilon^{\Omega t} - W_2\,\epsilon^{-\Omega t}) \end{aligned}$$

The equation of the transmitted wave is:

$$\begin{aligned} e_2'' &= u\,E_1\,\epsilon^{-at} + v\,E_1\,\epsilon^{-at}\sin(\omega t + \psi) \\ &= u\,E_1\,\epsilon^{-at} + V\,E_1\,\epsilon^{-at}\sinh(\Omega t + \Psi) \\ &= u\,E_1\,\epsilon^{-at} + E_1\,\epsilon^{-at}\,(J_1\,\epsilon^{\Omega t} - J_2\,\epsilon^{-\Omega t}) \end{aligned}$$

The definition of each of the symbols has been given in Appendix II and for the sake of brevity is not repeated here.

Values of $\alpha$, $\omega = j\,\Omega$, $x$, $y = Y/j$, $\phi = j\,\Phi$, $W_1$, $W_2$, $u$, $v = V/j$, $\psi = j\,\Psi$, $J_1$ and $J_2$ are tabulated for various combinations of $r$, $L$, $R$, $C$, $z_1$ and $z_2$ as follows:

1. Table I for $a = 0$ in $e_1 = (\epsilon^{-at}$ rectangular wave of unit height).
2. Table II for $a = 0.1 \times 10^6$.
3. Table II for $a = 0.2 \times 10^6$.

Curves drawn from values in Table I are plotted in Figs. 6 to 17 inclusive. They give the total voltage on each side of the reactor ($e_1'' = e_1 + e_1'$ and $e_2''$) resulting from the incident wave $e = \epsilon^{-at}$ where $a = 0$. Also on Figs. 6, 7, 8, 12, and 13, are drawn for comparison $e_1''$ and $e_2''$ corresponding to the incident wave $e_1 = 4\,(\epsilon^{-0.1t} - \epsilon^{-0.2t})$. This wave has a seven microsecond front, a crest value of unity, and the tail decreases to ½ of the crest value in 20 microseconds. The data used in plotting these latter curves were taken from Tables II and III. They are plotted below the zero axis to avoid interference with the waves corresponding to the rectangular incident wave.

The waves plotted on the left hand side of the figures give the voltages obtained with no resistor ($R = \infty$) shunting the reactor while those on the right hand side correspond to a 1000-ohm resistor shunting the reactor.

*Fig. 6.* Referring to Fig. 6 and Fig. 4 it will be noted that the curves apply to the case of an impulse coming from an overhead line and passing through a reactor into a capacitance to ground. This case represents a transformer at the end of a line with a reactor between it and the line. It also represents the case where all the feeders except one have been disconnected from the bus with the wave entering on this remaining

TABLE I
(Calculated) $a = 0$, $r = 100$, $L = 0.002$

| $Z_1$ | $Z_2$ | $C\ 10^{-6}$ | $R$ | $\alpha\ 10^6$ | $\omega\ 10^6$ | $x$ | $y$ | $\phi$ | $W_1$ | $W_2$ | $e_1''$ max. | n | p | $\psi$ | $J_1$ | $J_2$ | $e_2''$ max. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 400 | ∞ | 0.0050 | ∞ | 0.124 | 0.291 | 1.00 | 1.37 | 180 | .. | .. | 2.200 | 2.00 | 2.17 | −66.8 | .. | .. | 2.735 |
| " | " | " | 1000 | 0.168 | 0.224 | 1.00 | 1.13 | 210.4 | .. | .. | 2.064 | 2.00 | 2.01 | 263.7 | .. | .. | 2.227 |
| " | " | 0.0005 | ∞ | 0.125 | 0.092 | 1.00 | 0.40 | 180 | .. | .. | 2.225 | 2.00 | 2.02 | −82.8 | .. | .. | 3.392 |
| " | " | " | 1000 | 0.310 | 0.362 | 1.00 | 0.71 | 306 | .. | .. | 2.014 | 2.00 | 3.95 | −30.4 | .. | .. | 2.194 |
| 400 | 400 | 0.0050 | ∞ | 0.375 | 0.291 | 0.111 | 0.916 | 104.4 | .. | .. | 2.000 | 0.889 | 1.46 | 217.8 | .. | .. | 1.051 |
| " | " | " | 1000 | 0.418 | 0.020 | 0.102 | 0.780 | 24.5 | .. | .. | 1.438 | 0.898 | 4.60 | 191.2 | .. | .. | 0.898 |
| " | " | 0.0005 | ∞ | 2.625 | $j2.154$ | 0.111 | $-j0.124$ | $j2.66$ | .. | .. | 2.000 | 0.889 | $+j0.62$ | $-j1.16$ | −0.985 | −0.097 | 0.942 |
| " | " | " | 1000 | 3.310 | $j$ 3.035 | 0.102 | $-j0.452$ | $j0.67$ | 0.442 | 0.116 | 1.492 | 0.898 | .. | .. | −0.468 | 0.430 | 0.898 |
| 400 | 50 | 0.0050 | ∞ | 2.125 | $j1.85$ | −0.455 | $-j0.065$ | $j3.77$ | 1.445 | 0.001 | 2.000 | 0.182 | $-j0.104$ | $-j1.33$ | −0.195 | −0.014 | 0.191 |
| " | " | " | 1000 | 2.168 | $j1.96$ | −0.479 | $-j0.246$ | $j3.02$ | 0.924 | 0.016 | 1.431 | 0.185 | .. | .. | −0.122 | −0.063 | 0.185 |
| " | " | 0.0005 | ∞ | 20.13 | $j19.85$ | −0.455 | 0 | $j5.99$ | 1.455 | 0.000 | 2.000 | 0.182 | $-j0.030$ | $-j2.48$ | −0.183 | −0.001 | 0.182 |
| " | " | " | 1000 | 20.81 | $j20.61$ | −0.479 | $-j0.268$ | $j1.94$ | 0.927 | 0.019 | 1.431 | 0.185 | .. | .. | −0.117 | −0.068 | 0.185 |
| 50 | ∞ | 0.0050 | ∞ | 0.038 | 0.314 | 1.00 | 0.159 | 180 | .. | .. | 2.091 | 2.00 | 2.015 | 263.2 | .. | .. | 3.370 |
| " | " | " | 1000 | 0.132 | 0.296 | 1.00 | 0.165 | 215.3 | .. | .. | 2.029 | 2.00 | 2.040 | 281.0 | .. | .. | 2.601 |
| " | " | 0.0005 | ∞ | 0.038 | 0.999 | 1.00 | 0.05 | 180 | .. | .. | 2.042 | 2.00 | 2.001 | 267.9 | .. | .. | 3.774 |
| " | " | " | 1000 | 0.989 | 0.263 | 1.00 | 0.19 | 210.7 | .. | .. | 2.000 | 2.00 | 7.25 | 196.0 | .. | .. | 2.000 |
| 50 | 400 | 0.0050 | ∞ | 0.288 | 0.234 | 0.818 | 0.153 | 86.9 | .. | .. | 2.000 | 1.455 | 2.303 | 219.1 | .. | .. | 1.726 |
| " | " | " | 1000 | 0.382 | $j0.066$ | 0.815 | $-j0.108$ | $j0.76$ | .. | .. | 1.903 | 1.479 | $-j2.364$ | $-j0.59$ | .. | .. | 1.429 |
| " | " | 0.0005 | ∞ | 2.538 | $j2.25$ | 0.818 | $-j0.019$ | $j2.96$ | .. | .. | 2.000 | 1.455 | $+j0.758$ | $-j1.40$ | .. | .. | 1.517 |
| " | " | " | 1000 | 3.489 | $j3.28$ | 0.815 | $-j0.102$ | $j0.79$ | 0.113 | 0.024 | 1.918 | 1.479 | .. | .. | −0.945 | 0.534 | 1.479 |
| 50 | 50 | 0.0050 | ∞ | 2.038 | $j1.94$ | 0.500 | $-j0.013$ | $j4.33$ | 0.500 | 0.000 | 2.000 | 0.500 | $-j0.163$ | $-j1.84$ | −0.513 | 0.013 | 0.511 |
| " | " | " | 1000 | 2.132 | $j2.04$ | 0.476 | $-j0.077$ | $j3.42$ | 0.432 | 0.003 | 1.912 | 0.524 | .. | .. | −0.443 | 0.081 | 0.522 |
| " | " | 0.0005 | ∞ | 20.04 | $j19.94$ | 0.500 | 0 | $j5.99$ | 0.500 | 0.000 | 2.000 | 0.500 | $-j0.050$ | $-j2.99$ | −0.501 | 0.001 | 0.501 |
| " | " | " | 1000 | 20.99 | $j20.89$ | 0.476 | $-j0.105$ | $j2.12$ | 0.435 | 0.006 | 1.908 | 0.524 | .. | .. | −0.434 | 0.000 | 0.522 |

feeder. It seems probable that such cases rarely occur in practise.

It is to be noted that with a rectangular wave, the maximum voltage on the line side of the reactor is 2.2 times the incident wave and that the transmitted voltage is 2.74 times the incident wave. When the

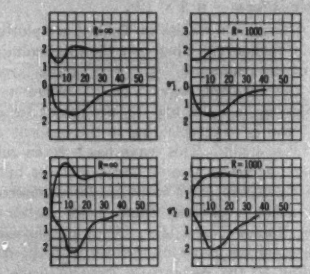


FIG. 6—$r = 100$, $L = 0.002$, $Z_1 = 400$, $Z_2 = \infty$, $C = 0.005 \times 10^{-6}$

reactor is shunted by a 1000-ohm resistor, the voltage on the line side is reduced to 94 per cent of the voltage without resistors and on the other side to 81½ per cent. With the wave having a 7-microsecond front, the voltage on the line side is practically unchanged by the shunt resistor while on the other side the voltage is reduced to 90 per cent of the voltage without resistors. A greater improvement would have resulted if the shunt resistance had been of approximately the same magnitude as the surge impedance $Z_1$.

*Fig. 7.* This case is very similar to that of Fig. 6. The capacitance to ground is only 1/10 of that of Fig. 6 and consequently, the voltages are higher and the improvement due to the resistor is greater, the line voltage and the transmitted voltage being reduced to 73 per cent and 64 per cent respectively of that without the resistor.

*Figs. 8 and 9.* These cases are similar to that of a bus system with overhead feeders. In such a system, $z_2$ would have reactors in it and would represent several feeders in parallel. It is believed that the inaccuracy due to not having reactors is partially offset by the use

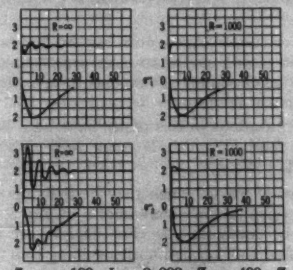


FIG. 7—$r = 100$, $L = 0.002$, $Z_1 = 400$, $Z_2 = \infty$, $C = 0.0005 \times 10^{-6}$

of the surge impedance of only one line. The fact that the transmitted voltage is low and that its wave front is not as steep as that of the incident wave (due to the shunt capacitance), in a measure justifies this simplification of the circuit.

The improvement due to the resistor is chiefly on the line side of the reactor. The voltage at this point is

TABLE II—(Calculated) $a = 0.1 \times 10^6$, $r = 100$, $L = 0.002$

| $Z_1$ | $Z_2$ | $C\ 10^{-4}$ | $R$ | $a\ 10^6$ | $\omega\ 10^6$ | $x$ | $y$ | $\phi$ | $W_1$ | $W_2$ | $u$ | $v$ | $\phi$ | $J_1$ | $J_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 400 | ∞ | 0.0050 | ∞ | 0.125 | 0.2905 | 1.471 | 1.494 | 198.4° | | | 2.353 | 2.362 | 265.1° | | |
| " | " | " | 1000 | 0.1679 | 0.2245 | 1.466 | 1.341 | 220.4° | | | 2.34 | 2.41 | 253.6° | | |
| " | " | 0.0005 | ∞ | 0.125 | 0.9922 | 1.041 | 0.4064 | 185.7° | | | 2.030 | 2.031 | 205.6° | | |
| " | " | " | 1000 | 0.811 | 0.358 | 1.022 | 1.35 | 335.8° | | | 2.03 | 4.44 | 333.8° | | |
| 400 | 400 | 0.0050 | ∞ | 0.3750 | 0.2905 | 0 | 1.068 | 113.3° | | | 1.250 | 1.721 | 229.6° | | |
| " | " | " | 1000 | 0.418 | 0.01063 | −0.01407 | 1.012 | 25.0° | | | 1.268 | 6.03 | 102.1° | | |
| " | " | 0.0005 | ∞ | 2.625 | −j2.154 | −0.1297 | −0.490 | j1.57 | 0.694 | 0.1177 | 1.153 | j0.705 | j1.64 | −0.734 | 0.437 |
| " | " | " | 1000 | 3.3107 | j3.034 | −0.1479 | −0.570 | j0.89 | | | 1.171 | | | | |
| 400 | 50 | 0.0050 | ∞ | 2.125 | j1.848 | −1.221 | −0.8990 | j1.66 | 0.0169 | 0.2020 | 0.3015 | −j0.1308 | j1.54 | −0.2369 | 0.0646 |
| " | " | " | 1000 | 2.168 | j1.963 | −1.1352 | −0.8455 | j2.33 | | 0.3015 | 0.2863 | j0.03812 | j2.71 | −0.2272 | 0.0656 |
| " | " | 0.0005 | ∞ | 20.125 | j19.85 | −1.299 | −0.2638 | j2.55 | 1.807 | 0.2967 | 0.2967 | | | | |
| " | " | " | 1000 | 20.51 | j20.61 | −1.360 | −0.3750 | j2.26 | | 0.0194 | | | | | |
| 50 | ∞ | 0.0050 | ∞ | 0.0375 | 0.3140 | 1.049 | 0.1573 | 198.1° | | | 1.951 | 1.900 | 281.3° | | |
| " | " | " | 1000 | 0.1321 | 0.2955 | 1.049 | 0.1793 | 223.2° | | | 1.941 | 2.22 | 290.1° | | |
| " | " | 0.0005 | ∞ | 0.0375 | 0.9993 | 1.005 | 0.04997 | 185.7° | | | 1.945 | 1.999 | 296.4° | | |
| " | " | " | 1000 | 0.9868 | 0.3026 | 1.004 | 0.205 | 330.7° | | | 1.993 | 8.40 | 193.8° | | |
| 50 | 400 | 0.0050 | ∞ | 0.2875 | 0.2342 | 0.7778 | 0.2250 | 99.1° | | | 2.222 | 2.846 | 231.3° | | |
| " | " | " | 1000 | 0.3821 | j0.00508 | 0.7723 | −j0.07912 | j1.20 | | | 2.278 | −j3.243 | j0.85 | | |
| " | " | 0.0005 | ∞ | 2.5375 | j2.250 | 0.7208 | −j0.02374 | j3.16 | | | 2.278 | −j0.483 | j1.61 | −1.811 | 0.543 |
| " | " | " | 1000 | 3.489 | j0.328 | 0.7119 | −0.1441 | j1.10 | 0.2169 | 0.0239 | 2.352 | | | | |
| 50 | 50 | 0.0050 | ∞ | 2.0375 | j1.9360 | 77.0 | 0 | | | 0 | 80 | −j2.065 | j4.33 | −80.012 | −0.012 |
| " | " | " | 1000 | 2.132 | j20.36 | 11.17 | | | 73 | 0.0035 | −10.43 | | | 11.71 | 1.28 |
| " | " | 0.0005 | ∞ | 20.0375 | j19.937 | −797 | 0 | | −10.27 | 0 | 800 | −j3.006 | | −800 | 0 |
| " | " | " | 1000 | 20.99 | j20.89 | 10.10 | | | 798 | 0.0042 | −9.133 | | | 9.215 | 0.060 |

approximately 75 per cent of the voltage without the resistor when the incident wave is rectangular. The improvement is less for sloping waves, being inappreciable for the 7-microsecond wave as is shown by the waves below the zero axis in Fig. 8. The actual improvement depends on the steepness of the waves which occur in practise.

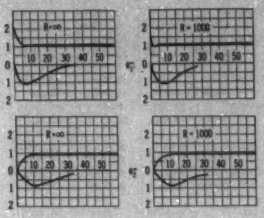


Fig. 8—$\tau = 100$, $L = 0.002$, $Z_1 = 400$, $Z_2 = 400$, $C = 0.005 \times 10^{-4}$

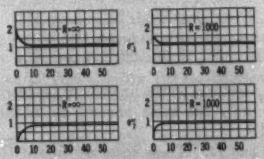


Fig. 9—$\tau = 100$, $L = 0.002$, $Z_1 = 400$, $Z_2 = 400$, $C = 0.0005 \times 10^{-4}$

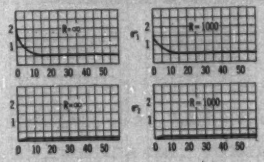


Fig. 10—$\tau = 100$, $L = 0.002$, $Z_1 = 400$, $Z_2 = 50$, $C = 0.005 \times 10^{-4}$

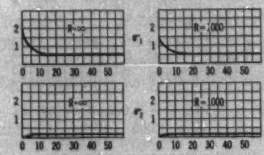


Fig. 11—$\tau = 100$, $L = 0.002$, $Z_1 = 400$, $Z_2 = 50$, $C = 0.0005 \times 10^{-4}$

*Figs. 10 and 11.* These cases are very similar to those of Figs. 8 and 9, the difference being in the change of the impedance $z_2$ from 400 ohms to 50 ohms. The cases of Figs. 8 and 9 merge into these as the number of feeders is increased. Here, also, the improvement

TABLE III
(Calculated) $\alpha = 0.2 \times 10^6$, $r = 100$, $L = 0.002$

| $Z_1$ | $Z_2$ | $C\ 10^{-4}$ | $R$ | $\alpha\ 10^6$ | $\omega\ 10^6$ | $x$ | $y$ | $\phi$ | $W_1$ | $W_2$ | $u$ | $v$ | $\psi$ | $J_1$ | $J_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 400 | ∞ | 0.005 | ∞ | 0.125 | 0.2905 | 1.889 | 1.452 | 217.8° | | | 2.222 | 2.295 | 284.5° | | |
| " | " | " | 1000 | 0.1679 | 0.2245 | 1.778 | 1.394 | 255.4° | | | 1.944 | 2.487 | 308.6° | | |
| " | " | 0.0005 | ∞ | 0.125 | 0.9922 | 1.081 | 0.4052 | 191.5° | | | 2.020 | 2.026 | 274.3° | | |
| " | " | " | 1000 | 0.8107 | 0.3584 | 0.9829 | 1.544 | 339.0° | | | 1.994 | 4.989 | 336.4° | | |
| 400 | 400 | 0.005 | ∞ | 0.375 | 0.2905 | −0.04348 | 1.2843 | 125.7° | | | 1.739 | 2.0304 | 238.9° | | |
| " | " | " | 1000 | 0.4179 | 0.01989 | −0.2537 | 1.4828 | 27.4° | | | 2.089 | 8.775 | 193.8° | | |
| " | " | 0.0005 | ∞ | 2.625 | $j$2.154 | −0.5484 | −$j$0.1667 | $j$2.93 | | | 1.613 | $j$0.8337 | $j$1.41 | | |
| " | " | " | 1000 | 3.3107 | $j$3.035 | −1.0614 | −$j$0.8770 | $j$1.30 | 1.6094 | 0.1195 | 2.1473 | | | −1.7033 | 0.4439 |
| 400 | 50 | 0.005 | ∞ | 2.125 | $j$1.848 | −4.448 | −$j$1.382 | $j$2.08 | 5.5345 | 0.0862 | 0.6897 | $j$0.2010 | $j$1.95 | −0.7040 | −0.0143 |
| " | " | " | 1000 | 2.168 | $j$1.962 | −32.25 | −$j$1.502 | $j$3.76 | 32.696 | 0.0172 | 4.375 | | | −4.3088 | 0.0662 |
| " | " | 0.0005 | ∞ | 20.125 | $j$19.85 | −4.344 | −$j$0.4035 | $j$3.28 | 5.3521 | 0.0076 | 0.6689 | $j$0.05827 | $j$ 3.13 | −0.6702 | −0.0012 |
| " | " | " | 1000 | 20.81 | 20.61 | −35.9 | | | 36.348 | 0.020 | 4.636 | | | −4.5670 | 0.0687 |
| 50 | ∞ | 0.005 | ∞ | 0.0375 | 0.314 | 1.080 | 0.1319 | 214.2° | | | 1.600 | 1.802 | 297.4° | | |
| " | " | " | 1000 | 0.1321 | 0.2955 | 1.073 | 0.1762 | 252.3° | | | 1.451 | 2.177 | 318.2° | | |
| " | " | 0.0005 | ∞ | 0.0375 | 0.9993 | 1.010 | 0.04942 | 191.4° | | | 1.951 | 1.977 | 279.2° | | |
| " | " | " | 1000 | 0.9893 | 0.2626 | 1.009 | 0.2430 | 334.7° | | | 1.927 | 8.926 | 347.5° | | |
| 50 | 400 | 0.005 | ∞ | 0.2875 | .2342 | 0.76 | 2.701 | 117.3° | | | 3.2 | 3.416 | 249.5° | | |
| " | " | " | 1000 | 0.3821 | $j$0.06608 | 0.6529 | −$j$0.1280 | $j$1.42 | | | 4.628 | $j$5.240 | $j$0.80 | | |
| " | " | 0.0005 | ∞ | 2.5375 | $j$2.2503 | 0.4 | −$j$0.0352 | $j$3.52 | 0.6005 | 0.0005 | 5.000 | $j$1.405 | $j$1.98 | −5.094 | −0.094 |
| " | " | " | 1000 | 3.489 | $j$3.280 | 1.625 | −$j$0.4984 | $j$.4984 | 2.5540 | 0.0243 | 21.87 | | | −21.32 | −0.56 |
| 50 | 50 | 0.005 | ∞ | 2.0375 | $j$1.937 | 1.5067 | | | −0.5066 | 0.0001 | −0.5333 | | | 0.5197 | −0.0137 |
| " | " | " | 1000 | 2.1321 | $j$1.036 | −2.845 | | | 3.6477 | −0.1025 | −0.3229 | | | 0.4083 | 0.0853 |
| " | " | 0.0005 | ∞ | 20.038 | $j$19.94 | 1.5006 | | | −0.5006 | 0 | −0.5031 | | | 0.5019 | −0.0013 |
| " | " | " | 1000 | 20.989 | $j$20.89 | 1.350 | | | −0.3957 | 0.0042 | −0.3061 | | | 0.3965 | 0.0904 |

due to the resistor is on the line side of the reactor and is of substantially the same amount as in the case of Figs. 8 and 9.

*Figs. 12 and 13.* These cases are similar to those of Figs. 6 and 7, differing only in that $z_1$ corresponds to a cable of 50 ohms surge impedance. Substantial oscillations occur in the transmitted wave causing it in

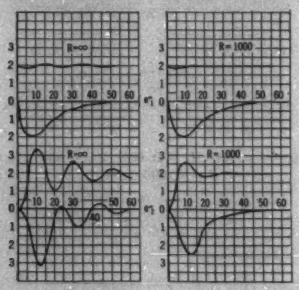


FIG. 12—$r = 100$, $L = 0.002$, $Z_1 = 50$, $Z_2 = \infty$
$C = 0.005 \times 10^{-4}$

the case of Fig. 12 to rise to 3.37 times the incident voltage and 3.77 times for Fig. 13. The reductions effected by the resistor for Figs. 12 and 13 are 23 per cent and 47 per cent respectively when the incident wave is rectangular and a much smaller amount for the 7-microsecond incident wave.

*Figs. 14 and 15.* These cases are similar to that of a bus system with underground cables. Here, the gain due to the resistor is not appreciable, due to the very large difference between the resistance of the resistor (1000 ohms) and the surge impedance of the cable (50 ohms). This does not represent a very practical case because $z_2$ would in practise, be considerably less than $z_1$, due to the large number of cables that would ordinarily be represented by $z_2$.

*Figs. 16 and 17.* This case represents the usual bus system with underground cable. Here again, the gain due to the resistor is negligible due to its high resistance. With a resistor of 50 ohms, the gain would be large as there would be no appreciable reflection and conse-

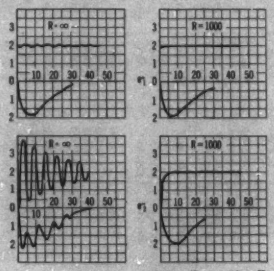


FIG. 13—$r = 100$, $L = 0.002$, $Z_1 = 50$, $Z_2 = \infty$,
$C = 0.0005 \times 10^{-4}$

quently, the line voltage would be very little higher than the incident wave. In other words, the voltage on the line side of the reactor would be decreased by the resistor from 2 times the incident voltage to not more than 1.1 times the incident voltage.

Attention is called to the fact that the resistance of the conductor ($r$) of the reactor is a variable depending on the steepness of the wave or the frequency of the

oscillation. For lightning waves, it is chiefly due to skin effect and its value for the reactor used in this investigation is of the order of 100 ohms. To treat the resistance as a variable in the equations makes their solution extremely difficult, if possible at all, due to the complicated manner in which the resistance changes

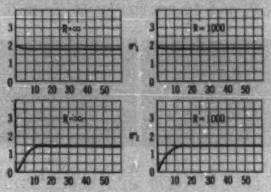


FIG. 14—$r$ = 100, $L$ = 0.002, $Z_1$ = 50, $Z_2$ = 400, $C$ = 0.005 × $10^{-6}$

with frequency or wave shape. For this reason, the calculations and curves have been made with ($r$) as a constant value of 100 ohms. This has not led to any

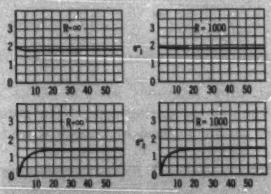


FIG. 15—$r$ = 100, $L$ = 0.002, $Z_1$ = 50, $Z_2$ = 400, $C$ = 0.0005 × $10^{-6}$

large error, except where $z_2$ is 50 ohms. Figs. 16 and 17 show cases where this applies. If ($r$) is considered as a constant of 100 ohms $e_1''$ approaches 1.5 times the incident wave and $e_2''$, 0.5 times as shown by the curves. Actually, ($r$) reduces down to much less than one ohm when the slope of the wave is zero. Therefore, $e_1''$ and $e_2''$ both approach the incident wave as a limit. One is chiefly interested in the wave at the time the voltages are maximum which occurs at the front of the wave. At this time, the resistance is of the order of 100 ohms and the voltages calculated are correct.

## VI. Experimental Results

In order to check the accuracy with which the transmitted wave, due to a given impulse may be calculated,

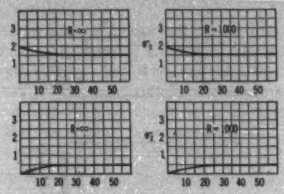


FIG. 16—$r$ = 100, $L$ = 0.002, $Z_1$ = 50, $Z_2$ = 50, $C$ = 0.005 × $10^{-6}$

tests were made, using the circuit shown at the top of Fig. 18. The results of these tests are tabulated in Table IV. The tested waves are shown by the oscillograms in Figs. 19, 20, 21, and 22. These waves are reproduced by curves below the oscillograms with the calculated voltages shown by points plotted on the curves.

The tests shown in Fig. 19 represent an impulse

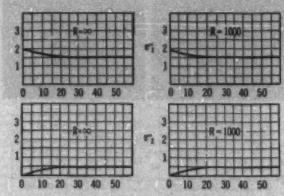


FIG. 17—$r$ = 100, $L$ = 0.002, $Z_1$ = 50, $Z_2$ = 50, $C$ = 0.0005 × $10^{-6}$

striking a reactor with the transmitted wave passing into a line of 600 ohms surge impedance. The tests shown by Fig. 20 are of the same nature except that the reactor is shunted by a resistor of 1200 ohms. These two tests are tabulated as Tests 1 and 2 in Table IV.

TABLE IV
Tests with L = 0.002 henry Reactor

| Test | $R_1$ | $R_2$ | $C_2$ | Crests kv. | | | Fronts microseconds | | | Frequency kilocycles | | Wavelengths | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $e_1$ | $e_2$ | $e_2/e_1$ | $e_1$ | $e_2$ | $e_2/e_1$ | $e_1$ | $e_2$ | $e_1$ | $e_2$ | $e_2/e_1$ |
| 1 | ∞ | 600 | 0 | 47 | 28.4 | 0.608 | 0.25 | 4 | 16.0 | 0 | 0 | 8 | 16 | 2.00 |
| 2 | 1200 | 600 | 0 | 47 | 25.6 | 0.545 | 0.25 | 3 | 12.0 | 0 | 0 | 8 | 9 | 1.12 |
| 3 | ∞ | ∞ | 0 | 47 | 86. | 1.83 | 0.25 | 1.8 | 7.2 | 0 | 275 | 11 | 12 | 1.09 |
| 4 | 1200 | ∞ | 0 | 47 | 52. | 1.105 | 0.25 | 0.25 | 1.00 | 0 | 0 | 13 | 13 | 1.00 |
| 5 | ∞ | ∞ | 0.00054 | 47 | 76.5 | 1.630 | 0.25 | 3.5 | 14.0 | 0 | 159 | 13 | 14 | 1.08 |
| 6 | 1200 | ∞ | 0.00054 | 47 | 53.2 | 1.130 | 0.25 | 2 | 8.0 | 0 | 0 | 11 | 10 | 0.91 |
| 7 | Thyrite | ∞ | 0.00054 | 47 | 51.1 | 1.086 | 0.25 | 0.25 | 1.00 | 0 | 150 | 13 | 13 | 1.00 |
| 8 | ∞ | ∞ | 0.0052 | 47 | 65.8 | 1.400 | 0.25 | 6 | 24.0 | 61.5 | 61.5 | 14 | 25 | 1.79 |
| 9 | 1200 | ∞ | 0.0052 | 47 | 51.1 | 1.086 | 0.25 | 6 | 24.0 | 0 | 48.5 | 9 | 8 | 0.89 |
| 10 | Thyrite | ∞ | 0.0052 | 47 | 52.7 | 1.122 | 0.25 | 0.25 | 1.00 | 0 | 50 | 13 | 13 | 1.00 |
| 11 | Thyrite | 0 | .. | 47 | 0 | 0 | 0.25 | .. | .. | 15.4 | 0 | 1.5 | .. | .. |
| 12 | 22 | 0 | .. | 47 | 0 | 0 | 0.25 | .. | .. | 0 | 0 | 1.5 | .. | .. |

They do not show any substantial difference in the transmitted wave although the resistor reduces the voltage 10 per cent. The chief value of the test is in showing how well the test checks with the calculation. Tests 3 and 4 represent an impulse striking a reactor at the end of an open ine. For the sake of brevity,

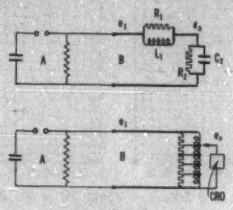


FIG. 18—TEST CIRCUITS

A. Impulse generator
B. Circuit under test

the oscillograms are not shown. The wave transmitted through the reactor without a resistor is oscillatory and is 1.83 times the wave on the other side of the reactor. When the reactor is shunted with a 1200-ohm

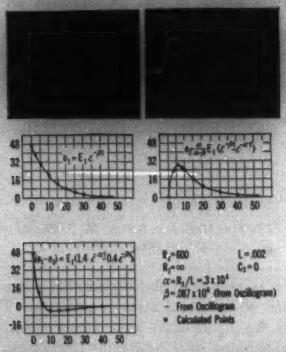


FIG. 19—IMPULSE TESTS ON REACTOR—NO SHUNT RESISTOR

resistor, the transmitted wave is not oscillatory and is only 1.10 times that on the other side of the reactor. The circuit of this test represents a feeder disconnected at the generating station. It may or may not be closed at the substation.

Tests 5, 6, and 7 represent an impulse striking a reactor in series with a transformer at the end of a line. The results of Tests 5 and 6 are shown in Figs. 21 and 22. When the reactor is not shunted by a resistor the transmitted wave is oscillatory and is 63 per cent greater than the wave on the other side of the reactor, while with a 1200-ohm resistor, the wave is not oscillatory and is only 13 per cent greater than on the other side. It will be seen from the calculated points plotted on Figs. 21 and 22, that the calculations agree closely with the tests. In Test 7, a thyrite resistor was used, having a resistance characteristic similar to that shown on Fig. 24. The transmitted wave was only 9 per cent greater than the wave on the other side.

Tests 8, 9, and 10 are similar to Tests 5, 6, and 7

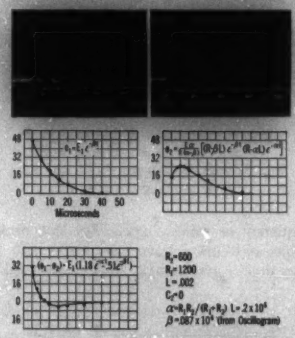


FIG. 20—IMPULSE TESTS ON REACTOR—WITH SHUNT RESISTOR

except that they represent several banks of transformers of the non-resonating type. The results of the test are very similar to those of Tests 5, 6, and 7.

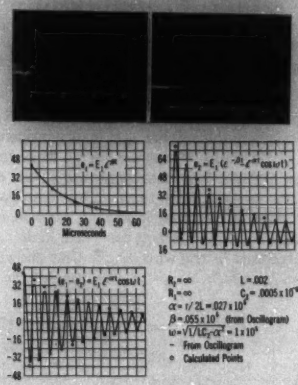


FIG. 21—IMPULSE TESTS ON REACTOR—NO SHUNT RESISTOR

The purpose of the tests described above was to check the general method of calculating the voltage transmitted through a reactor, due to an impulse. A definite total voltage ($e_1 = E_1\,\epsilon^{-\theta t}$) was applied to the test circuit shown in the upper diagram of Fig. 18 and the transmitted voltage was calculated and measured.

Transmitted voltages may be computed either in terms of the incident voltage (if it is known) or in terms of the total voltage at the reactor. These equivalent relationships are given by Equation (5), Appendix I. In the case of these tests, the impulse did not enter the reactor from a line, but was discharged from a capacitor close to the reactor, so that there was no incident wave

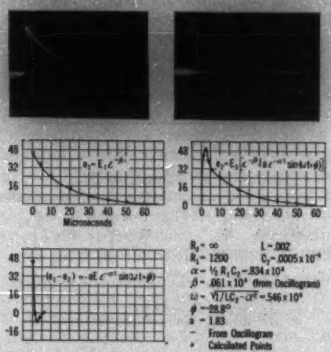


FIG. 22—IMPULSE TESTS ON REACTOR—WITH SHUNT RESISTOR

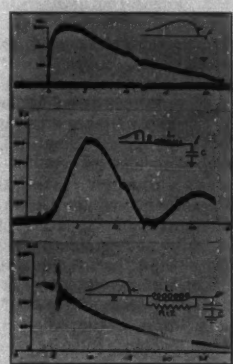

FIG. 23—IMPULSE TESTS WITH TRANSMISSION LINE TOP

Top: Open-circuited line
Middle: Reactor in series with transformer
Bottom: Reactor shunted by a resistor

(in the sense that the word is usually used). For this reason, the computed voltages are given in terms of the total voltage at the reactor. The close agreement between these tests and calculations shows that the general method of calculation is correct.

Tests* were made on a 5-mile length of a 66,000-volt transmission line under conditions similar to those for which Figs. 6, 7, 12, and 13 apply. The results of these tests are shown by the oscillograms in Fig. 23. The points of interest in these oscillograms are:

1. When the wave strikes the open end of the line, there is no oscillation.
2. When it passes, at the end of the line, through a reactor into a capacitance to ground an oscillation of greater crest voltage than in the first test, occurs.
3. When all the conditions are the same as in the second test, except that the reactor is shunted by a resistor, the oscillation is eliminated and the crest voltage is approximately the same as in the first test.

## VII. THE EFFECT OF A RESISTOR ON THE INTERNAL DISTRIBUTION OF VOLTAGE IN A REACTOR

In Appendix III are given formulas for calculating the internal distribution of voltage in a reactor both

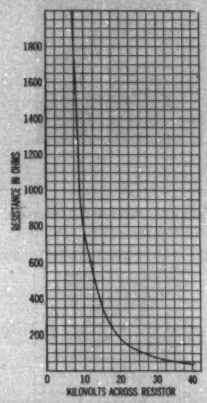


FIG. 24—VOLTAGE—RESISTANCE CHARACTERISTIC OF THYRITE

with and without a resistor in shunt. These formulas show that with no resistor, the distribution consists of a very complex oscillation superimposed on the linear distribution which represents the final state, but that with a properly chosen resistor, the oscillation is eliminated.

Tests were made to determine the internal distribution of voltage in a reactor of 0.002 henrys inductance with an applied wave of 50 kv. as follows:

1. Reactor not shunted by a resistor.
2. Reactor shunted by a 1000-ohm resistor with six intermediate points connected to the corresponding intermediate points of the reactor.

*These tests were made by Messrs. McEachron and Goodwin on the Turners Falls transmission line in 1929. The line is described in their paper, *Cathode Ray Oscillograph Study of Artificial Lightning Surges on the Turners Falls Transmission Line*, A. I. E. E. TRANS., Vol. 48, July 1929, p. 953.

3. Reactor shunted by a resistor having the characteristics shown in Fig. 24 and connected to intermediate points as noted under 2.

The circuit used in these tests is shown by the lower diagram of Fig. 18.

The results of the tests are shown in Figs. 25 and 26.

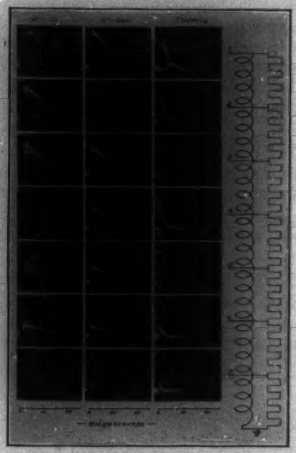

FIG. 25—OSCILLOGRAMS SHOWING INTERNAL VOLTAGE DISTRIBUTION IN REACTORS

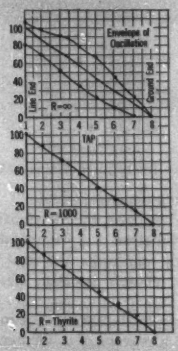


FIG. 26—EFFECT OF TIED-IN SHUNT RESISTOR ON INTERNAL VOLTAGE DISTRIBUTION

The oscillograms in Fig. 25 give the voltage across the reactor and also the voltage from the bottom terminal of the reactor to each of the points where the resistor was connected to the reactor. They show that there is quite an appreciable internal oscillation when the reactor is not shunted by the resistor but that the oscillation is eliminated when the reactor is shunted by the resistor.

The curves shown in Fig. 26 have been plotted from points taken from these oscillograms. They show that the distribution of voltage across the reactor is much more uniform than it is in a non-shielded transformer. The reason for this is that the ratio of ground capacitance to series capacitance in a reactor is relatively small. The absence of a secondary winding and a core make the ground capacitance small while the series capacitance is comparatively large. The curves show that the distribution is more nearly uniform with the reactor shunted by a resistor than it is with the reactor

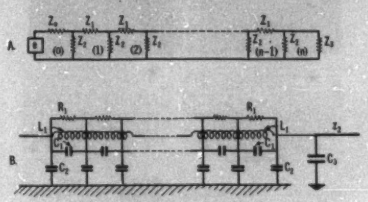


FIG. 27—NETWORKS OF PERIODIC SECTIONS

A. General impedances
B. Reactor with tied-in resistor units

not shunted. The resistor thus reduces the internal voltage stresses in the reactor by the elimination of the oscillations and making the voltage distribution more uniform.

## VIII. CONCLUSIONS

The following general conclusions can be drawn from the calculations and tests:

1. If an impulse passes into a circuit as shown in Fig. 4, where $z_2$ is very high or infinite, an oscillation results which gives rise to voltages which approach four times the incident voltage as a limit. These oscillations are entirely eliminated by shunting the reactor with a resistance approximately equal to the surge impedance $z_1$. Then the voltage rise is due to reflection and in the limit approaches two times the incident voltage.

2. If $z_2$ is not higher than $z_1$, no oscillations will occur, and the transmitted voltage will be equal to or lower than the incident wave. Here the advantage of the resistor is in lowering the reflected voltage on the line side of the reactor. In order to do this effectively, the resistance should be equal to or lower than the surge impedance ($z_1$) of the line. Then the reflected voltage will be very low and the maximum voltage on either side of the reactor will not be substantially greater than the incident voltage.

3. If a substantial voltage occurs across a reactor (due to an oscillation or to the reactor acting as a reflection point), the transient voltage that the line or bus has to stand as a result of the disturbance, is always reduced by shunting the reactor with a resistance of the proper value. Conversely, if shunting the reactor with the proper resistance does not reduce the transient voltage

that the line or bus has to stand, then it is because these transients are of such low frequency or such sloping wave fronts that they do not produce an appreciable voltage across the reactor.

### Summary

In general, through the use of a shunting resistor of proper value, three beneficial results are obtained: (a) Oscillations are completely eliminated, thereby limiting the maximum voltage which can occur on the bus to never more than twice that of the incident wave. (b) The initial rise in voltage on the line side of the reactor, due to positive reflections, is reduced and can be held down to the final value corresponding to the tail of an infinite rectangular incident wave. (c) The internal oscillations in the reactor itself can be eliminated, and the voltage distribution improved. The extent to which these improvements can be realized under a wide range of possible operating conditions is discussed and illustrated in this paper. With some combinations the improvements are very great, while for others, there is no appreciable gain. The criterion for utilization of shunt resistors is,—will the elimination of oscillations and the reduction of positive reflections, under the most unfavorable possible operating condition which can be experienced on a given system, be worth the cost?

### General Discussion

There are two essential conditions to be met in the design of shunt resistors for reactors. First, in order to give effective protection against lightning or other high-potential surges, the resistance should not be more than 400 ohms for overhead lines or 50 ohms for underground cables. Second, the resistor must not overheat when the reactor it is used with is undergoing short-circuit.

To meet the latter condition, a high resistance is necessary. The rate at which energy is absorbed by the resistor is $P = E^2/R$ where $E$ is the voltage across the resistor and $R$ is its resistance. Thus in a 13,800-volt circuit, the voltage across the reactor during short circuit is $13{,}800/\sqrt{3} = 7980$ volts, and if the reactor is for use with an underground cable, the resistor (in order to have maximum effectiveness in reducing transient voltages) should have a resistance of not over 50 ohms. The energy absorbed would then be at the rate of $\frac{7980^2}{50 \times 1000} = 1274$ kw. A resistor capable of absorbing so much energy without over-heating would be prohibitive in cost. For these reasons, a lower resistance for high voltages than for low voltages is essential. For instance, if the resistance is 600 ohms with 7980 volts r. m. s. across it and 50 ohms for 35 kv. crest (which is approaching the danger zone for 13.8 kv. circuits) it has the proper characteristic for the above case. In Fig. 24 is given the voltage-resistance curve of the type of resistor used. It will be noted that it has the required characteristics.

This investigation has treated only the effect of resistors upon voltages caused by impulses originating on a line and entering a bus system. High transient voltages may also originate on the bus itself, due to the interruption of a short-circuit. Such transients are trapped in the bus by the reactors in the outgoing feeders. By shunting each of these reactors with a resistor, a non-inductive path is provided for the escape of the energy of these voltages into the capacity of the feeders. The tendency for such a rise in voltage is thus materially reduced.

## Appendix I

### Relationships at a General Transition Point

One of the most general types of transition points met with in transmission systems consists of a junction at which there is a general impedance network to ground $Z_g(p)$; and $n$ transmission lines of surge impedances $(z_1, \ldots, z_n)$ joined through networks $Z_1(p) \ldots Z_n(p)$ respectively. Such a system is shown in Fig. 3. When an incident wave $e_1$ approaching along the line $z_1$ reaches the junction it will give rise to a wave $e_1'$ reflected back on line $z_1$; transmitted waves $e_2'', \ldots, e_n''$ on lines $z_2$ to $z_n$ respectively; and a potential $e$ at the junction. Now the total impedance at the end of $z_1$ is

$$Z_e(p) = Z_1(p) + Z(p) = Z_1(p) + \frac{1}{\dfrac{1}{Z_g(p)} + \displaystyle\sum_2^n \frac{1}{z_k + Z_k(p)}} \tag{1}$$

and the reflected potential wave on $z_1$ therefore is

$$e_1' = \frac{Z_e(p) - z_1}{Z_e(p) + z_1}\, e_1 \tag{2}$$

The total potential at the reflection point is

$$e_1'' = (e_1 + e_1') = \frac{2\,Z_e(p)}{Z_e(p) + z_1}\, e_1 \tag{3}$$

The current transmitted across $Z_1(p)$ is

$$i_1'' = \frac{e_1''}{Z_e(p)} = \frac{2}{Z_e(p) + z_1}\, e_1 \tag{4}$$

The potential at the grounding impedance network is

$$e = \frac{Z(p)}{Z_e(p)}\, e_1'' = \frac{2\,Z(p)}{Z_e(p) + z_1}\, e_1 \tag{5}$$

and the current through $Z_g(p)$ therefore is

$$i_g = \frac{e}{Z_g(p)} = \frac{Z(p)}{Z_e(p)}\,\frac{e_1''}{Z_g(p)} = \frac{2\,Z(p)}{Z_e(p) + z_1}\,\frac{e_1}{Z_g(p)} \tag{6}$$

The current and voltage waves transmitted to any line $k$ (where $2 \leq k \leq n$) are

$$i_k'' = \frac{e}{Z_k(p) + z_k} = \frac{Z(p)}{Z_e(p)}\,\frac{e_1''}{Z_k(p) + z_k} = \frac{2\,Z(p)}{Z_e(p) + z_1}\,\frac{e_1}{Z_k(p) + z_k} \tag{7}$$

$$e_k'' = z_k i_k'' = \frac{Z(p)}{Z_e(p)} \frac{z_k e_1''}{Z_k(p) + z_k}$$

$$= \frac{2Z(p)}{Z_e(p) + z_1} \frac{z_k e_1}{Z_k(p) + z_k} \tag{8}$$

The potential drops across the lumped impedance networks are

$$E_1 = e_1'' - e = \frac{Z_1(p)}{Z_e(p)} e_1'' = \frac{2Z_1(p)}{Z_e(p) + z_1} e_1 \tag{9}$$

$$E_k = e - e_k'' = \frac{Z_k(p)}{Z_k(p) + z_k} \frac{Z(p)}{Z_e(p)} e_1''$$

$$= \frac{Z_k(p)}{Z_k(p) + z_k} \frac{2Z(p)}{Z_e(p) + z_1} e_1 \tag{10}$$

The division of energy during the transition period at the junction furnishes a valid check in any specific case on the above relationships, and is of interest on its own account. At any time $t$, counting from the instant that the incident wave $e_1$ arrives at the junction, there is (dropping the $p$'s for simplicity)

$$\int_t^\infty e_1 \left( \frac{e_1}{z_1} \right) dt = \text{energy remaining in the incident wave} \tag{11}$$

$$\int_0^t e_1' \left( \frac{e_1'}{z_1} \right) dt = \text{energy in the reflected wave} \tag{12}$$

$$\int_0^t e_k'' \left( \frac{e_k''}{z_k} \right) dt = \text{energy in wave transmitted to line } k \tag{13}$$

$$\int_0^t E_k \left( \frac{E_k}{Z_k} \right) dt = \text{energy absorbed by impedance network } Z_k(p) \tag{14}$$

$$\int_0^t e \left( \frac{e}{Z_e} \right) dt = \text{energy absorbed by impedance network } Z_e(p) \tag{15}$$

Equating to the energy of the original incident wave, by the conservation of energy,

$$\int_0^\infty e_1 \left( \frac{e_1}{z_1} \right) dt = \int_t^\infty e_1 \left( \frac{e_1}{z_1} \right) dt + \int_0^t e_1' \left( \frac{e_1'}{z_1} \right) dt$$

$$+ \sum_2^n \int_0^t \left\{ e_k'' \left( \frac{e_k''}{z_k} \right) + E_k \left( \frac{E_k}{Z_k} \right) \right\} dt$$

$$+ \int_0^t E_1 \left( \frac{E_1}{Z_1} \right) dt + \int_0^t e \left( \frac{e}{Z_e} \right) dt \tag{16}$$

But the two terms involving $e_1$ may be combined as

$$\int_0^\infty e_1 \left( \frac{e_1}{z_1} \right) dt - \int_t^\infty e_1 \left( \frac{e_1}{z_1} \right) dt$$

$$= \int_0^t e_1 \left( \frac{e_1}{z_1} \right) dt \tag{17}$$

Then, discarding the integrals, there is the general relationship

$$\frac{e_1^2}{z_1} = \frac{e_1'^2}{z_1} + \sum_2^n \left\{ e_k'' \left( \frac{e_k''}{z_k} \right) + E_k \left( \frac{E_k}{Z_k} \right) \right\}$$

$$+ E_1 \left( \frac{E_1}{Z_1} \right) + e \left( \frac{e}{Z_e} \right) \tag{18}$$

Substituting throughout, in terms of $e_1$, from the previous equations of reflection and refraction, this expression reduces to an identity, thus proving that the reflection and refraction operators are consistent with the energy relationships.

The above operational equations, when applied to an infinite rectangular incident wave $e_1$, may be solved by the expansion theorem, or series expansion, or reference to a table of operational solutions. But when $e_1$ is any arbitrary time function, it must either be replaced by its operational equivalent, or else recourse made to Duhamel's theorem. Practially, the operational equivalents of only a relatively few simple functions have been tabulated; and the integrations required in an application of Duhamel's theorem also limit the arbitrary functions $e_1$ to just about the same simple cases.

However, the solution corresponding to

$$e_1 = E_1 \epsilon^{-at} \tag{19}$$

is usually easily effected by means of Heaviside's shifting theorem,

$$f(p) \epsilon^{-at} 1 = \epsilon^{-at} f(p - a) 1 \tag{20}$$

and then an application of the expansion theorem.

Now just as a curve may be approximated by a power series, or in the case of periodic functions by a trigonometric series, so the possibility of an expansion in terms of exponentials may be assumed, and $e_1$ fitted by

$$e_1 = f(t) = \sum_0^n A_s \epsilon^{a_s t} \tag{21}$$

Then if the solution corresponding to Equation (19) is $\xi_1(t)$, that corresponding to Equation (21) is

$$\xi(t) = \sum_0^n \xi_s(t) \tag{22}$$

Since the parameters $A_s$ and $a_s$ may be real, imaginary, or complex, a damped oscillation component in the incident wave may be represented as

$$A \epsilon^{-at} \sin(bt + c) = \left( \frac{A \epsilon^{jc}}{2j} \right) \epsilon^{(-a+jb)t} - \left( \frac{A \epsilon^{-jc}}{2j} \right) \epsilon^{(-a-jb)t}$$

$$= A' \epsilon^{-a't} - A'' \epsilon^{-a''t} \tag{23}$$

Usually, two terms of (21) suffice for the adequate description of the incident wave. The range is indicated in Fig. 5. More complex waves may be built up by the superposition of such solutions.

## Appendix II

### Equivalent Circuit of Lines, Reactors, and Terminal Apparatus

It was pointed out in the main body of the paper that a transformer acts like a capacitance to ground as far as its effect on the behavior of traveling waves is concerned. The reactor unit consists of an inductance $L$ having a series resistance $r$ (due principally to skin effect) and a shunt resistance $R$. In addition there are the distributed capacitances along the stack and to ground, leakage currents to ground, and mutual inductance; but the comparison of calculations and tests show that these latter circuit constants may be neglected in computing phenomena external to the reactor unit itself. However, the distribution of potential inside the coil stack of the reactor is greatly influenced by the distributed capacitances, in the same way as in transformers, and is the subject of Appendix III.

The equivalent circuit is shown in Fig. 4, where the incident wave $e_1$ is approaching the junction along line $z_1$. When this incident wave reaches the junction a part will be reflected back to the line $z_1$, as a reflected wave $e_1'$ and a part will pass through the protecting reactor as a transmitted or refracted wave $e_2''$. The analysis is a special case of that in Appendix I.

The generalized terminal impedance at the junction is

$$Z_e(p) = Z_1(p) + Z(p) = \frac{R(r + L p)}{r + R + p L} + \frac{z_2}{1 + z_2 C p} \tag{1}$$

By Equations (2) and (6) of Appendix I,

$$\frac{Z_e(p) - z_1}{Z_e(p) + z_1} = \frac{(R - z_1)}{(R + z_1)} \frac{p^2 + A p + B}{p^2 + 2 \alpha p + \omega_o^2}$$

$$= \text{reflection operator} \tag{2}$$

$$\frac{2 Z(p)}{Z_e(p) + z_1} = \frac{2}{C(R + z_1)} \frac{p + F}{p^2 + 2 \alpha p + \omega_o^2}$$

$$= \text{refraction operator} \tag{3}$$

where

$$\alpha = \frac{(R + z_1 + z_2) L + (r R + r z_1 + R z_1) z_2 C}{2 (R + z_1) z_2 L C}$$

$$\omega_o^2 = \frac{(z_1 + z_2)(r + R) + r R}{(R + z_1) z_2 L C}$$

$$\omega = j \Omega = \sqrt{\omega_o^2 - \alpha^2}$$

$$A = \frac{(R - z_1 + z_2) L + (r R - r z_1 - R z_1) z_2 C}{(R - z_1) z_2 L C}$$

$$B = \frac{(z_2 - z_1)(r + R) + r R}{(R - z_1) z_2 L C}$$

$$F = \frac{r + R}{L}$$

In Appendix I it was shown that solutions corresponding to a wide range of incident wave shape can be built up from the solution corresponding to an exponential wave. Let this incident wave be given by

$$e_1 = E_1 \epsilon^{-\alpha t} \tag{4}$$

where time is counted from the instant when the wave arrives at the junction. Applying the *reflection* and *refraction* operators of Equations (2) and (3) to (4) and using Heaviside's shifting theorem, there is, after some simplification,

$$e_1' = x E_1 \epsilon^{-\alpha t} + y E_1 \epsilon^{-\alpha t} \sin(\omega t + \phi) \tag{5a}$$

$$= x E_1 \epsilon^{-\alpha t} + Y E_1 \epsilon^{-\alpha t} \sinh(\Omega t + \Phi) \tag{5b}$$

$$= x E_1 \epsilon^{-\alpha t} + E_1 \epsilon^{-\alpha t} (W_1 \epsilon^{\Omega t} - W_2 \epsilon^{-\Omega t}) \tag{5c}$$

$$= \text{reflected wave}$$

$$e_2'' = u E_1 \epsilon^{-\alpha t} + v E_1 \epsilon^{-\alpha t} \sin(\omega t + \psi) \tag{6a}$$

$$= u E_1 \epsilon^{-\alpha t} + V E_1 \epsilon^{-\alpha t} \sinh(\Omega t + \Psi) \tag{6b}$$

$$= u E_1 \epsilon^{-\alpha t} + E_1 \epsilon^{-\alpha t} (J_1 \epsilon^{\Omega t} - J_2 \epsilon^{-\Omega t}) \tag{6c}$$

$$= \text{refracted wave}$$

where

$$x = \left(\frac{R - z_1}{R + z_1}\right)\left(\frac{a^2 - a A + B}{\omega_o^2 - 2 \alpha a + a^2}\right),$$

$$y = \frac{Y}{j} = \left(\frac{R - z_1}{R + z_1}\right) \frac{\sqrt{m^2 + n^2}}{(\omega_o^2 - 2 \alpha a + a^2)\,\omega},$$

$$\phi = j \Phi = \tan^{-1}\left(\frac{n}{m}\right) = j \tanh^{-1}\left(\frac{-j n}{m}\right)$$

$$m = [(A - a - \alpha)(\omega_o^2 - 2 \alpha a + a^2) - (a^2 - a A + B)(\alpha - a)]$$

$$n = \omega(\omega_o^2 - 2 \alpha a + a A - B)$$

$$u = \frac{2}{C(R + z_1)} \frac{(F - a)}{(\omega_o^2 - 2 \alpha a + a^2)},$$

$$v = \frac{V}{j} = \frac{2}{C(R + z_1)} \frac{\sqrt{k^2 + l^2}}{(\omega_o^2 - 2 \alpha a + a^2)\,\omega},$$

$$\psi = j \Psi = \tan^{-1}\left(\frac{l}{k}\right) = j \tanh^{-1}\left(\frac{-j l}{k}\right)$$

$$k = [\omega_o^2 - \alpha a - (\alpha - a) F]$$

$$l = (a - F)\,\omega$$

$$W_1 = \frac{R - z_1}{R + z_1} \frac{(m - j n)}{2 \Omega (\omega_o^2 - 2 \alpha a + a^2)}$$

$$W_2 = \frac{R - z_1}{R + z_1} \frac{(m + j m)}{2 \Omega (\omega_o^2 - 2 \alpha a + a^2)}$$

$$J_1 = \frac{1}{C(R + z_1)} \frac{(k - j l)}{\Omega (\omega_o^2 - 2 \alpha a + a^2)}$$

$$J_2 = \frac{1}{C(R + z_1)} \frac{(k + j l)}{\Omega (\omega_o^2 - 2 \alpha a + a^2)}$$

The total voltage at the reactor is

$$e_1'' = e_1 + e_1' \tag{7}$$

The three separate expressions given in both Equations (5) and (6) are mutually convertible through the relationships between the trigonometric, hyperbolic, and exponential functions of complex arguments. For computation, that expression is used for which the quantities are entirely real. Now when the quantities are entirely real in (5b) they are also entirely real in (5c), but the latter is the more convenient formula to use when $m$ and $n$ are close together. In fact, some of the calculations of this paper were made with values of $m$ and $n$ so near together as to make the use of Equation (5b) quite impossible. The same argument applies to Equations (6b) and (6c).

From the above equations it is evident that a simple exponential incident wave striking the junction gives rise, in both the reflected and transmitted waves, to an exactly similar wave plus a damped oscillation. This damped oscillation has a frequency and decrement factor depending on every circuit constant present. In the case that $(\alpha^2 > \omega_o^2)$ the oscillation ceases to exist, and the component degenerates to simple exponential decay.

The amplitude factors $(x, y, u, v)$, the instantaneous maximums, the frequency $f = \omega/2\pi$, and the displacement angles $\phi$ and $\psi$ have been tabulated for different conditions in Tables II, III, and IV of the paper. As a check on such computations it is worth observing from the previous equation, that (making $t = 0$)

$$x + y \sin \phi = x + Y \sinh \Phi = \frac{R - z_1}{R + z_1} \tag{8}$$

$$u + v \sin \psi = u + V \sinh \Psi = 0 \tag{9}$$

These conditions are also evident from physical considerations; for at the first instant the inductance acts as an open circuit and the capacitance as a short circuit to ground. Therefore at this first instant the potential at the capacitance must be zero, and $e_1'$ reflects as from a line grounded through a resistor $R$.

Owing to their transcendental character, the instantaneous maxima of Equations (5) or (6) cannot be found except by trial or graphically. However, the maximum amplitude of the damped oscillations are readily obtained by differentiating with respect to $t$ and equating to zero. These maxima occur at

$$t_1 = \frac{1}{\omega}\left(\tan^{-1}\frac{\omega}{\alpha} - \phi\right) \tag{10}$$

$$t_2 = \frac{1}{\omega}\left(\tan^{-1}\frac{\omega}{\alpha} - \psi\right) \tag{11}$$

and the maxima of the oscillations are

$$y\left(\frac{\omega}{\omega_o}\right) E_1\, \epsilon^{-\alpha t_1} \tag{12}$$

$$v\left(\frac{\omega}{\omega_o}\right) E_1\, \epsilon^{-\alpha t_2} \tag{13}$$

Obviously, they cannot exceed $(y E_1)$ and $(v E_1)$ respectively, but approach these limiting values as $\alpha \to 0$.

From the energy relationships of Appendix I the location of the energy at any time $t$ is found to be (using the solution for the oscillatory case):

$$w_o = \frac{1}{z_1}\int_0^\infty (e_1)^2\, dt = \frac{E_1^2}{2\,a\,z_1}$$

$$= \text{energy in incident wave} \tag{14}$$

$$w_1 = \frac{1}{z_1}\int_t^\infty (e_1)^2\, dt = \frac{E_1^2}{2\,a\,z_1}\,\epsilon^{-2\alpha t}$$

$$= \text{energy remaining at time } t \tag{15}$$

$$w_1' = \frac{1}{z_1}\int_0^t (e_1')^2\, dt = \frac{E_1^2}{z_1}\left\{\frac{x^2}{2\,a}(1 - \epsilon^{-2\alpha t})\right.$$

$$+ \frac{y^2}{4\,\alpha}(1 - \epsilon^{-2\alpha t}) + \frac{y^2}{4\sqrt{\alpha^2 + \omega^2}}\left[\sin\left(2\,\phi - \tan^{-1}\frac{\alpha}{\omega}\right)\right.$$

$$\left. - \epsilon^{-2\alpha t}\sin\left(2\,\omega\,t + 2\,\phi - \tan^{-1}\frac{\alpha}{\omega}\right)\right]$$

$$- \frac{2\,x\,y}{\sqrt{(a + \alpha)^2 + \omega^2}}\left[\sin\left(\phi - \tan^{-1}\frac{\alpha + a}{\omega}\right)\right.$$

$$\left.\left. - \epsilon^{-(a+\alpha)t}\sin\left(\omega\,t + \phi - \tan^{-1}\frac{a + \alpha}{\omega}\right)\right]\right\}$$

$$= \text{energy in the reflected wave at time } t \tag{16}$$

$$w_2'' = \frac{1}{z_2}\int_0^t (e_2'')^2\, dt = \frac{E_1^2}{z_2}\left\{\frac{u^2}{2\,a}(1 - \epsilon^{-2\alpha t})\right.$$

$$+ \frac{v^2}{4\,\alpha}(1 - \epsilon^{-2\alpha t}) + \frac{v^2}{4\sqrt{\alpha^2 + \omega^2}}\left[\sin\left(2\,\psi - \tan^{-1}\frac{\alpha}{\omega}\right)\right.$$

$$\left. - \epsilon^{-2\alpha t}\sin\left(2\,\omega\,t + 2\,\psi - \tan^{-1}\frac{\alpha}{\omega}\right)\right]$$

$$- \frac{2\,u\,v}{\sqrt{(a + \alpha)^2 + \omega^2}}\left[\sin\left(\psi - \tan^{-1}\frac{\alpha + a}{\omega}\right)\right.$$

$$\left.\left. - \epsilon^{-(a+\alpha)t}\sin\left(\omega\,t + \psi - \tan^{-1}\frac{a + \alpha}{\omega}\right)\right]\right\}$$

$$= \text{energy in the transmitted wave at time } t \tag{17}$$

$$W_o = \frac{C}{2}(e_2'')^2 = E_1^2\,\frac{C}{2}\,[u\epsilon^{-\alpha t} + v\,\epsilon^{-\alpha t}\sin(\omega\,t + \psi)]^2$$

$$= \text{energy stored in the capacitor at time } t \tag{18}$$

The difference between the energy in the initial wave and the sum of the above is the energy absorbed by the reactor unit,

$$W_1 = w - (w_1 + w_1' + w_2'' + W_o)$$

$$= \text{energy absorbed by reactor} \tag{19}$$

## Appendix III

### Distribution of Potential in a Reactor

Consider the circuit of Fig. 27A consisting of $(n-1)$ similar sections of series elements $Z_1$ and shunt elements $Z_2$, closed by an impedance $Z_3$, and supplied by a potential $e$ through an impedance $Z_o$.

Applying Kirchoff's Laws to the $k$th section there is

$$Z_1 i_k + Z_2 (i_k - i_{k+1}) - Z_2 (i_{k-1} - i_k) = 0 \qquad (1)$$

This is a "difference" equation as distinguished from the differential equation to which it reduces when the elements are taken infinitesimally close together. The general exponential may be assumed to satisfy either, so that

$$i_k = A\, \epsilon^{k\lambda} + B\, \epsilon^{-k\lambda} \qquad (2)$$

Substituting (2) in (1) and simplifying

$$(Z_1 + 2 Z_2 - Z_2 \epsilon^{\lambda} - Z_2 \epsilon^{-\lambda})\,(A\, \epsilon^{k\lambda} + B\, \epsilon^{-k\lambda}) = 0 \qquad (3)$$

$$\therefore \quad (\epsilon^{\lambda} - \epsilon^{-\lambda}) = 2 \cosh \lambda = \left(2 + \frac{Z_1}{Z_2}\right) \qquad (4)$$

For the 0th section

$$e = Z_o i_o + Z_2 (i_o - i_1) = A\,(Z_o + Z_2 - Z_2\, \epsilon^{\lambda}) + B\,(Z_o + Z_2 - Z\, \epsilon^{-\lambda}) \qquad (5)$$

and for the last, or $n$th section

$$0 = Z_3 i_n + Z_2 (i_n - i_{n-1}) = A\,(Z_3 + Z_2 - Z_2\, \epsilon^{-\lambda})\, \epsilon^{n\lambda} + B\,(Z_3 + Z_2 - Z_2\, \epsilon^{\lambda})\, \epsilon^{-n\lambda} \qquad (6)$$

Solving (5) and (6) simultaneously for the integration constants $A$ and $B$, and simplifying

$$A = \frac{0.5\,[Z_3 + Z_2\,(1 - \epsilon^{\lambda})]\, \epsilon^{-n\lambda}\, e}{-Z_2^2 \sinh (n-2)\,\lambda + (2\, Z_2^2 + Z_2\, Z_o + Z_2\, Z_3) \sinh (n-1)\,\lambda - (Z_2^2 + Z_2 Z_o + Z_2 Z_3 + Z_o Z_3) \sinh n\,\lambda} \qquad (7)$$

$$B = \frac{-\,0.5\,[Z_3 + Z_2\,(1 - \epsilon^{-\lambda})]\, \epsilon^{+n\lambda}\, e}{-Z_2^2 \sinh (n-2)\,\lambda + (2\, Z_2^2 + Z_2\, Z_o + Z_2\, Z_3) \sinh (n-1)\,\lambda - (Z_2^2 + Z_2 Z_o + Z_2 Z_3 + Z_o Z_3) \sinh n\,\lambda} \qquad (8)$$

The potential to ground at any $Z_2$ between sections $(k-1)$ and $(k)$ is

$$e_k = Z_2 (i_{k-1} - i_k) = A\, Z_2 (\epsilon^{-\lambda} - 1)\, \epsilon^{k\lambda} + B\, Z_2 (\epsilon^{\lambda} - 1)\, \epsilon^{-k\lambda} \qquad (9)$$

A reactor shunted by a resistor tied in at regular intervals is a circuit consisting of the following constants:

(a) Uniformly distributed self inductance $L_1 = L/(n-1)$

(b) Uniformly distributed capacitance to ground $C_2 = C_o/n$

(c) Uniformly distributed capacitance along the coil stack $C_1 = (n-1)\, C_o$

(d) Uniformly distributed series resistance $r$

(e) Lumped resistor units tied in at regular intervals $R_1 = R/(n-1)$

(f) Non-uniform distribution of mutual inductance $M$.

Of these, the series resistance $r$ is principally due to skin effect, and changes with the steepness of the wave front and tail, or the frequency of oscillation. Tests indicate that it may be taken as of the order of 100 ohms for surges similar to those due to lighting. But when the shunt resistance is of the order used with the reactors described in this paper, the effect of the series resistance may be neglected in comparison therewith. It will therefore be taken as $r = 0$ in this discussion. While the mutual inductance $M$ has a definite influence on the distribution, its effect is not so pronounced as to justify its inclusion in the mathematics; for to do so, even under the most simplifying assumptions as to the flux paths, changes the order of the differential equation by two, and introduces a variable coefficient. These complications prohibit a solution except for open and grounded terminal conditions. For these reasons the mutual inductance between coils will be neglected. Finally, on the assumption that the number of sections is large, either the distributed inductance and capacitances may be lumped between tie-in points, or the shunt resistance may be taken as a uniform distribution tied in at differential intervals. Fig. 27B applies, and $e$ is taken as the actual voltage at the terminals, as sum of the incident and reflected waves. As previously discussed in Appendix II, this may be computed by considering the entire reactor unit as a lumped network. Then

$$Z_o = 0, \qquad Z_2 = \frac{1}{p\, C_2}$$

$$Z_1 = \frac{R_1 L_1 p}{R_1 L_1 C_1 p^2 + L_1 p + R_1}, \quad Z_3 = \frac{z_3}{1 + z_3\, C_3\, p}$$

$$\cosh \lambda = 1 + \frac{R_1 L_1 C_2 p^2}{2\, R_1 L_1 C_1 p^2 + 2\, L_1 p + 2\, R_1}$$

$$= \left(1 + \frac{\lambda^2}{\underline{|2}} + \frac{\lambda^4}{\underline{|4}} + \ldots\right) \qquad (10)$$

Substituting Equations (7) and (8) into (9) for $Z_o = 0$ there is

$$e_k = \frac{(2\, Z_2 + Z_3) \sinh (n-k)\,\lambda \,.\, (1 - \cosh \lambda)}{(2\, Z_2 + Z_3) \sinh (n-1)\,\lambda\, (1 - \cosh \lambda)} \; \frac{-\, Z_3 \cosh (n-k)\,\lambda \sinh \lambda}{-\, Z_3 \cosh (n-1)\,\lambda \sinh \lambda}\; e\,(t) \qquad (11)$$

where $\lambda$, $Z_2$, and $Z_3$ have the values previously assigned. The initial distribution at $t = 0$ may be obtained from the above operational solution by substituting $p = \infty$. Then from Equation (10)

$$\lambda = \lambda' = \cosh^{-1}\left(1 + \frac{C_2}{2\, C_1}\right)$$

$$= \cosh^{-1}\left[1 + \frac{C_o}{2\, n\,(n-1)\, C_o}\right] \qquad (12)$$

$$e_k\Big]_{t=0} = \frac{(2\,C_3 + C_2)\sinh(n-k)\,\lambda'}{(2\,C_3 + C_2)\sinh(n-1)\,\lambda'} + \frac{2\,C_1\cosh(n-k)\,\lambda' \,.\, \sinh\lambda'}{+\,2\,C_1\cosh(n-1)\,\lambda' \,.\, \sinh\lambda'} \,.\, e\,(o) \qquad (13)$$

This equation shows that the *initial distribution* depends only on the capacitances of the circuit.

The *final distribution*, if $e\,(t)$ becomes constant, is given by substituting $p = 0$. In this case, by Equation (10), $\lambda = \sqrt{L_1\,C_2}\,p$, and therefore

$$e_k\Big]_{t=\infty} = \frac{(n-k)\sqrt{L_1/C_2} + z_3}{(n-1)\sqrt{L_1/C_2} + z_3} \,.\, e\,(\infty) \qquad (14)$$

This equation shows that the final distribution is also independent of the shunt resistance $R_1$, and is a straight line. The only influence of the shunt resistance $R_1$ is in controlling the transient between the initial and final states.

In order to study the effect of the shunt resistance on the nature of the transition from the initial to the final states, it will be assumed that the number of sections is very large, and that the voltage is applied at one end with the other end grounded. It is then evident from Equation (10) that $\lambda \to 0$ as $n \to 0$, so that

$$\lambda^2 = \frac{1}{n^2}\,\frac{(R\,L\,C_g\,p^2)}{(R\,L\,C_s\,p^2 + L\,p + R)} = \frac{\sigma^2}{n^2} \qquad (15)$$

and Equation (11) reduces to

$$e_k = e_x = \frac{\sinh(n-k)\,\lambda}{\sinh(n-1)\,\lambda}\,e = \frac{\sinh\sigma\,x}{\sinh\sigma}\,e \qquad (16)$$

where $x$ is the distance from the grounded end measured as a fraction of the total winding length.

If $e = 1$, Equation (16) is solved by the expansion theorem

$$e_x = \frac{Y\,(p)}{Z\,(p)}\,1 = \frac{Y\,(o)}{Z\,(o)} + \sum \frac{Y\,(p)\,\epsilon^{pt}}{p\,Z'\,(p)} \qquad (17)$$

$$Z\,(p) = \sinh\sigma = \sigma \prod_{1}^{\infty}\left(1 + \frac{\sigma^2}{\pi^2\,s^2}\right) \qquad (18)$$

from which the roots of $Z\,(p) = 0$ are

$$\sigma = \pm\,j\,\pi\,s \qquad \text{where } s = (1, 2, \ldots\ldots) \qquad (19)$$

From (15) and (19)

$$p = \frac{-\,\pi^2\,s^2 \mp j\,\pi\,s\sqrt{4\,R^2\,(C_s\,\pi^2\,s^2 + C_g)/L - \pi^2\,s^2}}{2\,R\,(C_s\,\pi^2\,s^2 + C_g)} = -\,\alpha_s \mp j\,\omega_s \qquad (20)$$

From (18), (19), and (20)

$$p\,Z'\,(p) = p\,\frac{d\,Z\,(p)}{d\,\sigma}\,\frac{d\,\sigma}{d\,p}$$

$$= \pm\,j\,\frac{\pi\,s}{C_g}\,(C_s\,\pi^2\,s^2 + C_g)\,.\,\cosh j\,\pi\,s$$

$$\left\{\frac{(C_s\,\pi^2\,s^2 + C_g)\,(2\,R^2 \mp j\,R\,\omega_s) - L\,\pi^2\,s^2)}{(C_s\,\pi^2\,s^2 + C_g)\,(R^2 \mp j\,R\,\omega_s) - L\,\pi^2\,s^2)}\right\} \qquad (21)$$

in which the outside ($\pm$) sign originated from (19) and is independent of the inside ($\pm$) sign, so that there are four combinations involved. Also

$$\cosh j\,\pi\,s = \cos\pi\,s = (-\,1)^s \qquad (22)$$

$$Y\,(p) = \sinh\sigma\,x = \sinh(\pm\,j\,\pi\,s\,x) = \pm\,j\sin(s\,\pi\,x) \qquad (23)$$

$$\frac{Y\,(o)}{Z\,(o)} = \frac{\sinh\sigma\,x}{\sinh\sigma}\Big]_{p=o} = \frac{\sinh\sigma\,x}{\sinh\sigma}\Big]_{\sigma=o} = x \qquad (24)$$

Substituting (20) to (24) in (17) and simplifying, there is

$$e_x = x + \sum_{s=1}^{\infty}\frac{2\,(-\,1)^s\,C_g\sin s\,\pi\,x}{\pi\,s\,(C_s\,\pi^2\,s^2 + C_g)}\,\epsilon^{-\alpha_s t}$$

$$\left\{\cos\omega_s\,t + \frac{\pi^2\,s^2\sin\omega_s\,t}{2\,R\,(C_s\,\pi^2\,s^2 + C_g)\,\omega_s}\right\} \qquad (25)$$

when there is no resistor in shunt ($R = \infty$) this reduces to

$$e_x = x + \sum_{s=1}^{\infty}\frac{2\,(-\,1)^s\,C_g\sin s\,\pi\,x}{\pi\,s\,(C_s\,\pi^2\,s^2 + C_g)}\cos\omega_s\,t \qquad (26)$$

Thus the distribution consists of a very complex oscillation, superimposed on the linear distribution representing the final steady state. If $R$ is large and $C_s$ is very small compared to $C_g$, the frequencies of the first few time harmonics are

$$f_s = \frac{s}{2\sqrt{L\,C_g}} \qquad (27)$$

and the circuit behaves as though the series capacitances were absent. But the higher harmonics approach the limiting frequency

$$f = \frac{1}{2\,\pi\sqrt{L\,C_s}} \qquad (28)$$

so that the series capacitance predominates at higher frequencies. Any group of frequencies in the oscillation may be suppressed by making

$$R^2 \leq \frac{\pi^2\,s^2\,L}{4\,(C_s\,\pi^2\,s^2 + C_g)} \qquad (29)$$

for that group.

Comparing (25) and (26) it is evident that the effect of the shunt resistance is two-fold. First, it introduces a decrement factor $\alpha_s$ which damps out any oscillations which are present; and second, it prohibits all frequencies for which (29) holds, so that the initial distribution tends to diffuse into the final distribution without oscillation.

If the applied wave is other than infinite rectangular, the corresponding voltage distribution may be found from Duhamel's theorem

$$e_s = E(o) \,.\, \phi(t) + \int_0^t \phi(\tau) \frac{\partial}{\partial t} E(t-\tau)\, d\tau \qquad (30)$$

where $\phi(t)$ is the solution given by Equation (25) corresponding to an infinite d-c. voltage suddenly applied (Heaviside's "unit function"); and $E(t)$ is any arbitrary applied voltage function.

If the applied wave is one of those of Fig. 5

$$E(t) = E(\epsilon^{-at} - \epsilon^{-bt}) \qquad (31)$$

then by Equations (25) and (30)

$$e_s = x E(\epsilon^{-at} - \epsilon^{-bt}) + E \sum_{s=1}^{\infty} \frac{4(-1)^s}{\pi^2 s^2} R C_s \alpha_s \sin s\pi x$$

$$\left\{ \frac{a(a-2\alpha_s)}{(a-\alpha_s)^2 + \omega_s^2} \epsilon^{-at} - \frac{b(b-2\alpha_s)}{(b-\alpha_s)^2 + \omega_s^2} \epsilon^{-bt} \right.$$

$$+ \frac{\epsilon^{-\alpha_s t}(\alpha_s^2 + \omega_s^2)}{\omega_s [\omega_s^2 + (a-\alpha_s)^2]^{1/2}} \cos\left(\omega_s t + \tan^{-1}\frac{a-\alpha_s}{\omega_s}\right)$$

$$\left. - \frac{\epsilon^{-\alpha_s t}(\alpha_s^2 + \omega_s^2)}{\omega_s [\omega_s^2 + (b-\alpha_s)^2]^{1/2}} \cos\left(\omega_s t + \tan^{-1}\frac{b-\alpha_s}{\omega_s}\right) \right\} \qquad (32)$$

where

$$\alpha_s = \pi^2 s^2 / 2R(C_s \pi^2 s^2 + C_g)$$

$$\omega_s = \sqrt{(2\alpha_s R/L - \alpha_s^2)}$$

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## Discussion

**F. J. Vogel:** This paper is on a subject of great interest to us and it is interesting to see that its conclusions are generally similar to our own. The application of an ordinary resistance is very difficult. The example given by the author illustrates this point very forcibly. In practically all cases we have found that the use of an ordinary resistance was prohibited from the standpoint of its energy loss. However, it has also been realized that there was a great possibility of the reactor entering into oscillation when at the end of a line and between the line and transformers and other equipment. Under these circumstances we have felt it desirable and have recommended the use of lightning arresters which have served to practically short circuit the reactor when voltages above a predetermined value were reached.

The resistor which is described in the paper has characteristics similarly tending to reduce the resistance as the voltage across the reactor goes up. We believe the two applications are very similar in character in so far as the net result obtained is concerned. We consider that the valve type lightning arrester has many decided advantages. It is not subject to any energy losses under any circumstances except when the voltage is in its discharge range. It is easy to apply since the arrester may be picked to have its cut off voltage at a reasonable value above the maximum voltage across the reactor under short circuit conditions. We believe these advantages make it preferable to the use of a resistance material which is permanently connected into the circuit.

Where reactors are used as ties between systems and in many other applications, there is no tendency for the reactor to enter into oscillation with any other equipment in the system. In this case the application of either a resistance or a lightning arrester is unwarranted. These considerations have been the rule and guide which we have followed in the application of reactors.

**S. I. Oesterreicher:** Shunting a reactor by resistance is a very live topic whenever or wherever such protective equipment is discussed. The authors of the paper who for years were the chief advocates of shunt resistors, leave us in a somewhat doubtful position by their criterion, which is, will the utilization of shunt resistors under the most unfavorable possible operating conditions be worth the cost?

About fifteen years ago a number of reactors began to act in a rather embarrassing manner. Naturally we all were somewhat annoyed and tried to diagnose the symptoms as well as to apply a remedy.

The remedy was most gratifying. We have produced a piece of apparatus which under the most severe operating conditions may be relied upon. However, this reliability does not depend upon shunt resistors but rather upon strong mechanical construction, large conductor cross section, and sufficient insulation, which are paramount. However, even after the reading of this paper, there is some optimism required to be convinced about the usefulness of shunt resistors.

With this statement I do not wish to reflect upon the merits of the paper. I believe the analytical part as to the manner in which the wave travels through the various inductances, capacitances, and resistances involved in the circuits through and around the reactors is a fine piece of work and the authors should be thanked for its publication.

A claim is made that thyrite has all the required characteristics which a shunt resistor for a reactor should have. Why? Is there anything wrong with the present resistors? It is stated that thyrite is a material having characteristics somewhat similar to dry process porcelain. If that is so, and if such a shunt resistor is able to protect a reactor from dangerous oscillations, then we wish to thank the authors for telling us about this. We did not know that the 16 dry process porcelain shields we put in every one of our reactors act as shunt resistors.

**K. K. Palueff:** In my paper *Effect of Transient Voltage on Power Transformer Design*[1] presented to the Institute in January, 1929, and in the later communication[2] presented in May of the same year, an attempt was made to direct the attention of the reader to the dangerous overvoltages that may be produced in transformers due to the use of a small inductance, such as choke coil, reactor, or current transformer, when con-

1. A. I. E. E. Quarterly Trans., Vol. 48, July 1929, p. 681.
2. *Ibid*, p. 998

nected in series with power transformer and not shunted with resistance. (See Fig. 1.) The physical and mathematical relations governing the phenomena were established in the paper.

It is gratifying to find that other investigators not only arrived at the same conclusions, but have developed a suitable resistor which eliminates the above mentioned oscillations, and thereby not only protects the reactor, but also the station apparatus. Since a reactor gives satisfactory service without resistor, the resistor should be looked upon primarily as a device protecting the more expensive part of the station equipment, as power transformers, busses, or generators, when the latter are connected directly to the lines.

The authors should be complimented on the excellent mathematical analysis of the phenomena: Many formulas derived in the paper are of such general scope that they could be used in solving many other allied problems.

Fig. 1

I should like to call your attention to the fact that the equivalent circuit of an ordinary transformer, when the latter is subjected to steep front long wave excitation, undergoes a very radical evolution during the first few hundred microseconds. Three stages can be recognized in this evolution.

For the first few microseconds, the transformer can be represented by a pure capacitance. For the following period of one or two hundred microseconds, or even more, it acts as a complex network, consisting of distributed capacitances and inductances, with mutual inductance between various elementary inductances playing a prominent role in the phenomenon. After the oscillation of this network dies out, the transformer equivalent circuit reaches its last stage in the evolution and becomes a pure inductance connected in series with resistance.

**R. B. George:** In order to obtain effective protection against lightning or other high potential surges, relatively low shunting resistance is required which will result in power losses causing heating in the resistor. With constant value of resistance the losses in the shunting resistor are directly proportional to the square of the voltage across the reactor. On sustained short circuits of comparatively long duration, the shunting resistor becomes a serious hazard instead of a protection for the reactor.

It is a well recognized principle that any protective device should be self-protecting in order to avoid the complications of auxiliary devices to protect the protective device. For general applications such as bus tie reactors and feeder reactors, it is often more economical to use additional clearances and high grade insulation to obtain reactors which will give an assurance of a high factor of safety against flashover.

If the reactor is connected in series with expensive terminal apparatus which justifies the expense of a shunting device, a lightning arrester fulfills all requirements.

When a reactor shunting device is required, it is very important that it possess the characteristics of a valve type arrester which acts as a shunt for high voltage only.

**F. H. Kierstead:** Referring to Mr. F. J. Vogel's discussion of our paper we agree that there are isolated cases where it is more advantageous to shunt the reactor with a lightning arrester than with a resistor. Such cases occur when the system voltage is sustained across the reactor for a relatively long period. In general, however, this voltage is sustained during the period of a short circuit lasting for only a few seconds. For this reason, we have found resistors having the characteristic described in the paper (higher resistance for low voltage than for high voltage) are better suited to use in shunting reactors than arresters.

We believe that Mr. Vogel advocates a too limited use of resistors. We also believe that Mr. S. Oesterreicher and Mr. R. B. George in assuming that the resistor is only a means of protecting the reactor from high voltage have overlooked its very broad field of usefulness. Therefore, a discussion of its field of application may be useful. Since it is relatively easy to design as simple a piece of apparatus as the reactor is, to stand the voltages it is subjected to in service, there is no justification for the use of resistors to protect the reactor from overvoltage. However, by shunting the reactor with a resistor the overvoltages that generators, transformers, station busses, current transformers, and other station equipment have to stand is materially reduced. In short, the system as a whole is protected by the resistor.

Resistors are most necessary where the feeders entering the station are overhead, for the reason that lightning disturbances are most dangerous to station equipment. Underground feeders are not only shielded from lightning disturbances but also overvoltages which may arise on them are more rapidly damped out. Resistors are therefore not so necessary for use with underground feeders. Another feature which may determine whether or not resistors are to be used is whether or not a large number of disturbances is occurring on the system. By the use of resistors the voltage of the disturbances is reduced and therefore the number of failures occurring on the system will also be reduced.

# Effect of Transient Voltage on Power Transformer Design

## The Behavior of Transformers with Neutral Isolated or Grounded through an Impedance

BY K. K. PALUEFF*

Member, A. I. E. E.

*Synopsis.—The results of theoretical and oscillographic study of transient voltage phenomena in shell type and core type transformers with neutral isolated from ground, and also with neutral grounded through impedances of different characteristics are briefly described.*

*In the case of isolated neutral, the majority of lightning traveling waves cause the potential of the entire winding, including neutral, to rise above ground to a value at least equal to the applied voltage.*

*In the case of switching surges, the voltage of the neutral, as well as of the rest of the winding, is apt to rise to a value considerably in excess of the applied voltage. In the case of transformers excited with damped oscillations similar to switching surges, oscillographic records of both shell and core type transformers indicate internal voltages to ground approximately four times the applied.*

*Grounding of a transformer through resistance, inductance, or capacitance does not reduce the above internal transient voltages, unless a certain relation is established between these constants, the constants of the transformer circuit, and the wave shape of the line surge.*

*If the proper relation of these constants is established, then internal transient voltages are reduced practically to those of a solidly grounded transformer.*

*A grounding device, called an "impedor," can be designed to have impedance at operating frequency equal to any desired value and to act at transient voltage frequencies as if its impedance were practically zero. An impedor can be designed for each transformer bank, or for a number of banks in parallel.*

*A non-resonating transformer, if grounded through a suitable impedor, retains its uniform transient voltage distribution.*

*During the last year and a half nearly 800,000 kv-a. of transformers of non-resonating type, have been built so that they can be operated with impedor in the neutral.*

### Introduction

THE effect of transients on design of power transformers operated with solidly grounded neutral was described by the author in a preceding paper of the same general title.[3]

The present paper describes in a non-mathematical way the behavior of a transformer with neutral isolated or grounded through any impedance, when subjected to transient voltages, and shows the effect of this behavior on transformer design.

While the majority of existing, very high voltage power transformers are operated with the neutral solidly grounded, there appeared recently a demand for grounding neutrals through inductance or resistance. This demand is stimulated by the desire to limit the harmful effect of excessive current flowing through the neutral in case of accidental one-wire or two-wire ground.

It has been shown[1] that the harmful effect of neutral current can be more effectively minimized by quickening switching operations and by improving relaying methods, than by insertion of an impedance between neutral and ground. However, these better methods are in a state of development, while grounding through a resistance or an inductance can be done successfully at the present time. It is expected therefore that for the time being a certain use will be made of impedance in the neutral of some strategically located banks in systems suffering from excessive short circuit neutral currents.

## Part 1. Principles Governing Transient Phenomena

It is assumed that the reader is already familiar with the preceding paper[3] of the author; therefore the principal laws governing transient voltage phenomena will be described here very briefly.

### Equivalent Circuit

At operating frequency many pieces of electrical apparatus act practically as pure inductance, capacitance, or resistance, but at high frequency, such as that produced by lightning, switching, and other disturbances, they behave as complex networks composed of elementary inductances, capacitances, and resistances distributed in a manner characteristic of the given piece of apparatus.

As has been shown in previous publications [2, 3, 4] the character of internal oscillations depends principally on values of $\frac{C_s}{C_g}$ and $\frac{M}{L}$ or $\left(1-\frac{M}{L}\right)$ where $C_s$ is capacitance between adjacent elements, $C_g$ is capacitance between the elements and ground, $M$ is mutual inductance between adjacent elements, and $L$ their self-inductance.

$\frac{C_s}{C_g}$ and $\frac{M}{L}$ have minimum values in a transmission line and maximum in a transformer.

*General Electric Company, Pittsfield, Mass.

3. For references see Bibliography.

*Presented at the North Eastern District Meeting of the A. I. E. E., Springfield, Mass., May 7-10, 1930.*



30-68

Examples of various equivalent circuits are given in Fig. 1. Resistance is neglected. The wavy line stands for self-inductance of an element of the winding. The loop stands for the mutual inductance between adjacent elements of the winding. For example, circuit No. 5 represents a winding having three turns per coil with high mutual inductance between the turns, and rather small mutual inductance between coils.

Generally a circuit exactly equivalent to a given piece of apparatus is extremely complicated and is

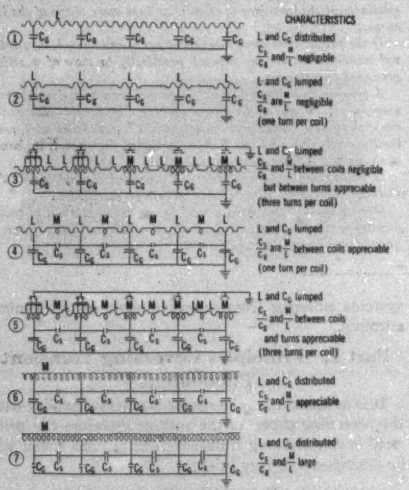


Fig. 1—Spectrum of High-Frequency Equivalent Circuit

employed only where an accurate numerical relation of various phases of the transient phenomena cannot be established without it. However, if it is desired to describe only some particular transient voltage characteristics a simplified equivalent circuit may be of assistance. To give a general idea of the behavior of transformers under certain transient conditions, the simplified circuit (Fig. 1) is found sufficiently accurate. This simplified circuit is quite unsatisfactory, however, for numerical analysis of transient phenomena because in actual transformers each coil acts as a chain of condensers, made up of capacitances of adjacent turns, while Fig. 1 is based on the assumption that coils act as solid metal plates.

## Conditions Necessary for a Transient

A circuit will pass through a transient state if the distribution of voltage in this circuit at the moment immediately following a sudden application of potential $E$ is different from one that finally takes place after $E$ has been maintained for an infinite length of time. Therefore the transient is the readjustment of local potentials from their initial to their final values.

## Initial and Final Voltage Distribution Produced by Infinitely Long Traveling Wave of Rectangular Front

*Case I.* When the equivalent circuit consists of pure inductances connected in series with pure capacitances in any sequence, then at the instant of sudden voltage application the terminal voltage distributes between inductances in direct proportion to their values, while voltage across all capacitances is zero. Since an infinitely long traveling wave acts as a constant voltage, the terminal voltage finally distributes itself between capacitances inversely to their values, and the voltage across inductances becomes zero.

*Case II.* When the equivalent circuit consists of an unbroken chain of condensers in parallel with an unbroken chain of inductances, both extending from one terminal of the circuit to the other and interconnected at different points either directly or through condensers or inductances, then the initial voltage distribution is controlled by the capacitance part of the circuit and final voltage distribution by the inductance part of the circuit, (see Figs. 1 and 2).

## Type of Transient

As was pointed out before, all circuits met with in practise consist of inductance, capacitance, and resistance. If, however, the effect of inductance or capacitance is small enough to be neglected, then the transient is unidirectional and non-oscillatory. During

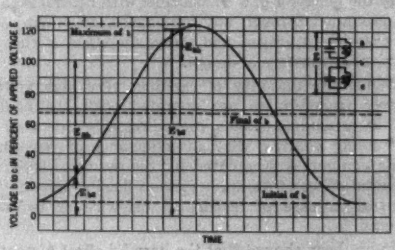


Fig. 2—Oscillation of Two Elementary Circuits Connected in Series Due to Infinite Rectangular Wave Excitation

the transient the potential of any point of the circuit with respect to either terminal changes by an amount equal to the difference between its initial and final value; the rate of change depends on the time constant of the circuit $\left(\frac{L}{R} \text{ or } RC\right)$.

In case the resistance can be neglected and the circuit contains both inductance and capacitance, the transient will be oscillatory and two conditions will be possible.

*Condition I.* When the oscillation takes place as if all the inductances of the system were lumped together and all capacitances were lumped together, the oscillation is of a single frequency and is determined by the product $L\,C$, where $L$ and $C$ are the effective lumped inductance and capacitance respectively (Fig. 2).

The amplitude of oscillation of various points is equal to the difference between their initial and final potential. Close examination of the figure reveals all the above characteristics.

*Condition II.* When inductance and capacitance cannot be separated and then lumped in "effective" $L$ and $C$, but must remain distributed, the oscillation of various points of the circuit is complex and may consist of a number of frequencies which depend on distributed constants. The amplitude of oscillation of each point depends, as before, on the difference between the initial and final voltage distribution but is not necessarily equal to it, following a more complex law, due to the fact that the difference between the initial and final voltage of any given point is a vector sum of the amplitudes of oscillation at that point of all frequencies composing the oscillation.[2,3]

## Part 2. Transformer with Neutral Isolated

### Lightning Surges

Traveling waves due to lightning are produced on the three phases of a transmission line simultaneously but are usually of different amplitude. Were the amplitudes of these waves equal, each transformer would act as if it were disconnected from the other two and the oscillation itself would become simpler. In such a case the internal oscillation of the transformers will be a maximum and higher than that which usually occurs. For these reasons we shall discuss the phenomena on the assumption that a transformer bank is subjected to three equal traveling waves.

In ordinary power transformers, either of shell or of core type, the initial voltage distribution produced by a steep front of a traveling wave is practically the same whether the neutral is solidly grounded or isolated. This occurs because at the first instant voltage concentrates across the line end of the winding, and the drop across a considerable part of the winding near the neutral end is only a few per cent of the total applied voltage. Obviously, grounding or isolating the neutral can have only negligible effect on the initial distribution.

The final voltage distribution in a transformer with isolated neutral, however, is radically different from that of a transformer with grounded neutral. The effect of the traveling wave on the transformer, after the crest value of voltage is reached and maintained, is similar to direct current. Therefore all points of an isolated winding finally acquire a potential above ground equal to the terminal voltage, ($A$, Fig. 3), while if the neutral of a winding were grounded the final voltage of various points would be proportional to turns between these points and the neutral. ($F$, Fig. 3.)

Referring to $A$ of Fig. 3, since the initial and final voltage distributions are different, the voltage throughout the winding will readjust itself from the initial to the final value through a complex oscillation. The line of final voltage distribution will serve as line of equilibrium or axis for the oscillation. The amplitude

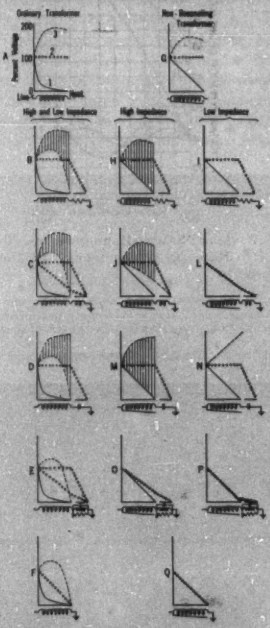


Fig. 3—Summary of Effect of Variation of Neutral Impedance from Zero to Infinity on Internal Transient Voltages in an Ordinary and a Non-Resonating Transformer Produced by Traveling Waves Met in Service

———— initial voltage distribution
– – – – envelope of maximum voltage to ground
. . . . . final voltage distribution
Shaded areas indicate the range in variation of voltages due to internal oscillation with increase of neutral impedance from zero to infinity
$A$ & $G$—neutral isolated
$F$ & $Q$—neutral grounded directly
$E$, $O$, $P$—neutral grounded through impedor
The remainder grounded as shown

of the oscillation of each point will depend on the difference between the initial and final potential of this point.

The initial voltage distribution curve, when referred to the line of equilibrium, gives the initial voltage distortion curve, which consists of a number of space harmonics (in terms of the length of the winding stack).

These space harmonics are of various time frequencies so that the composite amplitude of oscillation below the line of equilibrium is generally not equal to maximum composite amplitude of the same point above the line of equilibrium.

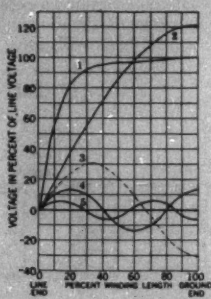


Fig. 4—Winding Space Harmonics of Transformer with Isolated Neutral at the Instant of Impact of the Traveling Wave

1. Initial voltage distortion curve (obtained from Curve 1, Fig. 2 of *Lightning Studies of Transformers by the Cathode Ray Oscillograph*, by F. F. Brand and K. K. Palueff, by referring it to its line of equilibrium of 100 per cent)

2, 3, 4, and 5 are first, third, fifth, and seventh space harmonics of curve 1

Fig. 5—Oscillations in a Shell Type Transformer with Isolated Neutral

1—Voltage at line terminal

2, 3, 4, and 5 are voltages-to-ground at points 75, 50, 25, 0 per cent away from neutral terminal with crest values of 158, 190, 204, 180 per cent of applied voltage respectively. Note all voltages recorded below zero line are taken with reversed polarity

On Fig. 4 the initial voltage distortion curve is shown as well as the first few space harmonics composing it.[3]

Referring once again to *A* of Fig. 3, imagine a very elastic solenoidal spring laid along line *L N*. If end *L*, firmly gripped, is moved sufficiently suddenly along the voltage axis to the hundred per cent point and held there, then at the initial moment, the spring would bend in a curve similar to the initial voltage distribution, (curve No. 1). A moment later it would begin to move toward the line of final state (curve No. 2) and on account of inertia would overshoot it. After it reaches a certain position beyond the final, somewhat similar to curve No. 3, it would start again toward the final position. The oscillation finally would die out and position of the spring would coincide with line 2.

Similarity between the oscillation of a spring and of simultaneous voltages along a winding, while superficial, is sufficient to assist in the description of the phenomena. (The relationship between space harmonics and their frequencies is so radically different in a spring and in a transformer that mathematical representation of the oscillation in the two cases is essentially different.)

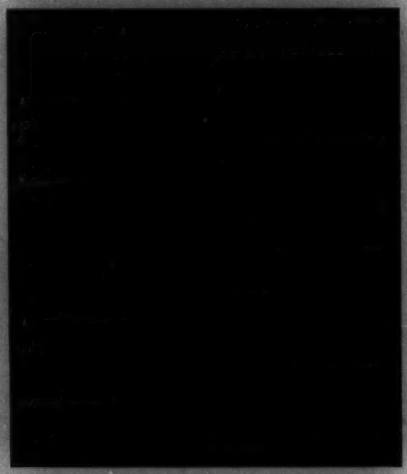

Fig. 6—Oscillation in a Core Type Transformer with Isolated Neutral

1—Voltage at line terminal

2—Voltage to ground at 50 per cent point with crest value of 182 per cent

3—Voltage to ground at neutral with crest value of 167 per cent

On Fig. 5 voltage oscillations at four points of a shell type transformer winding are shown. Note that the line voltage (that is, the final voltage) serves as an axis for all points, as was predicted. This is particularly evident on the bottom half of the oscillogram where line voltage, the voltage of the 50 per cent point, and that of the neutral are recorded with reversed polarity and properly superimposed. On Fig. 6 similar voltage oscillations at two points of a core type transformer winding are shown.

Curves 3 and 4 of Fig. 7 give the maximum voltage to

ground at various points of windings of these transformers obtained from oscillograms of Figs. 5 and 6 and of some others not shown in the paper.

### Switching Surges

The importance of switching transients is often underestimated due to the fact that the amplitude of the average switching transient is about half of that of the lightning wave but, as was pointed out in the previous paper, the switching transient is a damped

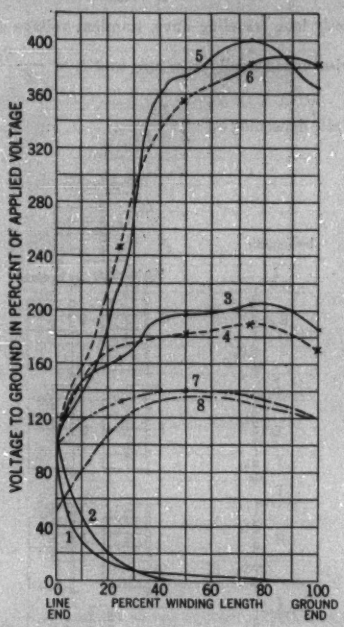


Fig. 7—Voltage-to-Ground in Shell and Core Type Transformers Due to Lightning and Switching Transients. (Test)

1 & 2—Initial voltage distribution
3 & 4—Maximum voltage-to-ground due to lightning
5 & 6—Maximum voltage-to-ground due to switching
(1, 3, & 5 refer to shell type—2, 4, & 6 refer to core type transformers)
7—Estimated voltages met in practise, due to lightning
8—Estimated voltages met in practise, due to switching

oscillation (see Fig. 8) and produces forced or cumulative oscillations in transformer windings. This means that amplitudes of internal oscillations increase with each succeeding half of a cycle of the switching transient (see Fig. 9). Thus while the terminal potential is reduced to half in comparison with lightning disturbances, the internal voltages, if expressed in per cent of terminal voltage, are at least doubled (curves 5 and 6 of Fig. 7). The result is that the absolute values of internal stresses produced by an average lightning or switching transient are very nearly the same. (Curves 7 and 8 of Fig. 7.)

The high ratio between applied and internal voltages, as shown by curves 5 and 6 of Fig. 7, is a result of resonance between the frequency of the switching surge applied and the natural frequency (or one of its harmonics) of the transformer winding. It may appear that the probability of such a coincidence is too small to be considered as one of service conditions. However, elementary calculations show that a very high ratio between applied and internal voltages can be created with the frequency of the applied surge some 40 per cent higher or lower than the natural frequency (or one of its harmonics) of the winding. Curve 5, for instance, was obtained with 20 per cent difference between the

Fig. 8—Oscillogram Showing Energizing a 132-Kv. Line of 70 Mi.

Oscillograph was stationed at approximately midpoint of line. Note complexity of the wave shape

applied frequency and the fundamental natural frequency of the transformer. As an ordinary transformer may have as many as eleven natural frequencies (and these frequencies are different for different transformers) it appears more probable than not, that with transmission systems being as complicated as they are, many switching operations produce surges of dangerous frequencies.

In actual service, the traveling waves due to a given lightning discharge are very rarely of the same amplitude on all three phases, and the switching surges are never simultaneous. The effect is that two out of three transformers of a star connected bank tend to bring down the potential of the neutral of the transformer subjected to the highest surge. Curves 7 and 8 of Fig. 7 were drawn on this basis with average applied lightning voltage taken as 100 per cent and average switching voltage as 50 per cent.

### Effect on Transformer Design

The obvious conclusion is that in the case of transformers operating with isolated neutral, the entire winding must be insulated for line voltage. This means that the winding must be capable of withstanding a high potential test of at least 3.46 times normal operating voltage from line to neutral (so-called "leg voltage").

Fig. 9—Oscillograms of Voltages in a Shell Type Transformer Produced by Damped Oscillations Similar to Switching

1—Voltage at the line terminal
2, 3, 4, and 5 are voltages to ground at points 75, 50, 25, and 0 per cent away from neutral terminal, with crest values of 218, 373, 400, 364 per cent of applied voltage, respectively

## Part 3. Neutral Grounded through Impedance

### A. *Neutral Grounded through Resistance*

#### Infinitely Long Traveling Wave

Two essentially different transients take place when a transformer grounded through resistance is subjected to a traveling wave. One transient is exponential and is governed by the transformer acting as a pure inductance while the neutral resistance and the surge impedance of the line act as pure resistances. The other transient is the oscillation of the transformer winding as described for the circuit of Fig. 1.

#### Exponential Transient

The equivalent circuit for the exponential transient is shown on *B* of Fig. 10. $Z$ is the surge impedance of the transmission line, $L_T$ the inductance of the transformer, and $R_N$ the neutral resistance.

At the instant immediately following the impact of the traveling wave of $E$ volts, $2\,E$ appears across $L_T$. The final voltage across $L_T$ is zero. The final voltage across $R_N$ is $E_N = 2\,E \times \dfrac{R_N}{Z + R_N}$. Thus with sufficiently long traveling wave, transient voltage across $R_N$ rises exponentially from zero to $2\,E \times \dfrac{R_N}{Z + R_N}$ at a rate depending on $\dfrac{L_T}{Z + R_N}$.

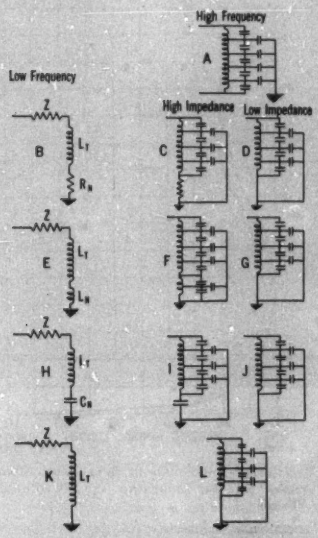


Fig. 10—Approximate Equivalent Circuits for High and Low Frequency Components of Transformer Oscillations for Transformers Grounded through Different Impedances

A—Isolated neutral
K, L—Solidly grounded neutral

#### Internal Winding Transient

It was shown in a preceding paper that since the surge impedance of transmission lines is of the order of a few hundred ohms its effect on internal transformer oscillations can be neglected. The equivalent circuit

for internal oscillations therefore is as shown on Fig. 10.

The initial distribution in a transformer grounded through resistance is the same as in a solidly grounded transformer.

With the neutral isolated, the winding potential rises, under the influence of a traveling wave, above applied voltage. The rate of this rise depends on natural frequencies of the winding. With neutral grounded through resistance the rate of rise of its potential depends on $\frac{L_T}{Z + R_N}$. If this rate is higher than that for isolated neutral the presence of resistance has practically no effect on maximum voltages to ground throughout the winding created by the oscillation. If it is lower, the presence of resistance tends to lower these voltages. The effect is greatest at the neutral point; the effect near line end is small. Thus the slower the exponential transient the more the transformer acts as if its neutral were solidly grounded.

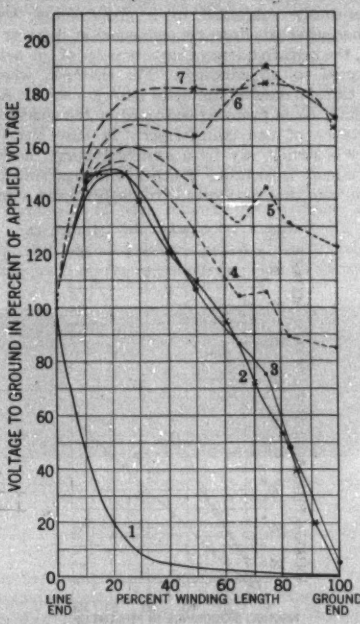


FIG. 11—EFFECT OF MAGNITUDE OF NEUTRAL RESISTANCE ON INTERNAL TRANSIENTS OF TRANSFORMERS. (TEST)

1—Initial voltage distribution
2, 3, 4, 5, 6, 7—Maximum voltages to ground for different resistances in the neutral
2—$R$ = 0 (Solidly grounded neutral)
3—$R$ = 500 ohm
4—$R$ = 5,000 ohm
5—$R$ = 25,000 ohm
6—$R$ = 100,000 ohm
7—$R$ = Infinite (Neutral isolated)

The maximum voltages to ground produced by waves of the same length but with transformer grounded through different neutral resistances were studied with the oscillograph on a 6600-kv-a. core type transformer and results are shown in Fig. 11. Note that voltage distribution with 500-ohm resistance in the neutral is the same as with solidly grounded neutral, while with 100,000-ohm resistance the voltage is practically the same as with neutral isolated.

## FINITE TRAVELING WAVE

As the final voltage of the exponential transient is $E_N = 2\,E \times \frac{R_N}{Z + R_N}$, with $Z$ of the order of 300 ohms, an appreciable voltage may finally appear at the neutral if the traveling wave is sufficiently long. Just what fraction of $2\,E\,\frac{R_N}{Z + R_N}$ a given wave will produce depends on the ratio of the length of the wave and the rate of the transient $\frac{L_T}{Z + R_N}$. Thus with a given length of the wave it is possible to limit the voltage at the neutral to any desired fraction of $2\,E\,\frac{R_N}{Z + R_N}$ by choosing $R_N$ of the proper value.

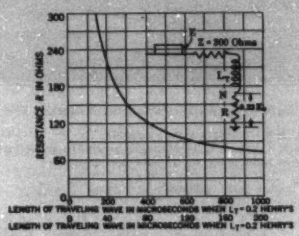


FIG. 12—RELATION BETWEEN NEUTRAL RESISTANCE AND LENGTH OF TRAVELING WAVE NECESSARY TO RAISE NEUTRAL VOLTAGE TO 33 PER CENT OF THE VOLTAGE OF THE TRAVELING WAVE. (CALCULATED)

Curve of Fig. 12 shows the relation between the length of the traveling wave and the neutral resistance, which gives an ultimate neutral voltage of 0.33 $E$ for the case of $Z$ = 300 ohms, and $L_T$ = 0.2 henry or 0.04 henry. (The inductance of a large power transformer will usually have a value between 0.04 and 0.2 henry.) The length of the wave causing an ultimate voltage of 0.33 $E$ with a given resistance varies in direct

proportion to inductance. The principal features of the transient, with resistance in the neutral, are shown by *B* of Fig. 3.

In practise the conclusions given above must be modified where ground resistors are metallic, as they may consist of many hundreds and sometimes thousands of feet of conductor. While the inductance of such devices can perhaps be neglected at operating frequencies, it cannot be neglected under transient conditions caused by lightning or switching surges and

FIG. 13—EFFECT OF INDUCTANCE ON NEUTRAL OSCILLATIONS

1, 2, 3, 4, 5, & 6—Voltages at line terminal

1 *A*, 2 *A*, 3 *A*, 4 *A*, 5 *A*, 6 *A*—Voltages neutral to ground with different ratios of neutral inductance to transformer inductance

| | | | | | |
|---|---|---|---|---|---|
| Ratio $\frac{L_N}{L_N + L_T}$ | | | | | |
| $\frac{L\ A}{1}$ | $\frac{2\ A}{0.725}$ | $\frac{3\ A}{0.67}$ | $\frac{4\ A}{0.48}$ | $\frac{5\ A}{0.26}$ | $\frac{6\ A}{0.097}$ |

consideration of grounding through such resistances must take into account the conclusions reached in the next part of the paper.

### *B. Neutral Grounded through Inductance*

### INFINITELY LONG TRAVELING WAVE

With a transformer grounded through an inductance the initial voltage distribution will be the same as in the case of a solidly grounded transformer and the final voltage at the neutral will be $E_N = E \times \frac{L_N}{L_N + L_T}$ ($E$ is the voltage applied between line terminal and ground, $L_N$ and $L_T$ are neutral and transformer inductances respectively.) Thus the axis of transformer internal oscillation is a straight line connecting the potential of the line terminal with the final potential $E_N$ of the neutral terminal. (See *C* of Fig. 3.) On Fig. 14 curve 1 gives maximum voltage $E_N$ max between neutral and ground as a function of $\frac{L_N}{L_T}$ obtained by scaling oscillograms of Fig. 13. Curve 2 gives the final voltage $E_N$ at the neutral calculated by the above formula. Dots on this curve are the points of equilibrium about which the oscillations of the neutral were actually taking place, as shown by oscillograms of Fig. 13.

The coincidence of the dots with the curve confirms the theory of oscillation of the neutral when grounded through inductance.

It must be realized that $L_T$, the transformer inductance, depends on three conditions: first, the number of transformers of a given bank that are simultaneously subjected to a given surge; second, whether other windings are connected in delta or star; third, the high-frequency characteristics of the network connected to all windings. For example, when all three transformers of star delta bank are struck, say by lightning, $L_T$ is equal to one-third of the short circuit inductance of one transformer. In case one transformer is struck, say by a switching surge, $L_T$ is the open circuit inductance if other windings are disconnected from their networks. In the first case, a neutral

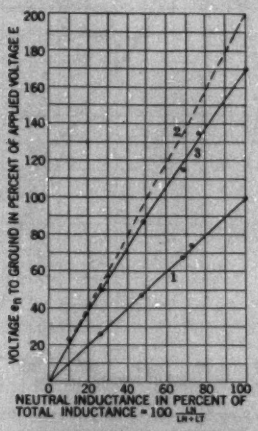


FIG. 14—EFFECT OF NEUTRAL INDUCTANCE ON TRANSIENT VOLTAGE FROM NEUTRAL TO GROUND

1—Line of equilibrium for voltage oscillations at the neutral. (Calculated—dots represent tested data obtained from oscillograms Fig. 13)

2—Maximum voltage of neutral to ground that could be expected in service

3—Maximum voltage of neutral to ground (Test data)

inductance of 5 per cent (based on rated kv-a. of one transformer of the bank) will cause transient voltage at the neutral of the order of the applied voltage, if the transformer short circuit inductance is, say 10.5 per cent, because then $\frac{L_N}{L_N + L_T} = \frac{5}{5 + 3.5} = 0.59$ and from Fig. 14 $E_N$ max. equals 1.18 $E$. Still higher voltage will appear with greater neutral inductance. For instance with inductances of 100 per cent (based

again on rated kv-a. of one transformer of the bank), which is the order of magnitude of the Peterson coil,

$$\frac{L_N}{L_N + L_T} = \frac{100}{100 + 3.5} = 0.97 \text{ and } E_N \text{ max. equals}$$

$1.94\,E$.

### Finite Traveling Wave

The neutral voltage will not reach the above values in case the length of the wave is less than half of the period of oscillation of the neutral.[3]

### C. *Neutral Grounded through Capacitance*

#### Infinitely Long Traveling Wave

The initial voltage distribution along a transformer winding grounded through capacitance is the same as in a solidly grounded transformer.

The final voltage at the neutral is equal to the applied voltage $E$, because with a constant voltage suddenly applied and maintained across the terminals of the circuit, the voltage across the capacitance will start to oscillate in very much the same manner as if the transformer winding were a pure inductance. That is the voltage

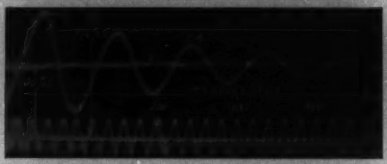

Fig. 15—Oscillation of Neutral Voltage with Condenser in the Neutral of the Transformer

1 —Voltage at line terminal
1 *A*—Voltage from neutral to ground

across the capacitance beginning with zero, will oscillate with amplitude equal to the applied voltage $E$ about a point of equilibrium $E$ volts above ground (see Fig. 15). Neglecting the surge impedance of the line, the frequency of the oscillation is $f = \frac{1}{2\pi\sqrt{L_T C_N}}$ ($L_T$ is transformer inductance, and $C_N$ is neutral capacitance provided $C_N$ is big enough in comparison with transformer electrostatic capacitance.) After the oscillation dies out the voltage across the capacitance becomes $E$.

In addition to this oscillation the entire winding will oscillate similarly to previous cases, at its natural frequencies. As in the case of a transformer grounded through resistance, the line end of the axis of the internal oscillation will remain at the hundred per cent point. But contrary to the case of neutral resistance the neutral end of the axis will tend to oscillate at frequency $f$. Whether it will succeed or not depends on the ratio of the fundamental natural frequency of the transformer with neutral isolated and the frequency, $f$, of the neutral grounded through capacitance. The smaller of the two dominates the phenomena. Since the internal transient is a damped oscillation the position of its axis is of importance (as far as the effect of this oscillation is concerned) only for the period $t$ microseconds, at the end of which the amplitude of internal oscillation reduces below dangerous value. In case $C_N$ is big enough to control the frequency at the neutral, and this frequency is such that at the end of $t$ microseconds the neutral voltage rises to only a small fraction of the applied voltage, the internal oscillation will be practically identical with that of a solidly grounded transformer. If this frequency is so high that at a small fraction of $t$ microseconds the voltage of the neutral reaches a value comparable with the applied voltage, the transformer oscillation will approach that of a transformer with isolated neutral. The envelopes of maximum voltages to ground occurring during $t$ microseconds for various values of neutral capacitance are similar in appearance to curves of Fig. 11.

In case the neutral frequency $f$ is so low that the transformer winding oscillates practically as if it were grounded for the period of $t$ microseconds, the voltages of all points of the winding will oscillate after $t$ microseconds, at frequency $f$. The axis of the latter oscillation will be a horizontal line drawn through the point corresponding to the applied voltage $E$, and the entire winding will oscillate as a perfectly rigid rod with the line end remaining stationary at $E$ volts above ground and the neutral end oscillating between zero and $2\,E$ volts.

#### Finite Traveling Wave

In practise the traveling waves are finite and the voltages at different points of the transformer winding depend not only on the just mentioned relations but also on the relation of the length of the wave, the fundamental natural frequency of the transformer, and the frequency $f$ of the neutral.

The relation between the length of the wave and the internal transformer oscillations was described in a preceding paper.[3] Fig. 16 shows the relation between maximum neutral voltage and the ratio of the length of traveling wave to period of $f$. Therefore it is possible by a proper choice of the neutral capacitance to make transformers behave under finite traveling wave excitation as if they were solidly grounded.

### D. *Neutral Grounded through Impedor*

It was found by various investigators that the short circuit neutral current can be reduced to a safe value by grounding some of the transformer banks of a system through either resistance or reactance.

The ohmic values of the grounding resistance or reactance depend on system characteristics and, naturally, vary over quite a wide range. The order of magnitude of maximum resistance, however, is not

expected to exceed 300 to 400 ohms. In most of the cases, values below a hundred ohms were found to be satisfactory at large substations; the maximum value of neutral reactance (Peterson Coil) is of order of 100 per cent and the minimum is probably 5 per cent (both based on capacity of one phase of the sub-station). These values if expressed in henrys are somewhere between 0.01 and 2.0 henrys.

With resistance of the above order of magnitude only

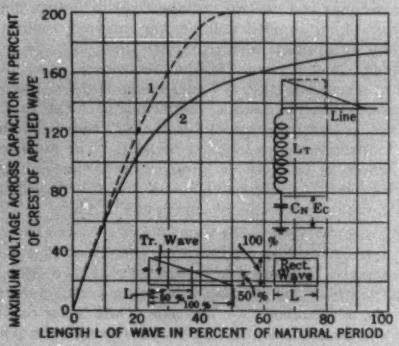


Fig. 16—Relation between Maximum Voltage from Neutral to Ground, and the Ratio of Length of the Applied Wave to the Natural Period of the Neutral Oscillation. (Single Frequency Oscillation)

1—For rectangular wave
2—For triangular wave

the very long traveling waves and switching transients are capable of raising the voltage at the neutral to a considerable fraction of the applied voltage. Fig. 17 indicates that waves of many hundreds of microseconds in length must be of comparatively low amplitude to be able to propagate along a transmission line without arcing over its insulators. In such a case, the neutral potential, while it may rise to an appreciable fraction of the applied voltage, is proportionately lower in its absolute value. Since voltage resonance between transformer and the neutral resistance is physically impossible, it appears that with resistance of not more than some 30 or 40 ohms the neutral potential under lightning or switching transient excitation will not exceed some 20 per cent of the impulse arc-over of a given transmission line insulation.

It was found that in most of the cases reactance in the neutral is preferable to resistance. Unfortunately, the desirable values of the neutral reactance are generally such that the transient neutral potential would necessarily rise to dangerous magnitudes under most voltage disturbances.

Furthermore, during switching out operations, when breaking single- or two-phase ground shorts, sudden rupturing of the neutral current may produce an "inductive kick" of a very destructive magnitude. The inductive kick of a neutral reactor is usually more severe than that of a transformer because the neutral reactor is generally of air core type and the residual magnetism, reducing the magnetic kick in a transformer, is absent.

As was shown, the neutral transient voltage is proportional to $\frac{L_N}{L_N + L_T}$. The selection of the values of $L_N$ and $L_T$ cannot, however, be governed by transient voltage considerations, but must depend entirely on operating frequency requirements. This makes special measures necessary when it is desired to keep the rise of neutral transient voltage below values which would be attained with only inductance $L_N$ between the neutral and ground.

Careful consideration of all aspects of the problem makes it appear that the most satisfactory means of controlling neutral transient voltage is an addition of capacitance and resistance in shunt with the inductance. The capacitance and resistance are so selected that on

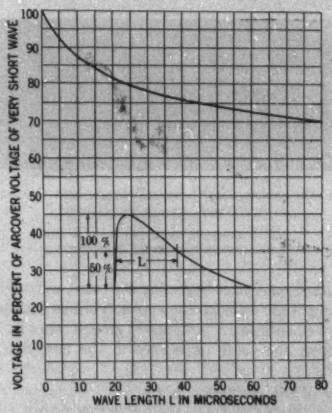


Fig. 17—Relation between Arc-over Voltage of a String of Insulators and Length of Traveling Wave

one hand, the neutral voltage does not rise above a specified fraction of the applied voltage regardless of the type of the line transient, and on the other hand, the impedance of such a grounding device at operating frequency is equal to the desired value. In addition the rate of rise of neutral potential, produced by any surge, is made so slow in comparison with the natural frequency of the transformer that the transformer winding oscillates as if it were solidly grounded. It is suggested to call the above device an impedor.

Under short circuit the operating frequency neutral

voltage rises to a certain value $e_1$ depending on the ratio of the neutral reactance to the transformer reactance and the reactance of the rest of the system. For this reason $e_1$ is chosen as a criterion for the selection of the constants of the impedor. They are chosen so that equivalent transient stresses do not exceed $2\,e_1$, which is the value of the high potential test that the impedor and the neutral end of the transformer must be subjected to, if their operating voltage is $e_1$. Fig. 18 shows the relation between the operating frequency voltage

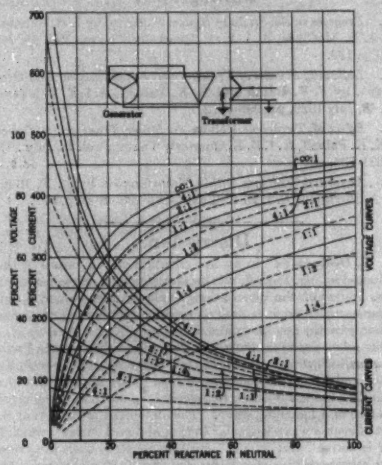


FIG. 18—OPERATING FREQUENCY VOLTAGE AND CURRENT OF NEUTRAL REACTORS FOR LINE TO GROUND FAULT, WITH VARIOUS RATIOS OF GENERATOR TO TRANSFORMER CAPACITY

Solid lines—generator reactance equals 20 per cent (Steam turbine)
Dotted lines—generator reactance equals 35 per cent (Hydro turbine)
Transformer reactance in both cases equals 10 per cent
Ratios given on the curves are ratios of generator capacity to transformer capacity

and current of a neutral impedor as function of its reactance for various ratios of kv-a. generating capacity of the station to the kv-a. capacity of the transformer bank involved in a single-phase short-circuit.

## Part 4. Impedor with Non-Resonating Transformer

A non-resonating transformer which is designed for solidly grounded neutral when grounded through ordinary resistance or capacitance oscillates very much like an ordinary transformer, as shown diagrammatically on Fig. 3. It does so because, while its "initial" voltage distribution is a straight line, similar to the voltage distribution of a non-resonating transformer with solidly grounded neutral, it does not coincide with its "final" voltage distribution which is the same horizontal line as that of an ordinary transformer. To design a shield which would give initial distribution as a straight horizontal line would mean to secure infinite capacitance between the shield and the winding, which, of course, is impossible. However, the neutral capacitance may be so chosen that for the finite waves which are found in practise the neutral will remain substantially at ground potential, and thus the initial and final voltage distributions will coincide and the transformer will not oscillate. To prevent the possibility of resonance between the neutral capacitance and the inductance of the transformer as a whole under oscillatory transient, a resistance is placed in shunt with the capacitance. Under such conditions the transient voltage distribution along the winding will be uniform. Since impedance of such an impedor at operating frequency can be made very high, the transformer may be made to act at operating frequency as if its neutral were isolated.

A bank of non-resonating transformers, if designed with insulation of the neutral sufficient to withstand the dynamic voltage rise of the neutral, could, in most cases, be grounded through a pure resistance (*i. e.*, non-

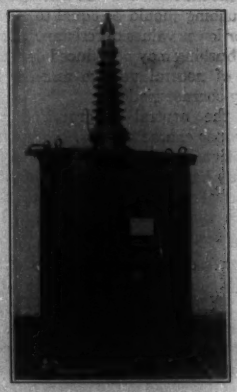

FIG. 19—IMPEDOR FOR BANK OF (3) 40,000-KV-A. 220-KV. TRANSFORMERS

inductive) of 30 to 40 ohms and act even under severe transient voltages practically as if they were solidly grounded.

When it is desired not only to retain the non-resonating characteristics but also to keep the neutral voltage below $E\,\dfrac{L_N}{L_N + L_T}$, under transient conditions, an impedor is designed to hold the neutral voltage and its rate of rise below a specified value for the longest traveling wave possible in practise.

During the last year and a half nearly 800,000 kv-a.

of transformers of non-resonating type, have been built so that they can be operated with impedor in the neutral.

## Conclusions

### Ordinary Transformers

It has been shown in previous papers that the insulation of ordinary transformers, with solidly grounded neutral, should not be graded in the order of the normal frequency voltage stress to ground, due to the presence under transient voltage stress of high voltages to ground along a major portion of the winding from line toward the neutral. The insulation immediately adjacent to the neutral terminal (say the last 10 per cent) and the neutral bushing itself may be of lower insulation strength.

In this paper it is shown that:

1. Where the neutral is not solidly grounded but is grounded through inductance, the insulation of the whole of the winding and neutral bushing must be equal to that of the line terminal.

2. Where the neutral is grounded through resistance, if this resistance exceeds 300 to 400 ohms per transformer bank, the insulation of the whole of the winding and neutral bushing should be equal to that of the line terminal. For lower values of resistance, the insulation of the neutral bushing may be reduced depending on the dynamic rise of neutral voltage and the transformer high-frequency characteristics.

3. Where the neutral is grounded through an impedor of proper characteristics, the neutral bushing and the insulation between neutral end of the winding and ground may be reduced depending on the dynamic rise of the neutral voltage, but the insulation between the rest of the winding and ground and low voltage winding cannot be graded.

### Non-Resonating Transformers

1. Where the neutral is solidly grounded the insulation from line terminal to neutral can be graded in the order of the normal frequency voltage stress.

2. Grounding the neutral through an inductance is not permissible with a non-resonating transformer of the construction described in the papers referred to.

3. Grounding the neutral through a resistance not exceeding 30 or 40 ohms is permissible with non-resonating transformers. The insulation of the winding may be graded in the order of the fall of voltage from line terminal to the neutral under the maximum value of dynamic neutral voltage rise. For higher values of resistance, a capacitance shunt across the ground resistance must be used.

4. Grounding the neutral through an impedor of proper characteristics is permissible with non-resonating transformers. The insulation of the winding may be graded in the order of the fall of voltage from line terminal to the neutral under the maximum value of dynamic neutral voltage rise. The impedor may consist of:

(a) A combination of resistance and capacitance.

(b) A combination of resistance, capacitance, and inductance, when the latter is required by short circuit considerations.

The author wishes to express his indebtedness to Mr. J. H. Hagenguth for his assistance with tests and calculation of curves, and to Messrs. A. N. Garin and S. T. Martin for editing the paper during the author's absence.

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2. *Lightning Studies of Transformers by the Cathode Ray Oscillograph*, by F. F. Brand and K. K. Palueff, A. I. E. E. Trans., Vol. 48, July 1929, pp. 998-1012.

3. *Effect of Transient Voltage on Power Transformer Design*, by K. K. Palueff, A. I. E. E. Quarterly Trans., Vol. 48, July 1929, pp. 681-706.

4. *Abnormal Voltages within Transformers*, by L. F. Blume and A. Boyajian, A. I. E. E. Trans. ,Vol. 38, 1919, p. 577.

## Discussion

**J. K. Hodnette:** In an investigation of the nature of that conducted by Mr. Palueff, it is necessary to make certain assumptions. Some of the assumptions made by Mr. Palueff do not appear correct and it is desired to substitute more logical ones and compare the results obtained.

This refers particularly to Part 2 of the author's text, *Transformer with Neutral Isolated*. It is evident from the descriptive matter and from the oscillograms reproduced in the paper that the author has assumed an extremely long wave as being representative of a lightning wave. The statement is made that the effect of such a wave is similar to that of direct current, which in itself is correct, but it is incorrect to construe such a wave as being representative of a lightning wave. Recently published data[1] giving the result of many tests in the field indicate that the maximum length of lightning surges expected in service probably would not exceed 60 microseconds to half value and the most rapid rise was about one microsecond to maximum value. Such a wave, which could easily be reproduced in the laboratory, would be representative of the most severe conditions with regard to stresses in transformers expected from any lightning surges. A wave of this character was used in obtaining the following test results.

Fig. 1 of this discussion compares the initial voltage distribution obtained by Mr. Palueff in a shell type and a core type transformer with the distribution in 30,000-kv-a. shell type transformer of modern design. The initial distribution is a function of electrostatic circuit of the transformer, or a function of proportions of the transformer. The author intimates that these curves are representative of the initial distribution in shell and core type transformers in general. Fig. 1 illustrates the error that would be introduced by making such a generalization.

Fig. 2 of this discussion shows the maximum voltage to ground in the transformers by oscillation. Curves 1 and 2 are reproduced from the author's curves Fig. 7, which were taken from the oscillograms of Figs. 5 and 6. It is to be noted that the author has used the extremely long wave in producing these oscillations. The amplitude of the oscillations depends upon the initial distortion, the length of the wave, and the natural period of the transformer. Under these conditions high percentage of overvoltage would naturally be expected. Curve 3 of Fig. 2 shows

1. *Symposium on Lightning Investigations*, see p. 857.

the maximum voltage to ground in a 25,000-kv-a. isolated neutral transformer produced by the 60-microsecond surge. Note that the maximum voltage is 74 per cent as compared to 240 per cent by Curve 2. Had the author made his experiments with a wave comparable to a lightning wave his results would have been more of the order of Curve 3. In view of these facts I cannot see how the author justifies Curves 5, 6, and 7 of Fig. 7 as test values of the maximum voltage to ground due to lightning.

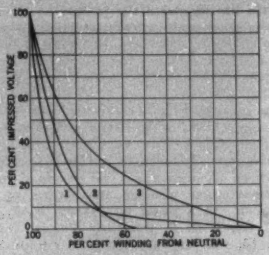


Fig. 1—Initial Voltage Distribution

1. Mr. Paluef's shell type transformer
2. Mr. Paluef's core type transformer
3. 30,000-kv-a. shell type transformer (test)

In the preliminary conclusions for ordinary transformers the statement is made that the grading of insulation in a solidly grounded neutral transformer in the order of the normal frequency stress is not permissible. The author gives no data to substantiate that conclusion but refers to previous papers for proof. In these papers he has proceeded with the same assumptions made here, that is, that a lightning wave is extremely long, an obviously incorrect assumption. On the contrary, an analysis of the stresses in transformer windings[2] based on lightning surges, both in magnitude and shape, and coordinated with field and laboratory tests on the transmission insulation, has shown clearly that the grading of insulation is a permissible practise.

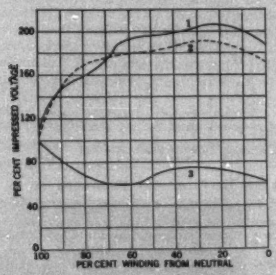


Fig. 2—Internal Voltages to Ground in Transformers Due to Lightning Transients

1. Mr. Paluef's shell type transformer (extremely long rectangular wave)
2. Mr. Paluef's core type transformer (extremely long rectangular wave)
3. 25,000-kv-a. shell type transformer with 60-microsecond impressed surge (test)

2. *The Effect of Surges on Transformer Windings*, J. K. Hodnette, A. I. E. E. Quarterly Trans., Jan. 1930, p. 68.

Referring to the author's text on switching surges, it would be of interest to know the source of information for the statement that the amplitude of the average switching transient is about half of that of the lightning wave. Many data have been obtained in recent years on the amplitude of switching surges.[3] These data taken on many systems indicate that surges as high as 4.5 times normal are rare and occur on but few of the systems. The average switching surge based on these data would probably not exceed one and one-half times normal. Also most switching transients were recorded unidirectional, or the attenuation was so rapid that only one crest occurred above normal voltage. This is illustrated by the author's Fig. 8 where the decay is from 4.5 times normal to about 1.5 times normal in the first cycle or a decrease of 65 to 70 per cent.

The author, however, disregarded this fact in representing a switching transient for his experiments by a damped oscillation

Fig. 3

which has a decrement of about 25 per cent. Fig. 3 of this discussion shows the forced oscillations in the 25,000-kv-a. shell type transformer above produced by a damped oscillation having a 45 per cent decrement. Practically exact resonance exists between the applied voltage and the transformer oscillations whereas the author's oscillograms, Fig. 9, were taken with a 20 per cent discrepancy from resonance. Even with this discrepancy the maximum voltage in the first case is less than one-half that of the latter. Had the author used a more rapidly decaying oscillation, such as Fig. 8, the internal voltages would have been greatly reduced.

Sufficient data are not available at present for drawing

3. *Klydonograph Surge Investigations*, J. H. Cox, P. H. McAuley, and L. G. Huggins, A. I. E. E. Trans., Vol. 46, 1927, p. 315. *Symposium on Surge Voltage Investigation*, A. I. E. E. Quarterly Trans., Oct. 1928, pp. 1111-1154

conclusions as to the intensity of stress setup by switching transients. Failures of transformers from this type of transient are practically unknown, which is the true criterion for the sufficiency of the design or the relative intensity of the stress. Therefore, until more conclusive data are presented, it appears that the author's conclusions are drawn from insufficient evidence.

**F. J. Vogel:** I should like to refer to Mr. Palueff's Fig. 11. In common with his other curves he has assumed a definite kind of lightning surge. This has been a surge which has been of infinite length. We also have taken test data using the surge which we have assumed to be more representative of actual lightning conditions than the surge which he has picked. Fig. 4 shows oscillations with different values of resistance at the

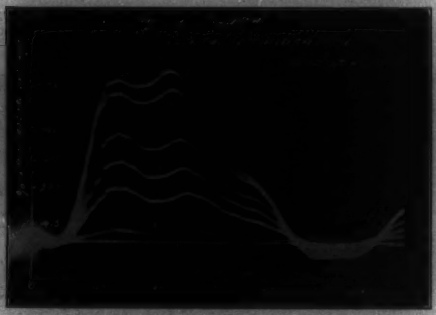

Fig. 4

1—$R$ = ∞
2—$R$ = 100,000 ohms
3—$R$ = 25,000 ohms
4—$R$ = 11,000 ohms
5—$R$ = 5,000 ohms
6—$R$ = 460 ohms

neutral. Curve 6 shows practically the same results that Mr. Palueff has given. Comparison of the other values would be 62½ per cent versus 171 per cent for approximately 100,000 ohms; and also, 40 per cent versus 125 per cent, for 25,000 ohms.

Continuing, we note on page 1185, the first paragraph, second column, that the "voltage distribution with 500 ohm resistance in the neutral is the same as with solidly grounded neutral." We are very much inclined to agree. However, on page 1188 and in the conclusions, he makes quite different statements. I believe that he cannot justify these latter statements on the basis on which they are calculated. They are calculated from the data given under the heading "Finite Traveling Wave." He has assumed a certain value of $L_T$. He estimated the time necessary to reach the final distribution, using this value of $L_T$. If this is followed to its conclusion, you will find the current large, which means there would be iron losses and magnetization. The effect of the iron on $L_T$ cannot be neglected. $L_T$ will be far from a constant during the first part of the surge and at times very large. For that reason, his test data are much more valuable than what he has obtained from his calculations.

Figs. 13 and 14 are again made by assuming infinitely long waves which the author was not actually able to obtain. Further, there is not an exact comparison between Figs. 13 and 14 because the data given under 2A, 4A, and 5A and the points on the curves do not correspond. Good correspondence with the calculated values was not actually obtained.

There is, in the literature published by different Westinghouse and General Electric Company engineers, a discrepancy in the impulse voltage flashovers for insulators. It is unnecessary to go into that except to state that there are considerable data published by Mr. J. J. Torok for a 60-microsecond wave. That is the only point we can check on the author's curve, Fig. 17. Torok's data practically show no impulse factor whatever, whereas the author shows a considerable impulse factor for a 60-microsecond wave. This means that the author is estimating on a higher voltage due to long waves than we are. This difference is quite considerable.

Mr. Hodnette has discussed the preface to the conclusions. The second conclusion is also already covered. I wish to make an addition to the third conclusion and that is, that either an impedor such as the author has worked out or other protective means will give very nearly the same results as the solidly grounded neutral.

I wish also to state that under these conditions graded insulation is permissible, which is a direct contradiction to this part of the conclusion.

**J. H. Hagenguth:** It probably will be of interest to show the agreement between calculation and test results of oscillations in an ordinary transformer winding, the neutral of which was directly grounded. In a paper by Messrs. F. F. Brand and K. K. Palueff (A. I. E. E. Quarterly Trans. Vol. 48, 1929, p. 1005), Fig. 15, was shown a series of curves which were obtained from oscillograms. Fig. 5 of this discussion shows

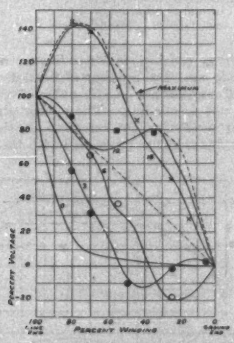


Fig. 5—Voltage Distribution Produced in an Ordinary Transformer by a Single Traveling Wave. (Calculated)

0 Initial voltage distribution at impact of traveling wave
3, 6, 12, 18 simultaneous voltage distribution throughout the winding after 3, 6, 12, and 18 microseconds. Dotted line represents envelope of maximum voltages. $x$ indicates test value

similar curves which represent calculated values. The abscissa represents per cent winding, and ordinate the voltage at different points in per cent of applied voltage. The calculation is relatively simple but quite laborious. Curve $O$ represents the initial voltage distribution due to impact of traveling wave and was obtained by test. It can also be calculated as has been shown before. This curve has been analyzed into its space harmonics with respect to the line of final voltage distribution. As has been shown previously, these harmonics do not oscillate at the frequency which their order indicates but at a higher order. For instance, the second harmonic may oscillate at a frequency between 2½ to 4 times the fundamental or even higher. By superimposing the amplitudes of these harmonics at different points of the winding, when oscillating at their proper frequencies, the volt-time relations, as well as simultaneous voltage distributions, can be obtained. Simultaneous voltage distributions

are shown at 0, 3, 6, 12, and 18 microseconds. It should be noted how rapidly the change of voltage takes place. For instance, at the 30 per cent point the voltage increases from 15 to + 78 per cent in six microseconds. The dotted curve represents the envelope of maximum voltages which is not simultaneous. In order to show the accuracy of the calculations a few points are plotted from actual oscillograph records. The greatest error is only 10 per cent, which is not much considering

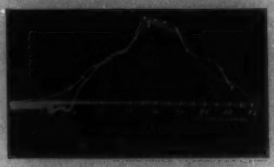

Fig. 6—Volt-Time Characteristics of a Point 56.7% from Neutral Due to a Single Traveling Wave

Curve 1 oscillographic record
Curve 2 calculated values

the complexity of the transformer circuit for high-frequency phenomena. On Fig. 6 the volt-time characteristic for impulse waves of a single point is shown. Curve 1 is the oscillographic record. Curve 2 represents calculated values. The tested curve is slightly lower, which may be attributed to damping, but the close resemblance in almost every detail can be easily seen. The damping up to the first half cycle is almost negligible. It has not been taken care of at all in the calculations. The maximum rise at this point, 58 per cent from neutral, is 115 per cent. On Fig. 7 the voltage rise of the transformer neutral with neutral isolated and neutral grounded through capacitor is shown. The great difference in time at which maximum occurs should be noted. When the neutral is isolated the maximum is reached in 25 microseconds; when grounded through the capacitor, in 180 microseconds. It has been shown in the paper that for all practical purposes the frequency of oscillation of the neutral can be calculated from the relations $f = \frac{1}{2\pi\sqrt{LC}}$, where $L$ is the equivalent reactance of transformer and neutral grounding device and $C$ grounding capacitor.

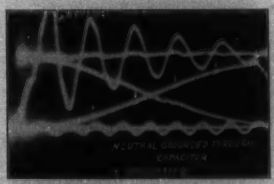

Fig. 7—Voltage Rise of the Neutral Due to a Single Traveling Wave

1. Neutral isolated
2. Neutral grounded through capacitor

1 $A$ and 2 $A$ are applied waves
Frequency of the oscillator wave is 50,000 cycles

To prove this point the rise of neutral voltage has been calculated, taking in this case the short circuit reactance of the transformer, which by the way represents the reactance of a bank of three 40,000-kv-a. transformers 220,000 $Y$, and the capacitance in the neutral.

The crosses on the film indicate calculated values and they check very closely the test results.

It may be mentioned that there is a difference in the applied waves for the two conditions shown on Fig. 7, but the resulting voltage rises at the neutral can be compared. For Condition 1, *i. e.*, neutral isolated, the maximum voltage at the neutral would be reached if the applied wave has a length of at least half of the natural period, which in this case is a rectangular wave of 25 microseconds. It can be seen that up to 25 microseconds the two applied waves almost coincide, and therefore the comparison of the maximums is correct for the applied wave of condition 2. For a rectangular wave of 25 microseconds duration, the maximum voltage at the neutral under condition 1 would be the same as for the very long wave shown on the figure, *i. e.*, 164 per cent, while for condition 2 the maximum voltage would be 27 per cent instead of 92 per cent as for the applied wave 2$A$. The capacitor used for this test was much smaller than would be used in service to permit the superposition of both conditions on one film, by decreasing the natural period and thereby increasing the neutral rise.

**W. A. McMorris:** In the design of these impedors, the neutral grounding resistor or reactor used is determined by the operating frequency requirements. The problem is then to modify the high-frequency characteristics of the installation, so that the transient voltage appearing at the neutral will be limited to a predetermined value and wave shape.

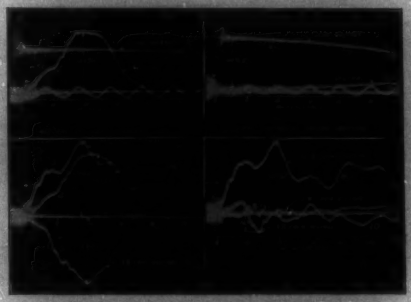

Fig. 8—Effect of Impedor on Impulse Voltages at Neutral and Internal Points of Transformer Winding

1 to 5—Neutral grounded through reactor
6 to 10—Neutral grounded through impedor
1 and 6—Applied wave
2 and 7—Voltage at neutral
3 and 8—Voltage at 75 per cent from neutral
4 and 9—3 per cent from neutral
5 and 10—13 per cent from neutral (obtained with reversed polarity)

The oscillograms of Fig. 8 herewith show the voltages produced by a single traveling wave at the neutral and at several points of a transformer winding. The oscillograms on the left half of the figure were made with the neutral grounded through a reactor. The neutral voltage rises rapidly to a value even in excess of the applied voltage, and severe oscillations occur within the winding.

The oscillograms on the right half of the figure were made with conditions the same, except that a capacitor was connected in parallel with the reactor. The neutral voltage rises gradually, and reaches only a small fraction of the applied voltage. No internal oscillations are forced in the windings of the transformer or reactor. The transformer behaves substantially the same as if it were solidly grounded.

Calculation of the capacitance required is a simple matter, and may be accomplished in a short time by the use of a set of design curves. Using the curves of Fig. 9 herewith, the required natural period can be found when the ratio of neutral inductance to total inductance, and the allowable voltage rise at the neutral are given. From the ratio $\frac{L_N}{L_T + L_N}$ read vertically to the per cent voltage rise, horizontally to the length of the traveling wave, then vertically to the required natural period.

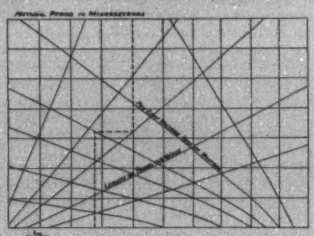

Fig. 9—Chart for Determining Required Natural Period

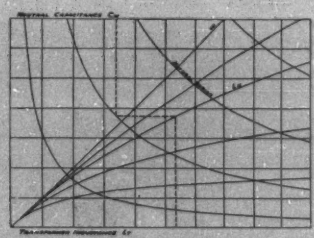

Fig. 10—Chart for Determining Required Capacitance

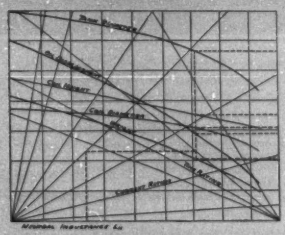

Fig. 11—Chart for Determining Dimensions and Weight of Reactor

Using the curves of Fig. 10 herewith, the required capacitance can be found when the transformer inductance, neutral inductance, and natural period are given. From the transformer inductance $L_T$ read vertically to $L_N$, horizontally to natural period, then vertically to neutral capacitance $C_N$.

After the circuit constants have been determined, the weights, costs, and dimensions of the apparatus can be determined from other curve sheets. Fig. 11 herewith shows such a sheet for neutral reactors designed for a given high-potential test. From $L_N$ read vertically to current rating, horizontally to time rating, then vertically to curves showing dimensions and weights.

In Fig. 19 of Mr. Paluéff's paper is shown a grounding impedor for a bank of three 40,000-kv-a., 220-kv. transformers. This unit is entirely self-contained. The only external leads are the high-voltage bushing, which is to be connected to the transformer neutral, and a grounding terminal, which is to be connected to the station ground bus.

**K. K. Palueff:** I wish to answer first Mr. J. H. Hodnette's criticisms on the following points.

A: "More logical" shape of wave should have been used for some of the data given.

B: Comparison of initial or electrostatic distribution in core and shell type transformers.

C: Maximum voltage to ground produced by traveling wave in a transformer with isolated neutral.

D: Amplitude and the rate of decay of damped oscillations and "average surge."

E: Internal voltages produced by damped oscillations.

F: Experience with graded insulation transformers.

A: In the paper presented by the author to the Institute in January, 1929, considerable space was given to the description of the influence of the shape of the incident traveling wave and of the natural frequency of the transformer on the magnitude of voltages produced in the winding.

I am glad to see Mr. Hodnette quote this relation without challenge.

In the present paper, as well as in the preceding papers, an attempt was made, first to present separately the effect on the phenomenon of various factors involved, then to combine them in a manner that would represent conditions met in practise, so as to be able to draw conclusions of practical interest. For this reason very long waves have been applied to the transformer to record its free oscillations fully developed and undistorted by the shape of the incident wave. After such records are obtained, the amplitude and the shape of the voltage wave of any given point in the winding, for any shape of the incident wave, can be computed with a high degree of precision, as was shown in the papers referred to above.

In the above criticism, Mr. Hodnette refers to Part II of the paper. The section entitled "Finite Traveling Wave," deals with the effect of wavelengths found in practise.

B: The fact that in a shell type transformer the initial or electrostatic distribution causes at the line end at least as high a concentration of voltage as in a core type transformer, was proved by Mr. Hodnette's and the author's tests. Those interested in this phase of the phenomenon, I should like to refer to Mr. Hodnette's paper and my discussion of it. (A. I. E. E. Quarterly Trans., Vol. 49, Jan. 1930, p. 68.) If Curve No. 3, Fig. 1 of his present discussion was obtained in the same manner, as some of the similar data given in the paper referred to, then it is as much in error as were those and for the same reason. More than eighteen years of experimenting with high-frequency transients, taught us that exceptional care should be exercised in all details of the experiment.

I again suggest that Mr. Hodnette present an analytical proof, accompanied by a numerical example, of his statement that shell type transformers by virtue of their very wide coils and relatively short stack have more uniform initial voltage distribution than is found in longer stacks of narrow coils.

I should like to repeat that it would be of general interest should he find it possible to publish data on *sphere-gap* measurements of impulse voltage between the line terminal and turns not only on outside, but also on *inside edges* of coils. Such a test, if properly conducted, gives a truer picture of initial voltage distribution.

C. This question for the solidly grounded transformers was also answered very completely in my discussion of Mr. Hodnette's paper just referred to.

I pointed out, in that discussion, a very substantial discrepancy existing between Mr. Hodnette's oscillographic records, and the curves plotted from them.

I have pointed out in a previous paper the simple relation existing between the ratio of natural period of oscillation to the length of the applied wave and the magnitude of maximum voltage produced inside of the transformer winding. This relation can also be derived from Fig. 16. For example, with natural frequency of 12,500 cycles, the voltage to ground of the half of the winding next to neutral produced by a 60 microsecond wave will be approximately 70 per cent higher than in a transformer whose natural frequency is 3300 cycles.

The latter frequency is approximately equal to the natural frequency of the 25,000-kv-a. transformer referred to by Mr. Hodnette in his present discussion. The natural frequency of 12,500 was found by Mr. Hodnette in some other shell type transformer he tested and referred to in the closing discussion of his paper. Curve 3 of Fig. 2 of this discussion therefore becomes Curve 3*A* for the transformer with natural frequency of 12,500 cycles. (See Fig. 12 of this discussion.) Curve 7 of Fig. 7 of the present paper is reproduced as Curve 7 on Fig. 12 herewith. Curve 3 of Fig. 12 is a reproduction of Curve 3 of Fig. 2 of Mr. Hodnette. The natural frequency of transformers, of both shell and core type, varies over a wide range (between say 2000 and some 40,000 cycles), so that there is bound to be a

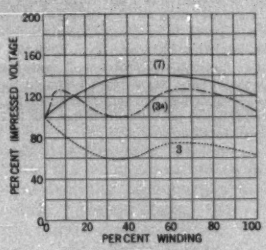


Fig. 12

difference in voltage produced in various transformers by a given wave. Therefore, the agreement between Curve 7 and 3*A* is indeed as satisfactory as could be expected.

It is Curve 7 and not 3 and 4 of Fig. 7 that represents the author's idea of voltages found in practise. Curves 3 and 4 give voltage to ground found in transformers when an extremely long wave is applied, while Curve 7 is described as "estimated voltage found in practise."

On this account, in Fig. 2 of this discussion, in place of Curves 1 and 2, Curve 7 of Fig. 7 should have been reproduced for comparison with Mr. Hodnette's Curve 3.

More than 95 per cent of total published oscillographic data on the shape of the natural lightning wave, referred to by Mr. Hodnette, has been obtained by my associates, and I therefore had the unusual opportunity of studying these data in the original. In spite of this, I am of the opinion that it is too early to speak with authority of the length and shape of the most dangerous lightning waves that are encountered in practise.

E: Switching surges above five times normal are on record. Some of these records have been obtained by Mr. Hodnette's associates.

Since most of the records were secured by means of surge voltage recorder and klydonograph, the data on the shape of the wave are not sufficient to allow anyone to speak with certainty of the damping factor.

Mr. Hodnette, in his closing statement, admits that his knowledge of switching surge characteristics is not sufficient. At the same time he definitely states that I am not justified in using a damped oscillation with 25 per cent damping factor for Fig. 9, while he considers his tests with damping factor of 40 per cent to be representative of the worst conditions found in service.

It is generally recognized that the corona loss is responsible for the high damping factor of voltage transients on overhead lines. For this reason, the damping effect reduces with successive cycles of the oscillation as the corona loss decreases very rapidly with reduction in magnitude of the voltage. Therefore, the damping effect becomes very small when the transient voltage is only two or three times normal.

Voltage within winding resonating to a surge increases with each successive half cycle. This increase is proportional to the amplitude of the respective half cycle of the applied wave. Thus, a highly damped surge (decrement 75 per cent) consisting of three half cycles of, say, 5, 2.5, and 1.25 times normal (total 8.75) will produce internal oscillations approximately 20 per cent lower than those produced by a damped oscillation consisting of 9½ cycles (decrement 36 per cent), with amplitude as follows: 2.5, 2, 1.6, 1.3, 1.04, 0.83, 0.67, 0.56, 0.47 times normal (total 10.97).

All investigators, including those associated with Mr. Hodnette, agreed that the damped oscillations of two and one-half times normal are very common in all systems.

For these reasons, the rarity of oscillatory transients of extremely high amplitude, to which Mr. Hodnette attaches so much importance, is not important at all, in the case of cumulative oscillations.

From the above it appears that should Mr. Hodnette's tendency to regard switching surges as of little practical importance, because they seldom attain extremely high magnitude, be made use of in transformer design, a difficulty may arise in practise.

On Fig. 8 of the present paper appears the only cathode ray oscillogram of switching surge so far published. It should be noted that the damping factor drops after the first cycle from 50 per cent to 20 per cent, and the oscillation persists for many cycles.

F: It is my conviction that data given in Mr. Hodnette's paper and several papers published by me, as well as my discussion of Mr. Hodnette's paper, prove conclusively that the use of graded major insulation, even in solidly grounded transformers, is a hazardous practise. Mr. Hodnette refers to service record as being the final proof of suitability of such a design. It is difficult to use service records as an argument in a discussion like this, because there are no published data on failures of transformers. My knowledge of operating experience with this type of transformer is therefore very limited. I understand that in Canada, some 220-kv. transformers with graded insulation have failed during lightning, in spite of the fact that the line insulation adjacent to the transformers was even weaker than the rule of coordination of line and transformer insulation calls for.

I also know that in Germany, at first, graded transformers were used in conjunction with the Petersen coil. This practise caused so much trouble that it was abandoned. That such a practise should cause trouble follows directly from the conclusions arrived at in the present paper.

I should now like to answer Mr. Vogel's discussion. He, like Mr. Hodnette, wants to see in my use of an extremely long wave for some of the test data, a sign that, to my mind, such waves are representative of natural lightning waves. As I have explained before, this is not true.

To derive sufficiently general conclusions from tests made with a 60-microsecond wave or any other short wave, it is necessary to test a great many transformers and perform a very laborious calculation. The use of very long waves saves all this time, as it simplifies the calculations and tests.

Mr. Vogel and Mr. Hodnette invite us to approve gradings of

major insulation on the ground that one of the three transformers they have tested happened to have a natural frequency of about 3300 cycles, and therefore it gave, under most favorable conditions of single traveling wave excitation, results satisfactory to them. It would be of interest to see the results of their tests on the two other transformers which Mr. Hodnette mentioned in his paper and his closing discussion, particularly on the transformer whose natural frequency was 12,500, according to his measurements.

Mr. Vogel speaks of the effect of iron loss and magnetization of the core on magnitude of $L_T$. Should he analyze the flux distribution produced in the transformer when lightning waves simultaneously strike all three transformers of a given bank, he would discover that for the period of time that we are interested in, the effect of the iron is absolutely negligible. Conditions under which it is not negligible are stated in the paper on page 1186.

Oscillograms of Fig. 13 and curves of Fig. 14 of the paper were obtained, as stated, under the assumption of simultaneous excitation of all three transformers of the bank. $L_T$, therefore, was measured and calculated. Of course, Mr. Vogel realizes that under such conditions the accuracy of calculation is a matter of a few per cent, which is ample for the purpose.

The discrepancy between the amplitude of oscillograms 2A, 4A, and 5A, as marked on Fig. 13, and position of corresponding dots on Fig. 14 is due to error in marking the oscillograms (on the advance copies). There is a complete agreement between actual maximum amplitude of voltages as recorded by these oscillograms, and the dots of Fig. 14. This can be verified by scaling the oscillograms of Fig. 13. However, the correctness of the law suggested in the paper and demonstrated by Figs. 13 and 14 is obvious. (The values on Fig. 13 are now correct.)

The controversy on impulse ratio is too involved to be answered here. Mr. Peek's data shown on Fig. 17 were obtained with waves similar to those found in service. Mr. Torok's data were secured with flat top waves which so far were not observed in service except of extremely low amplitude. It is hoped that in due time different investigators will agree on the interpretation of the data secured under different test conditions.

The neutral impedor may consist of either special resistance connected from the neutral to ground (with or without gap) or of special resistor and condensor connected in shunt with the resistor. The values of the constants and the choice between the two types of impedor are determined by the characteristics of the transformer and the character of the impedance that it is desired to use for the limitation of the short-circuit current.

As was observed in the paper, the internal high-frequency voltages in transformer grounded directly or through a resistance of some 500 ohms, is very nearly the same. However, when the transformer is struck by a very long traveling wave, in addition to the high-frequency internal oscillation, the entire winding begins to rise above ground potential, as was shown on page 1184. The conclusions on page 1185 refer to voltages due to high-frequency internal oscillations. The conclusions on the last page are general, and refer to voltages that can be produced by any type of transient mentioned in the paper. They also refer to any size of power transformer. There is, therefore, no contradiction between the two conclusions. This is illustrated by Fig. 10.

Mr. Hodnette remarked that I am exaggerating the danger of the transient voltages, because the average transient voltage waves are not as high as those I mentioned. I believe that by this remark he emphasized the principal difference between his and our attitude toward the problem of transformer design. While he proposes to base transformer design on the average or the most probable conditions, we believe that conditions that can reasonably be considered the very worst that can be experienced, should be the basis for design.

# Report of the Board of Directors

## FOR THE FISCAL YEAR ENDING APRIL 30, 1930

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Forty-sixth Annual Report, for the fiscal year ending April 30, 1930. A general balance sheet showing the condition of the Institute's finances on April 30, 1930, together with other detailed financial statements, is included herein. The following is a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in the Institute JOURNAL.

**Directors' Meetings.**—The Board of Directors held seven meetings during the year, five in New York, one at Swampscott, Mass., and one at Chicago, Ill. The Executive Committee acted upon various matters during intervals between Board Meetings.

Information regarding the more important activities of the Institute which have been under consideration by the Board of Directors, the committees, and the various officers is published each month in the section of the JOURNAL devoted to "Institute and Related Activities."

**President's Visits.**—President Smith attended the two national conventions and one district meeting held since the beginning of his administration. He has visited a large majority of the Sections, also groups of members in several centers having no Sections. Members of Branches located near Sections have been invited to attend the meetings, and in addition he visited some of the neighboring Branches.

The following is a list of places visited in addition to many trips to Institute headquarters in New York: Winnipeg, Can.; Regina, Sask., Can.; Vancouver, Can.; Seattle, Wash.; Spokane, Wash.; Portland, Ore.; San Francisco, Calif.; Santa Monica, Calif. (Pacific Coast Convention); Salt Lake City, Utah; Denver, Colo.; Omaha, Nebr.; Des Moines, Iowa; Kansas City, Mo.; St. Louis, Mo.; Sharon, Pa.; Syracuse, N. Y.; Fort Wayne, Ind.; Milwaukee, Wis.; Minneapolis, Minn.; Madison, Wis.; Chicago, Ill. (District Meeting); Urbana, Ill.; Lafayette, Ind.; Washington, D. C. (A. E. C. Meeting); Pittsburgh, Pa.; Buffalo, N. Y.; Toledo, Ohio; Erie, Pa.; New York, N. Y. (including Winter Convention); Cincinnati, Ohio; Louisville, Ky.; Memphis, Tenn.; Oklahoma City, Okla.; Dallas, Houston, and San Antonio, Texas; Mexico City, Mexico; Havana, Cuba; New Orleans, La.; Birmingham, Ala.; Atlanta, Ga.; Raleigh, N. C.; Norfolk, Va.; Washington, D. C.; Baltimore, Md.; Philadelphia, Pa.; Rochester, N. Y.; Ithaca, N. Y.

On April 25, he addressed a joint meeting of the Boston, Connecticut, Lynn, Pittsfield, Providence, Springfield, and Worcester Sections at Worcester.

President Smith served as one of the Institute's representatives at the Fiftieth Anniversary Celebration of the American Society of Mechanical Engineers held in New York, Hoboken, and Washington in April.

During May and June, the president will attend the Springfield District Meeting, the Summer Convention in Toronto, Canada, and will visit several Sections.

**Meetings.**—Three national conventions of the Institute were held during the year: Summer, Pacific Coast, and Winter. District meetings under the auspices of the Geographical Districts were held in Dallas, Texas, District No. 7, in May, and in Chicago, Ill., District No. 5, in December, 1929.

**Annual Meeting.**—The Annual Business Meeting was held at the New Ocean House, Swampscott, Mass., on Tuesday morning, June 25, 1929, during the annual Summer Convention. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1929, was presented, and the Tellers Committee made its report upon the election of officers for the administrative year beginning August 1, 1929.

**Summer Convention.**—The forty-fifth annual Summer Convention was held at Swampscott, Mass., June 24-28, 1929. Twenty-six papers were presented at five technical sessions, and eighteen technical committee reports were presented at two additional sessions. Other sessions were the Annual Business Meeting mentioned above, and one at which an address on Astronomy was given by Dr. Harlowe Shapley. The Annual Conference of Officers and Delegates, under the auspices of the Sections Committee and the Committee on Student Branches, was held on Monday, June 24, and forty-nine Sections were represented. The entertainment features included golf and tennis tournaments, a dinner, and an all-day trip to Rye Beach, N. H. The Lamme Medal, awarded by the Institute, and the John Scott Medal, awarded by the Board of City Trusts of Philadelphia, were presented to Allan B. Field at the dinner. More than 1000 members and guests attended the convention.

**Pacific Coast Convention.**—The eighteenth Pacific Coast Convention was held at Santa Monica, Calif., September 3-6, 1929. At four technical sessions, eighteen papers were presented. Eleven technical papers by students were presented at two additional sessions. An illustrated address was given by Dr. W. V. Houston on Wednesday evening. The program included various social events and trips. The attendance was about 440.

**Winter Convention.**—The eighteenth Winter Convention was held in New York, January 27-31, 1930. Fifty technical papers were presented at ten sessions. At an evening session, the Edison Medal was presented to Professor Charles F. Scott, and a lecture on "Discovery and Excavation at Olynthos" was given by Dr. David M. Robinson. Numerous inspection trips, a smoker, and a dinner-dance were held. Attendance about 2,000.

**District Meetings.**—The first District meeting of the year was held at Dallas, Texas, May 7-9, 1929. The program included fifteen papers presented at four sessions and eleven papers by students presented at two other sessions. Attendance about 540. The second was held at Chicago, Ill., District No. 5, December 2-4, 1929. At four of the sessions, nineteen papers were presented, and thirteen papers by students were presented at a fifth session. Attendance about 600.

**World Engineering Congress.**—Many members of the Institute, including four past-presidents and the National Secretary, participated in the World Engineering Congress in Tokyo, Japan, in October-November, 1929. The official delegates of the Institute were: F. C. Hanker, F. L. Hutchinson, P. M. Lincoln, L. A. Osborne, R. F. Schuchardt, Elmer A. Sperry, and Charles W. Stone.

Twenty-six countries were represented at the Congress and about 800 papers were presented. The total attendance exceeded 1,000, including about 500 from foreign countries, of whom about one-half were from the United States.

The Tokyo Sectional Meeting of the World Power Conference was held concurrently, and about 150 papers were presented during its sessions.

**Honorary Members.**—Three distinguished American engineers were elected Honorary Members of the Institute by the Board of Directors on June 25, 1929: Herbert Hoover, Charles F. Scott, and Charles F. Brush (posthumously). Dr. Motoji Shibusawa, Dean of Engineering at Tokyo Imperial University, Japan, was elected an Honorary Member by the Board of Directors on August 6, 1929. He was installed at a special meeting of the Institute held in Tokyo, November 7, 1929, during the World Engineering Congress.

**Sections.**—The Sections have, with very few exceptions, been active during the year. Many excellent technical programs have been presented, and there has been a good variety of programs of other types. Considerable attention has been given to the desirability of the individual participation of engineers in public affairs.

The New York Section organized four technical groups, Communication, Illumination, Power, and Transportation, and each held two or more meetings during the year, with a total of twelve, in addition to the regular Section meetings. The Power Group of the Chicago Section held three meetings. The group meetings in both cities have been very successful.

The Chicago Section and the Western Society of Engineers cooperated in arranging for two lecture courses for practicing engineers who wish to supplement their technical education: "Engineering Economics" at Armour Institute of Technology and "Recent Developments in Electron Physics and Chemistry" at the University of Chicago.

Many joint meetings were held with neighboring Branches, and the programs were supplied partly or entirely by students at twenty-two or more meetings. Many Sections held joint meetings with other local groups.

Three meetings were held by the Pittsfield, Schenectady, and Seattle Sections, at which their younger members presented papers in competition for prizes.

Nearly all of the District Executive Committees held meetings during the year.

President Smith has visited a large majority of the Sections, and will visit others before the end of the administrative year.

President Smith's message in the September issue of the JOURNAL was devoted to the activities of the Sections.

The Birmingham, Iowa, and North Carolina Sections were organized during the year, and all have been active. The existence of the Panama Section, which has been inactive for several years, was terminated by the Board of Directors at its meeting held March 14, 1930.

In April, each Section was supplied with the names of its Associates whose dues were to become $15.00 on May 1, and it was recommended that each Section appoint a small committee to review the names and remind all such Associates who are clearly qualified for the higher grades to submit their applications promptly.

**Student Activities.**—Nearly all of the Branches have been very active during the year both in their individual meetings and in coöperative relations with other Branches and with Sections.

Eight of the Districts held Conferences on Student Activities.

Ten Student Conventions were held, six sponsored by District Committees on Student Activities, three by Sections, and one by a Branch.

The increased interest of the students has been shown by the larger number of talks by them, a greater number of Branch meetings at which special types of programs were presented, and a considerable number of statements by Branch officers that the student programs usually produce better attendance and greater interest than do other kinds.

Meetings of some of the Branches were devoted to general discussions on particular subjects (one subject per meeting), debates, and mock trials. Students supplied the programs at twelve joint meetings with

Sections, and parts of the programs at ten or more such meetings.

At its meeting on January 29, 1930, the Board of Directors approved the recommendations of a special committee that Enrolled Students be permitted to enter as Associates without paying the usual entrance fee. The necessary Constitutional amendments were submitted to a vote of the membership, and the results will be announced at the Annual Business Meeting on June 23.

The message of President Schuchardt in the May issue and that of President Smith in the October issue of the JOURNAL were directed especially to Branch members.

The Board of Directors authorized the payment of traveling expenses at the rate of ten cents per mile one way for an annual visit of each Vice-President to each Branch within his District.

As a result of recommendations made the Counselor Delegates at the Summer Convention at Swampscott, Mass., a set of cards was sent to each Counselor in February, giving the names of Enrolled Students of the Institute who had been at his institution at the time of enrollment, with the names of those who had not paid their fees for 1930 on cards of a different color.

New Branches were organized at Michigan College of Mining and Technology, University of New Mexico, North Dakota Agricultural College, Pratt Institute, Southern Methodist University, and Texas Technological College. All of them have been active.

**Section and Branch Statistics.**—

| | For Fiscal Year Ending | | | |
|---|---|---|---|---|
| | April 30 1924 | April 30 1926 | April 30 1928 | April 30 1930 |
| SECTIONS | | | | |
| Number of Sections | 47 | 51 | 52 | 56 |
| Number of Section meetings held | 381 | 405 | 431 | 480 |
| Total Attendance | 58,945 | 58,959 | 64,276 | 84,615 |
| BRANCHES | | | | |
| Number of Branches | 77 | 86 | 96 | 106 |
| Number of Branch meetings held | 530 | 714 | 915 | 1,009 |
| Total Attendance | 25,674 | 35,270 | 44,334 | 50,401 |

**Meetings and Papers Committee.**—A major phase of the work of the Meetings and Papers Committee consisted of arranging the technical sessions of conventions. The Committee has also coöperated with Local District Meeting Committees and has assisted with the arranging of technical sessions and supplying the local committees with lists of technical papers available.

Three national conventions and two District meetings were held during the year. The number of papers presented and the attendance at each convention or meeting are given above under appropriate headings. The total attendance for national conventions was about 3400. The total attendance for District meetings was about 1150, making a grand total attendance of approximately 4550. A total of 146 papers were presented, including 18 technical committee reports. During the year, over 200 papers were reviewed by technical committees; of these 118 were passed on for the TRANSACTIONS.

Due to (1) the increase of technical subject matter submitted for Institute presentation and publication, (2) a tendency toward a higher degree of specialization, and (3) the President's call for suggestions, a careful study of Institute Policies in regard to Meetings and Papers was made in order to determine the best way of providing for the above changes and needs. With a view toward meeting these needs, the Committee has decided to present at the coming Summer Convention the Technical Committee Reports by title only and provide opportunity for their discussion together with the discussion on the session on selected subjects. More sessions have been arranged in parallel and on Wednesday morning three sessions will be in parallel. These changes are to be tried at the Summer Convention, in an effort to provide a greater outlet for technical subject matter submitted for Institute presentation by the membership.

A subcommittee on Technical Program and Publication Policies was formed to draw up definite recommendations. A report of this subcommittee on "Proposed Changes in the A. I. E. E. Policies in Regard to Meetings and Papers," dated January 30, 1930, was submitted to the Board of Directors, with a copy to the Publication Committee for its information.

At a meeting held September 20, 1929, a budget for the fiscal year beginning October 1st, based on the proposed number of papers, 139, at an estimated expense of $23,000, was accepted. The estimate was based on the cost of meetings of previous years 1926-1929 and cost for the year 1928-1929.

The reviewing of technical papers and recommending of technical papers for publication has comprised another important phase of the Committee's work throughtout the year. Furthermore, Committee members have assisted the Committee on Award of Institute Prizes by recommending papers worthy of final consideration for national prize awards. The Committee has rendered other assistance upon request such as recommending lecturers to National Convention Committees and suggesting the names of authors best qualified to prepare papers for special occasions.

The technical program for the 1930 Toronto Summer Convention Program has been completed. The programs for the Pacific Coast Convention and the Middle Eastern District Meeting are taking definite form. Consideration is also being given to appropriate subjects for the 1931 Winter Convention.

**Publication Committee.**—The question of Institute Publications has been growing in importance in recent years, and it has been the subject of probably more discussion than any other activity, particularly during the past year. The Publication Committee in its endeavor to make this Institute activity as useful as possible to all the membership, began about a year ago a thorough systematic survey for the purpose of obtaining the viewpoints of the members all over the country, as to what changes, if any, should be made in Institute Publications. This nation-wide survey has now been completed, the replies analyzed, and the results discussed at considerable length at the meeting of the Committee held on March 7.

After studying the results of the survey the Committee agreed on a general plan which is now being drawn up in final form, together with definite recommendations for submission to the Board of Directors at the May meeting. It is proposed to include in this plan the broad general policies only, leaving many of the details to be worked out by the Publication Committee in cooperation with the editorial staff, it being understood that some of the details will necessarily be modified from time to time. An estimate will also accompany the report, showing approximately what the additional cost will be to carry out such a plan.

Since changing the policy of Institute publications is a matter of such importance, the Committee suggested that before action is taken by the Board, the report be presented for discussion at the Conference of Officers, Delegates, and Members at the Toronto Convention in June. The Board concurred and arrangements have been made with the Sections Committee for the inclusion of this discussion in its program.

**Coordination Committee.**—The Committee corresponded with the officers of all Districts and Sections, and obtained their views regarding national and District meetings during the year 1931, resulting in recommendations to and adoption by the Board of Directors, in January and March, 1930, of a complete schedule of national and District meetings to be held during 1931.

The Committee has considered the coördination of the work of the A. I. E. E. technical committees with that of similar committees of other societies, and expects to recommend to the Board of Directors the adoption of an amendment to Section 82 of the By-laws, which states the functions of the technical committees.

**Standards Committee.**—During the past year, the Standards Committee's work has been largely confined to the consideration of revisions of existing Standards and the development of proposed standards. The work of revision has been carried on generally through subcommittees of two of the technical committees, *i. e.*, the Electrical Machinery Committee and the Instruments and Measurements Committee. No new Standards have been published, but revisions of six existing Standards have been approved and five reports on proposed standards have become available. The Sectional Committees of the American Standards Association, of which the Institute is sponsor or joint sponsor, have been active, especially the Sectional Committee on Scientific and Engineering Symbols and Abbreviations. This committee is rapidly completing the work originally laid out for it, and its accomplishments should prove of great value to industry, particularly to those who deal with publications and drawings.

The Institute is now sole sponsor for eight projects and joint sponsor for fifteen, and is represented on thirty-one Sectional Committees which are under the sponsorship of other organizations. One development of interest has been the agreement reached with the National Electrical Manufacturers' Association to consolidate under a joint sponsorship of A. I. E. E. and N. E. M. A. the Sectional Committees dealing with Rotating Electrical Machinery. These projects have been making but little progress for several years and it is hoped that the new arrangement will not only reduce the total number of man-hours required to carry on the work, but will also expedite the final approval by the electrical industry of several Standards which are vital. At a special meeting of the Standards Committee of January 7, 1930, there was approved, in principle, a proposition for the formation of a joint agency of the electrical industry for the purpose of carrying out the necessary standardization activities of that industry. It is contemplated that this agency will have three distinct functions: (a) The Standards Committee of the electrical industry in the United States; (b) The Electrical Advisory Committee of the American Standards Association; (c) The U. S. National Committee of the I. E. C., and of any other international organizations for the handling of electrical matters. The Standards Committee's recommendations were transmitted to the Board of Directors, which approved and transmitted them to the present Electrical Advisory Committee, where they are now under consideration. This project was described more fully in the President's message published in the March, 1930, JOURNAL.

**U. S. National Committee of the I. E. C.**—During the past year a number of important meetings of advisory committees have been held abroad as follows:

The Advisory Committee on Nomenclature has held a number of meetings throughout the year and the international vocabulary which is in preparation has been advanced very greatly thereby. This work is under the direction of Dr. C. O. Mailloux.

An international subcommittee under the chairmanship of Dr. A. E. Kennelly has been considering the question of Magnetic Units. This subcommittee was unable to find solutions for the questions referred to it; but decided to invite and elicit discussions on them, prior to the next plenary meeting, among the various national committees. In this connection a paper was presented by Dr. Kennelly at the Winter Convention of the

Institute with the idea of eliciting expressions of opinion in this country. It is hoped that some decision on this very difficult and contentious matter may be reached at the next Plenary Meeting of the Commission.

The International Advisory Committee on Rating of Electrical Machinery met in London on July 10th, 11th, and 12th and took certain important action in regard to dielectric tests and methods of testing; but because of lack of time was unable to bring matters to as satisfactory a conclusion as was hoped for in the direction of rating temperature rise. The difficult matter of temperature rises was left in the hands of a subcommittee consisting of Messrs. Everest, Kloss, Robinson, and Roth. This subcommittee has been actively engaged ever since in an endeavor to agree on all points which will be acceptable to the Advisory Committee when next it meets. The United States was represented by Dr. A. E. Kennelly, Dr. C. O. Mailloux, Dr. L. T. Robinson, Mr. L. L. Elden, Mr. R. E. Ferris, Prof. W. L. Upson, Prof. H. Pender, Mr. A. Wright, and Mr. W. W. Lewis.

At a meeting of the Advisory Committee on Steam Turbines held in London from July 1st to July 8th, the United States was represented by Prof. W. F. Durand as chief delegate and Mr. F. Hodgkinson and Mr. Irving E. Moultrop as advisory delegates. Mr. C. B. Le Page was present as representing the Secretariat. The Advisory Committee brought the specifications and test code for Steam Turbines to a point where adoption in large part can be anticipated at the Stockholm meeting.

The Advisory Committee on Aluminum met in Berlin on November 6th, the United States being represented by Mr. W. C. Binz, Mr. L. Braasch, and Dr. C. O. Mailloux. Among other things a value was tentatively agreed to for the conductivity of hard-drawn aluminum, which is to be submitted to the forthcoming Plenary Meeting.

The Advisory Committee on Electric Traction Equipment met in London on July 8th and 9th, the United States being represented by Mr. R. E. Ferris, official delegate, and Dr. A. E. Kennelly, Dr. L. T. Robinson, and Prof. W. L. Upson in an advisory capacity. This work proceeded in a satisfactory manner.

The Advisory Committee on Measuring Instruments met in Berlin on the 6th and 7th of November, 1929, the United States not being represented by any official delegate. The Committee made great progress in the formulation of a Code for meters of the less accurate or Class 2 type. This entire matter will come up for consideration at the Plenary Meeting.

A Plenary Meeting of the Commission is to be held this year in Scandinavia. The preliminary program calls for the first assembly in Copenhagen on June 27th, departure for Sweden on June 28th, Technical Sessions in Stockholm from June 30th to July 5th, arrival at Oslo on July 6th, excursions to power plants on July 7th and 8th, and final Plenary Meeting on July 9th. It is expected that the United States will be adequately represented at this meeting. Preparations looking forward to it have been going on throughout the year and have occupied the USNC and its various groups of Advisors continuously during this time.

A joint committee has discussed the proper relationships between the USNC and the American Standards Association and a report has been prepared giving a basis on which closer and more satisfactory contacts and interconnections might be worked out with advantage to both bodies. The further discussion of this matter has been postponed by mutual consent pending the outcome of the recent movement looking to the establishment of a standardizing committee of the electrical industry with which the USNC might, in due course, be affiliated or amalgamated.

**U. S. National Committee of the International Commission on Illumination.**—During the year, various matters in connection with the International Illumination Congress and Plenary Meeting of the International Commission on Illumination held in Saranac in September, 1928, were completed. The final accounting of funds raised for the purposes of this meeting through the Committee of the Illuminating Engineering Society showed a surplus which was distributed pro rata among the contributors.

The volume of Proceedings of the Congress and Plenary Meeting, amounting to 1443 pages and constituting a very valuable collection of information on the art and science of illumination as of to-day, was distributed by the Illuminating Engineering Society.

The National Committee was able to make effective use of its contacts with the National Committees which constitute the International Commission in connection with the celebration of Light's Golden Jubilee. It was desired in this country that other nations should join in the observance of this important epoch, and the United States National Committee approached the other National Committees with information as to what was being planned in this country and the suggestion that some form of observance adapted to national conditions might be desirable in other countries. Following this the other National Committees were kept informed of the progress and plans in this country. In a number of countries, notably Italy, Japan, and the Netherlands and, on a less pretentious scale, in France, Austria, Germany, and Sweden, effective observances of this Jubilee were held.

The next Plenary Meeting of the Commission is to be held in Great Britain in 1932. In connection with this, it has been the privilege of the United States National Committee to submit to the Central Office and to the British National Committee the results of the experience gained here in connection with the Saranac meeting with a view to giving whatever assistance might be given toward making the next meeting the great success which the British Committee is endeavoring to achieve.

The Committee, as Secretariat for Aviation Lighting, has coöperated in a meeting held in London, having as its object the unification of practise in order to facilitate international flying. Another meeting on this subject was held in Berlin in April.

The Committee has been otherwise engaged in routine matters including the exchange of documents and other information with other National Committees and in preparations looking to effective participation in the next Plenary Meeting.

The International Commission on Illumination has recently been accorded a very definite recognition of its status in that the International Committee on Weights and Measures in requesting of its Advisory Committee on Electricity a report on the procedure whereby the International Bureau can take over the supervision of the matter of an international standard of light gave to that Committee definite authority to coöperate with the International Commission on Illumination. At the present stage this project is largely in the hands of the several national laboratories, but the machinery of the International Commission on Illumination gives a channel through which the organized interests concerned with illumination can be informed regarding developments and can be given an opportunity to make their influence felt through guidance and stimulation.

**Technical Committees.**—Reports of Technical Committees embracing an outline of the year's work and a summary of progress in the industry will be presented at the annual Summer Convention and printed in the TRANSACTIONS.

**Membership.**—The fundamental duty of the Membership Committee, as defined by the By-laws, is to "bring the advantages of membership to the attention of desirable candidates for admission to the Institute." The advantages of membership can be presented to them most effectively by carefully selected Section Membership Committees.

In order to appeal to their Section loyalty and thus most effectively stimulate the activity of the Section Membership Committees, a slight change was made this year in the method of carrying out the work of the Membership Committee. This change consisted in establishing contact of the candidate directly with the Section instead of with National Headquarters. This was effected by having the names of candidates forwarded by the suggesting member directly to his own Section Membership Committee Chairman instead of to National Headquarters. It is believed that the direct personal contacts thus locally established have been somewhat more successful than the more impersonal method formerly employed.

The additions to, and deductions from, the membership are shown in the following table. In accordance with the established policy of the Institute, emphasis has continued to be placed on the qualifications of candidates. The total membership as of April 30, is 18,003.

| | Honorary | Fellow | Member | Associate | Total |
|---|---|---|---|---|---|
| Membership on April 30, 1929 | 8 | 687 | 3,377 | 14,061 | 18,133 |
| Additions: | | | | | |
| Transferred | 2 | 24 | 227 | | |
| New Members qualified | 1 | 4 | 73 | 1,139 | |
| Reinstated | | 1 | 7 | 56 | |
| Total | 11 | 716 | 3,684 | 15,256 | 19,667 |
| Deductions: | | | | | |
| Died | 1 | 12 | 29 | 59 | |
| Resigned | | | 27 | 365 | |
| Transferred | | 1 | 14 | 238 | |
| Dropped | | 1 | 56 | 861 | |
| Membership on April 30, 1930 | 10 | 702 | 3,558 | 13,733 | 18,003 |

**Deaths.**—The following deaths have occurred during the year.

*Honorary Members:* Charles F. Brush, Sebastian Ziani de Ferranti.

*Fellows:* William S. Andrews, Alfred H. Cowles, Edward B. Craft, Walter C. Fish, Arthur H. Ford, David L. Huntington, Peter Junkersfeld, Charles S. Lawson, John W. Lieb, Walter H. Millan, Thomas E. Murray, Harry W. Weller.

*Members:* Eugene H. Abadie, Armistead K. Baylor, John R. Benton, Henry W. Blake, John J. Barger, Wallace W. Briggs, Bedford J. Brown, Sidney Hand Browne, Henry A. Coles, John A. Cressey, Frederic Cutts, Edmund P. Edwards, William L. Fey, John H. Finney, F. A. T. FitzGerald, Ralph W. Goddard, Everett D. Hall, Joseph A. Hebert, James T. Hutchings, Harry W. Jeannin, Samuel M. Kennedy, Charles B. Larzelere, Maurice A. Oudin, Arthur C. Scott, Everett H. Smith, Harry L. Tanner, Arthur E. Walden, James T. Watson.

*Associates:* Charles S. Allen, Isaac M. Beatty, Nicholas F. Brady, Charles C. Chatley, Wallace S. Clark, Herbert A. Clarke, John L. Curtiss, J. Maurice De Vean, Clark E. Diehl, Andrew E. Dobson, William D. Forster, N. Govindraj, John H. Graybill, Clarence G. Hadley, Fred C. Hamer, Shimpei Hayase, James F. Hillock, Tsuyoshi Hirayama, Harold J. Horn, Henry C. Houck, Noboru Inouye, Allan F. Jacobson, John M. Jolly, Frederick L. Jones, William E. Keily, Fred M. Kimball, Charles W. Kincaid, Ralph V. S. Kirkwood, Leo R. Lake, Paul Liunge, Calvin O. Loewenberg, Oscar S. Major, Allen M. Manning, Frederick M. Martinego, Marshall J. McMuran, Frank R. Mistersky, Percy N. Moore, Max G. Newman, Joseph H. Owsley, Edward F. Peck, George A. Plank, Ralph W. Pope, Francis C. Pratt, J. Lloyd Prince, Robert M. Searle, Guido Semenza, Charles A. Tripp, Carl E. Trube, Ralph E. Tuttle, Miner H. Vallas, Ferdinand Voelker, Jr., Roy A. Walker, J. Wallace, Ralph L. Werden,

Herbert B. Whyte, Albert E. Wing, William O. Winston, Jr., Charles T. Wright, John W. Wright.

**Board of Examiners.**—The Board of Examiners held nine meetings during the past year, averaging about three and one-quarter hours. A total of 3796 cases was considered, divided as shown in the following table:

| | | |
|---|---|---|
| APPLICATIONS FOR ADMISSION | | |
| Recommended for grade of Associate | 989 | |
| Not recommended | 21 | 1010 |
| Recommended for grade of Member | 82 | |
| Not recommended | 23 | 105 |
| Recommended for grade of Fellow | 5 | |
| Not recommended | 0 | 5 |
| Recommended for enrolment as Students | | 2406 |
| APPLICATIONS FOR TRANSFER | | |
| Recommended for grade of Member | 211 | |
| Not recommended | 29 | 240 |
| Recommended for grade of Fellow | 28 | |
| Not recommended | 2 | 30 |
| | | 3796 |

**Institute Prizes.**—Four National Prizes and eleven District Prizes for papers were awarded during the year, as announced through the Institute JOURNAL. These prizes were for papers presented at Institute meetings during 1928. The National Prizes were presented at the 1929 Summer Convention and the District Prizes at various meetings in the respective Districts. The National Prizes consist of $100.00 each and a certificate, while the District Prizes consist of $25.00 cash and a certificate.

**Scholarships.**—The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute committee. The scholarships pay $350.00 toward annual tuition with provision for reappointment.

Complete details governing prizes and scholarships may be obtained by applying to the National Secretary of the Institute.

**Edison Medal.**—The Edison Medal, founded by associates and friends of Thomas A. Edison, is awarded annually by a committee consisting of twenty-four members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1929 was awarded to Professor Charles F. Scott, "for his contributions to the science and art of polyphase transmission of electrical energy." The medal was presented at the Winter Convention of the Institute, January 29, 1930.

**John Fritz Medal.**—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of Civil, Mining, Mechanical, and Electrical Engineers, awarded the twenty-sixth medal to Ralph Modjeski for "notable achievement as an engineer of great bridges combining the principles of strength and beauty." The medal was presented by the Board of Award at the annual banquet and reception of the A. S. C. E., New York, January 15, 1930.

**Hoover Medal.**—The Hoover Medal, established through a trust fund created by the gift of Conrad N. Lauer, is to be awarded periodically by a Board of Award, composed of representatives of the national societies of Civil, Mining, Mechanical, and Electrical Engineers, "to a fellow engineer for distinguished public service." The first award was made to President Herbert Hoover to commemorate his civic and humanitarian achievements, and the medal was presented at the A. S. M. E. Anniversary Dinner in Washington, D. C., April 9, 1930.

**Lamme Medal.**—The Lamme Medal was founded as a result of a bequest of the late Benjamin G. Lamme, Chief Engineer of the Westinghouse Electric and Manufacturing Company, who died on July 8, 1924. The bequest provides for the award by the Institute of a gold medal (together with a bronze replica thereof) annually to a member of the A. I. E. E. "who has shown meritorious achievement in the development of electrical apparatus or machinery" and for the award of two such medals in some years if the accumulation from the funds warrants.

The Lamme Medal Committee of the Institute awarded the second (1929) Lamme Medal to Rudolf E. Hellmund, "for his contributions to the design and development of rotating electrical machinery." Arrangements are being made for the presentation of the medal at the annual Summer Convention at Toronto, Canada, June 23-27, 1930.

**Commission of Washington Award.**—The Washington Award for 1930 was made to Dr. Mortimer E. Cooley, Dean Emeritus of the Colleges of Engineering and Architecture, University of Michigan, "for vision and constructive leadership in the education of the engineer."

The award is made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of nine representatives of the Western Society of Engineers and two each from the A. S. C. E., the A. I. M. E., the A. S. M. E., and the A. I. E. E.

**Employment Service.**—The employment service which the Institute has maintained for many years is conducted as a cooperative bureau in conjunction with a similar service maintained by the National Societies of Civil, Mining, and Mechanical Engineers under the title, "Engineering Societies Employment Service." In addition to the main office in the Engineering Societies Building, New York, offices have been opened in Chicago in cooperation with the Western Society of Engineers and in San Francisco under similar arrangements with the California Section, American Chemical Society, and Engineers Club of San Francisco. It is hoped to continue this development from year to year as conditions warrant. The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the Employment Service announcements in the monthly JOURNAL, weekly subscription bulletins are issued for those seeking positions.

**American Engineering Council.**—Since its organization nearly ten years ago, American Engineering Council has experienced a steady, normal growth. It now includes in its membership twenty-four national, state, and local engineering societies which have a total membership of more than 57,000 professional engineers.

The Council represents its constituents at conferences, conventions, and congressional hearings upon matters involving engineering and on important national committees. It also extends valuable individual service to its member organizations. Several notable surveys on matters of concern to the entire engineering profession have been conducted.

The Fourth Conference of Secretaries of Engineering Societies, sponsored by the American Engineering Council, was held in Chicago, June 6 and 7, 1929.

A standing Committee on Engineering and Allied Technical Professions has been organized to enable the Council to enter upon an extensive program designed to secure information upon and to improve the general status of the engineering profession.

Other standing committees are Constitution and By-laws, Finance, Membership and Representation, Public Affairs, Publicity and Publications, and Regional Activities.

The Council has nineteen special committees including those on Airports, Bridges, Communications, Flood Control, Government Reorganization, Patents, Power, Radio Broadcasting, Reforestation, Water Resources, etc.

Approximately 150 bills introduced in the present session of Congress have been considered by the Council. A few of the important bills which have received specific attention are: Boulder Canyon Dam, Communications Commission, Uniform Government Contracts, Pay Status of Government Employees, National Hydraulic Laboratory, Inter-oceanic Canal Commission, Patent System, Radio Commission, Reforestation, Topographic Surveys, and Water Resources.

The Council has continued the publication of a quarterly known as the A. E. C. Bulletin.

**Engineering Foundation, Inc.**—This organization which succeeded United Engineering Society, by change of name only, was set up by the four national societies of Civil, Mining, Mechanical, and Electrical Engineers to hold in trust and to administer for them the Engineering Societies Building, in which their headquarters are located, certain funds, and the Library. Its charter gives it broad powers for the advancement of the engineering arts and sciences.

Extracts from the annual financial report of Engineering Foundation, Inc., were published in the March, 1930, JOURNAL.

**Engineering Societies Research Board.**—This Board, a department of Engineering Foundation, Inc., is the successor to Engineering Foundation which was established in 1914 by the national societies of Civil, Mining, Mechanical, and Electrical Engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It was conceived by Ambrose Swasey, of Cleveland, Ohio, and he has made three gifts toward its endowment. The fund has been generously increased through the gifts of Edward D. Adams and others, and also through a bequest of the late Henry R. Towne.

Appropriations have been made for various research projects, and cooperation has been extended in others.

**Engineering Societies Library.**—The Library is administered as a free public library under the direction of the Library Board of Engineering Foundation, Inc., this Board being composed of representatives of the national societies of Civil, Mining, Mechanical, and Electrical Engineers.

The Library contains about 125,000 books and pamphlets, and receives regularly about 1700 technical periodicals in 18 languages.

A staff of technically trained searchers and translators is maintained. The staff is prepared to furnish the following types of service: photoprints, abstracts, translations, bibliographies, searches, etc. Special arrangements have been made for lending books.

**Representatives.**—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years, and has accepted sponsorship and appointed representatives upon a number of new

Sectional Committees of the American Standards Association. A complete list of representatives is published frequently in the JOURNAL.

**Finance Committee.**—During the year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws.

Haskins & Sells, certified public accountants, have audited the books, and their report follows:

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON,

*National Secretary.*

New York, May 23, 1930.

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS
OFFICES IN THE PRINCIPAL CITIES OF THE UNITED STATES OF AMERICA
—AND IN—
LONDON, PARIS, BERLIN, SHANGHAI, MANILA, MONTREAL, HAVANA, MEXICO CITY
CABLE ADDRESS "HASKSELLS"

NEW YORK CENTRAL BUILDING
75 EAST 45TH STREET
NEW YORK

May 16, 1930.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have audited your accounts for the year ended April 30, 1930, and submit the following exhibits and schedule:

Exhibit

A—Balance Sheet, April 30, 1930.

Schedule 1—Reserve Capital Fund—Securities.

B—Summary of Income and Profit and Loss for the Year Ended April 30, 1930.

WE HEREBY CERTIFY that in our opinion Exhibits A and B set forth the financial conditions of the Institute at April 30, 1930, and the results of its operations for the year ended that date.

Yours truly,
HASKINS & SELLS

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

**Exhibit A.** **Balance Sheet, April 30, 1930**

### ASSETS

| | | | |
|---|---|---|---|
| **Real Estate:** | | | |
| One-fourth interest in Land, Building, and Building Equipment of Engineering Foundation, Inc., 25 to 33 West 39th Street (depreciation carried on books of Engineering Foundation, Inc.) | | | $493,352.60 |
| **Equipment:** | | | |
| Library—Volumes and fixtures | | $ 41,562.23 | |
| Works of art, paintings, etc | | 3,001.35 | |
| Office furniture and fixtures | $30,285.41 | | |
| Less reserve for depreciation (including $8,931.79 funded) | 13,419.85 | 16,865.56 | |
| Total equipment | | | 61,429.14 |
| **Working Assets:** | | | |
| "Transactions," etc | | $ 5,596.00 | |
| Text and cover paper | | 3,393.98 | |
| Badges | | 1,430.84 | |
| Total working assets | | | 10,420.82 |
| **Current Assets:** | | | |
| Cash | | $ 9,195.82 | |
| Accounts receivable: | | | |
| Members—for dues | | 20,891.26 | |
| Advertisers | | 1,579.45 | |
| Miscellaneous | | 1,804.75 | |
| Accrued interest on investments | | 3,351.82 | |
| Total current assets | | | 36,823.10 |
| **Funds:** | | | |
| Reserve Capital Fund: | | | |
| Securities—Schedule 1 | | $210,226.88 | |
| Life Membership Fund: | | | |
| Cash | $ 6,837.74 | | |
| Chicago, Burlington & Quincy Railroad Company 4% bonds, 1958, registered, face value, $5,000.00 | 4,868.75 | | |
| Accrued interest | 33.33 | 11,739.82 | |
| International Electrical Congress of St. Louis—Library Fund: | | | |
| Cash | $ 1,185.30 | | |
| New York City 4½% corporate stock, 1957, par value, $2,000.00 | 2,204.05 | | |
| New York Telephone Company 4½% bond, 1939, registered, face value, $1,000.00 | 878.75 | | |
| Accrued interest | 67.50 | 4,335.60 | |
| Mailloux Fund: | | | |
| Cash | $ 2.30 | | |
| New York Telephone Company 4½% bond, 1939, registered, face value, $1,000.00 | 1,000.00 | | |
| Accrued interest | 22.50 | 1,024.80 | |
| Lamme Medal Fund: | | | |
| Cash | $ 267.32 | | |
| Baltimore and Ohio Railroad Company 6% refunding and general mortgage series "C" bonds, 1995, face value, $4,000.00 | 4,330.00 | | |
| Accrued interest | 100.00 | 4,697.32 | |
| Depreciation of Furniture and Fixtures Fund: | | | |
| Cash | $ 3,921.79 | | |
| Cleveland Union Terminals Company 5% sinking fund series "B" gold bonds, 1973, registered, face value, $4,000.00 | 4,010.00 | | |
| Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property, Nos. 75-79 Prospect Street, East Orange, N. J.) 5½%, due 1933 | 1,000.00 | 8,931.79 | |
| Total funds | | | 240,956.21 |
| Total | | | $842,981.87 |

### LIABILITIES

| | | |
|---|---|---|
| **Current Liabilities:** | | |
| Accounts payable | $ 11,296.69 | |
| Dues received in advance | 2,740.84 | |
| Entrance fees and dues advanced by applicants for membership | 498.50 | |
| Subscriptions for "Transactions" received in advance | 539.00 | |
| Total current liabilities | | $ 15,075.03 |
| **Fund Reserves (Not Including Depreciation Reserve):** | | |
| Reserve Capital Fund | $210,226.88 | |
| Life Membership Fund | 11,739.82 | |
| International Electrical Congress of St. Louis—Library Fund | 4,335.60 | |
| Mailloux Fund | 1,024.80 | |
| Lamme Medal Fund | 4,697.32 | |
| Total fund reserves (not including depreciation reserve) | | 232,024.42 |
| Surplus, Per Exhibit "B" | | $595,882.42 |
| Total | | $842,981.87 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### SUMMARY OF INCOME AND PROFIT AND LOSS FOR THE YEAR ENDED APRIL 30, 1930

EXHIBIT B.

| | | | |
|---|---|---|---|
| **INCOME:** | | | |
| Dues | | *$228,251.20 | |
| Students' fees | | 12,166.00 | |
| Entrance fees | | 11,955.00 | |
| Transfer fees | | 1,295.00 | |
| Advertising | | 88,272.58 | |
| "Journal" subscriptions | | 11,464.11 | |
| "Transactions" subscriptions | | 1,141.30 | |
| Miscellaneous sales | | 10,363.92 | |
| Badges sold | $ 3,635.50 | | |
| Less cost | 3,404.78 | 230.72 | |
| Interest on securities in reserve capital fund | | 10,213.32 | |
| Interest on securities in depreciation reserve fund | | 244.16 | |
| Interest on bank balances | | 1,655.62 | |
| Total | | | $377,252.93 |
| **EXPENSES:** | | | |
| Publications: | | | |
| "Journal" | $87,463.37 | | |
| "Transactions" | 34,859.65 | | |
| Year book | 9,328.66 | | |
| Miscellaneous | 4,266.50 | $135,918.18 | |
| Institute meetings | | 24,625.08 | |
| Administrative expenses | | 64,005.19 | |
| Presidents' special appropriation | | 3,738.20 | |
| Board of Directors, traveling expenses | | 4,643.54 | |
| National Nominating Committee, traveling expenses | | 1,003.35 | |
| Institute representatives, traveling expenses | | 132.24 | |
| Sections | | 37,539.15 | |
| Geographical Districts' expenses: | | | |
| Traveling expense: | | | |
| Executive Committee | $ 2,790.00 | | |
| Vice-Presidents | 895.97 | | |
| District best paper prize | 63.00 | | |
| District prize for initial paper | 63.00 | 3,811.97 | |
| Branches | | 12,421.98 | |
| Membership | | 7,632.49 | |
| Finance | | 400.00 | |
| Code Committee | | 60.00 | |
| Technical Committees | | 235.38 | |
| Law Committee | | 1,046.16 | |
| Headquarters Committee | | 181.50 | |
| Forward | | $395,871.37 | $377,252.93 |
| TOTAL INCOME—FORWARD | | | $377,252.93 |
| **EXPENSES—FORWARD** | | $395,871.37 | |
| Standards | | 9,959.01 | |
| American Standards Association | | 1,500.00 | |
| International Electrotechnical Commission | | 1,453.61 | |
| Engineering Societies Library, maintenance | | 10,196.56 | |
| Engineering Foundation, Inc., assessment | | 5,713.56 | |
| American Engineering Council | | 17,596.00 | |
| Engineering Societies Employment Service | | 1,635.00 | |
| Institute prizes | | 440.00 | |
| Edison Medal Committee | | 194.26 | |
| United States National Committee of International Commission on Illumination | | 300.00 | |
| Honorary Secretary | | 2,000.00 | |
| Total | | | 348,382.41 |
| NET INCOME | | | $ 28,870.52 |
| **PROFIT AND LOSS CREDITS:** | | | |
| Adjustment of value of library volumes and fixtures | | $ 109.93 | |
| Unused balance of Winter Convention Fund | | 26.70 | |
| Profit on dinner dance | | 120.20 | |
| Profit on furniture and fixtures sold—Net | | 11.50 | |
| Adjustment of Life Membership Fund Reserve—Excess of fund over required amount as determined by the Institute in accordance with the by-laws | | 739.92 | |
| Total | | | 1,008.25 |
| GROSS SURPLUS FOR THE YEAR | | | $ 29,878.77 |
| **PROFIT AND LOSS CHARGES:** | | | |
| Uncollectible dues and members charges written off | | $ 9,302.64 | |
| Provision for depreciation of furniture and fixtures | | 2,156.66 | |
| Total | | | 11,459.30 |
| SURPLUS FOR THE YEAR | | | $ 18,419.47 |
| SURPLUS, MAY 1, 1929 | | $616,319.20 | |
| Less transferred to Reserve Capital Fund in accordance with resolution of the Board of Directors | | 38,856.25 | 577,462.95 |
| SURPLUS, APRIL 30, 1930 | | | $595,882.42 |

*Includes $90,665.00 allocated to JOURNAL subscriptions.

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### Reserve Capital Fund—Securities

### April 30, 1930

Exhibit A.

Schedule No. 1.

| | Face Value | Book Value |
|---|---|---|
| **Railroad Bonds:** | | |
| Baltimore and Ohio Railroad Company 4½% convertible gold bonds, due 1933, registered | $ 10,000.00 | $ 9,387.50 |
| Baltimore and Ohio Railroad Company 6% refunding and general mortgage series "C" bonds, due 1995, registered | 8,000.00 | 8,940.00 |
| Central of Georgia Railway Company 5½% refunding and general mortgage series "B" bonds, due 1959, registered | 5,000.00 | 5,283.75 |
| Chicago and Erie Railroad Company 5% first mortgage gold bonds, due 1982, registered | 1,000.00 | 1,105.00 |
| Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series "A" gold bond, due 1971, registered | 1,000.00 | 1,010.00 |
| Chicago, Terre Haute & Southeastern Railway Company 5% first and refunding mortgage gold bonds, due 1960 | 8,000.00 | 7,940.00 |
| Florida East Coast Railway Company 5% first and refunding mortgage series "A" gold bonds, due 1974, registered | 10,000.00 | 9,818.75 |
| Great Northern Railroad Company 5½% general mortgage series "B" gold bonds, due 1952, registered | 10,000.00 | 9,847.50 |
| New York Central Railroad Company 5% refunding and improvement mortgage series "C" bonds, due 2013, registered | 6,000.00 | 5,742.50 |
| Pennsylvania Railroad Company 4½% general mortgage series "A" gold bonds, due 1965, registered | 5,000.00 | 5,130.00 |
| St. Louis, San Francisco Railway Company 5% prior lien mortgage series "B" bonds, due 1950, registered | 6,000.00 | 5,497.50 |
| Southern Railway Company 5% first consolidated mortgage gold bonds, due 1994, registered | 1,000.00 | 980.00 |
| Total (Forward) | $ 71,000.00 | $ 70,682.50 |

| | Face Value | Book Value |
|---|---|---|
| Total (Forward) | $71,000.00 | $ 70,682.50 |
| **Public Utility Bonds:** | | |
| American Telephone and Telegraph Company 5% sinking fund gold debentures, due 1960, registered | $ 15,000.00 | $ 14,625.00 |
| Consolidated Gas Company of New York 5½% gold debentures, due 1945, registered | 5,000.00 | 5,187.50 |
| Detroit Edison Company 6% first and refunding mortgage series "B" gold bonds, due 1940, registered | 5,000.00 | 5,178.13 |
| Duquesne Light Company 4½% first mortgage series "A" gold bonds, due 1967, registered | 3,000.00 | 2,970.00 |
| New York Telephone Company 6% gold debenture bond, due 1949 | 5,000.00 | 5,525.00 |
| Northern States Power Company 5½% first lien and general mortgage gold bond series "B", due 1950 | 10,000.00 | 10,400.00 |
| Pacific Gas & Electric Company 5½% first and refunding mortgage gold bonds series "C", due 1952, registered | 5,000.00 | 5,137.50 |
| Philadelphia Company secured 5% gold bond series "A", due 1967 | 10,000.00 | 10,000.00 |
| Shawinigan Water and Power Company first mortgage and collateral trust sinking fund gold bond series "A" 4½%, due 1967 | 5,000.00 | 4,581.25 |
| United Light and Power Company 5½% first lien and consolidated mortgage gold bond, due 1959 | 5,000.00 | 4,975.00 |
| Total | $ 68,000.00 | $ 68,579.38 |
| **Industrial Bonds:** | | |
| American Smelting and Refining Company 5% first mortgage gold bonds series "A," due 1947, registered | $ 9,000.00 | $ 9,085.00 |
| Bethlehem Steel Company 5% purchase money and improvement mortgage sinking fund gold bonds, due 1936, registered | 5,000.00 | 5,033.75 |
| Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property Nos. 75-79 Prospect Street, East Orange, N. J.) 5½%, due 1933 | 14,000.00 | 14,000.00 |
| New York Steam Corporation 6% first mortgage gold bonds, due 1947, registered | 10,000.00 | 10,837.50 |
| United States Rubber Company 5% first and refunding mortgage series "A" bonds, due 1947, registered | 2,000.00 | 1,915.00 |
| Western Electric Company 5% debenture bonds, due 1944, registered | 10,000.00 | 9,818.75 |
| Youngstown Sheet and Tube Company first mortgage sinking fund gold bonds series "A" 5%, due 1978, registered | 20,000.00 | 20,275.00 |
| Total | $ 70,000.00 | $ 70,965.00 |
| Total | $209,000.00 | $210,226.88 |

# INDEX OF AUTHORS


## A

Ackerman, O., *Discussion* ..... 933
Alger, P. L., *Paper* ..... 1055
Alger, P. L., *Discussion* ..... 1067
Amberg, E. J., *Discussion* ..... 942
Andrews, F. E. and C. L. Stroup, *Paper* ..... 959
Andrews, F. E., *Discussion* ..... 939, 996, 1127
Austin, A. O., *Discussion* ..... 944

## B

Barnes, B. L., *Discussion* ..... 837
Beck, Edward and J. H. Cox, *Paper* ..... 857
Beck, Edward, *Discussion* ..... 936
Beck, Edward and J. H. Cox, *Discussion* ..... 945
Bell, E. and A. L. Price, *Discussion* ..... 948
Bergvall, R. C., *Discussion* ..... 1025, 1113
Bewley, L. V., F. H. Kierstead, and H. L. Rorden, *Paper* ..... 1161
Bewley, L. V., *Discussion* ..... 929, 988, 1042, 1084, 1118
Boehne, E. W., *Discussion* ..... 940
Boothby, C. R. and P. H. Trickey, *Discussion* ..... 1041
Boyajian, A., *Discussion* ..... 1093
Brookes, A. S., *Discussion* ..... 935

## C

Chadbourn, R. W., *Discussion* ..... 1093
Charlton, O. E. and W. D. Ketchum, *Paper* ..... 1095
Charlton, O. E., *Discussion* ..... 1101
Clem, J. E., *Paper* ..... 970
Clem, J. E., *Discussion* ..... 989, 996, 1119
Colburn, W. H., *Discussion* ..... 996, 1127
Conwell, R. N. and C. L. Fortescue, *Paper* ..... 872
Coombs, R. D., *Discussion* ..... 1127
Cox, J. H. and Edward Beck, *Paper* ..... 857
Cox, J. H., *Discussion* ..... 944
Cox, J. H. and Edward Beck, *Discussion* ..... 945

## D

Dreese, E. E., *Paper* ..... 1033
Dreese, E. E., *Discussion* ..... 1042
Dwight, Herbert Bristol, *Paper* ..... 1115
Dwight, Herbert Bristol, *Discussion* ..... 1121

## E

Eaton, J. R. and R. H. George, *Paper* ..... 877
Edgerton, H. E., *Discussion* ..... 1024
Espenschied, Lloyd and William Wilson, *Paper* ..... 1152
Espenschied, Lloyd, *Discussion* ..... 1160

## F

Faus, H. T. and I. F. Kinnard, *Paper* ..... 949
Fechheimer, C. J., *Discussion* ..... 856
Fetsch, J. T., *Paper* ..... 1068
Fetsch, J. T. *Discussion* ..... 1085
Fortescue, C. L. and R. N. Conwell, *Paper* ..... 872
Fortescue, C. L., *Discussion* ..... 938, 946
Foust, C. M. and W. W Lewis, *Paper* ..... 917
Frey, H. A. and E. M. Skipper, *Paper* ..... 990
Frey, H. A., *Discussion* ..... 996

## G

Gardner, M. F., H. L. Hazen, and O. R. Schurig, *Paper* ..... 1102
Gay, F. W., *Discussion* ..... 845
George, E. E., *Discussion* ..... 931
George, R. B., *Discussion* ..... 1178
George, R. H. and J. R. Eaton, *Paper* ..... 877
George, R. H., *Discussion* ..... 947
Graham, Q., *Discussion* ..... 855

## H

Hagenguth, J. H., *Discussion* ..... 1192
Hazen, H. L., O. R. Schurig, and M. F. Gardner, *Paper* ..... 1102
Hellmund, R. E. and C. G. Veinott, *Paper* ..... 1043
Hellmund, R. E., *Discussion* ..... 853, 1031, 1042, 1053, 1066
Hemstreet, J. G., W. J. Rudge, and K. B. McEachron, *Paper* ..... 885
Hildebrand, L. E., *Paper* ..... 848
Hildebrand, L. E., *Discussion* ..... 856
Hodnette, J. K., *Discussion* ..... 942, 1190
Hunter, E. M., *Discussion* ..... 1120
Huntington, E. K., *Discussion* ..... 846

## J

Jackson, D. C., Jr., *Discussion* ..... 1093
Jackson, R. E., *Discussion* ..... 1121
Jennings, C. H., *Discussion* ..... 837
Johnson, J. A., *Discussion* ..... 1101
Jordan, C. A., *Discussion* ..... 942

## K

Kelly, J. T., *Discussion* ..... 969
Ketchum, W. D. and O. E. Charlton, *Paper* ..... 1095
Ketchum, W. D., *Discussion* ..... 1101
Kierstead, F. H., H. L. Rorden, and L. V. Bewley, *Paper* ..... 1161
Kierstead, F. H., *Discussion* ..... 1178
Kinnard, I. F. and H. T. Faus, *Paper* ..... 949
Kirke, W. B., *Discussion* ..... 1160
Koch, C. J., *Discussion* ..... 1041, 1067
Kouwenhoven, W. B. and C. L. Lemmon, *Paper* ..... 952

## L

Lemmon, C. L. and W. B. Kouwenhoven, *Paper* ..... 952
Lennox, J. S., *Discussion* ..... 845
Lewis, W. W. and C. M. Foust, *Paper* ..... 917
Lincoln, J. C., *Discussion* ..... 838
Lloyd, W. J., Jr., and P. Sporn, *Paper* ..... 905
Longley, F. R., *Discussion* ..... 1129, 1151
Lyman, W. J., *Paper* ..... 825
Lyman, W. J., *Discussion* ..... 831
Lyons, John M., *Paper* ..... 998
Lyons, J. M., *Discussion* ..... 1010
Lyons, W. V., *Discussion* ..... 1041

## M

McEachron, K. B., J. G. Hemstreet, and W. J. Rudge, *Paper* ..... 885
McEachron, K. B., *Discussion* ..... 943, 947
McMorris, W. A., *Discussion* ..... 1193
Melvin, H. L., *Discussion* ..... 939
Monteith, A. C., *Discussion* ..... 935

## N

Newman, S., Jr., *Discussion* ..... 1031
Norinder, Harald, *Discussion* ..... 937

## O

Oesterreicher, S. I., *Discussion* ..... 1177

## P

Palueff, K. K., *Paper* ..... 1179
Palueff, K. K., *Discussion* ..... 1177, 1194
Peck, E. P., *Discussion* ..... 929
Peek, F. W., Jr., *Discussion* ..... 933
Powel, C. A., *Discussion* ..... 831
Price, A. L. and Nicholas N. Smeloff, *Paper* ..... 895
Price, A. L. and E. Bell, *Discussion* ..... 948

## R

Randall, H. S., *Discussion* ..... 930
Ritter, J. G. and Morris Stone, *Paper* ..... 832
Ritter, J. G., *Discussion* ..... 838
Roper, D. W., *Discussion* ..... 929
Rorden, H. L., L. V. Bewley, and F. H. Kierstead, *Paper* ..... 1161
Rudge, W. J., K. B. KcEachron, and J. G. Hemstreet, *Paper* ..... 885
Rudge, W. J., *Discussion* ..... 932

# Transmission System Relay Protection—III*

WILLIAM W. EDSON[1]

Member, A. I. E. E.

*Synopsis.—A paper was presented in 1919, followed by Part II in 1921, giving a resumé of the relay protective systems up to those dates. The various important developments since 1921 warrant a third paper on this subject. There has been a general realization of the importance of shortening the time for removing a fault, and this has led to the production of high-speed circuit breakers combined with very fast relays, the total time of clearing trouble being reduced to from two to eight cycles. There is a tendency towards types of relays and schemes which are inherently selective in operation, such as the "distance" relays, balanced or differential schemes, pilot wire relays, etc.*

*Due to the increased reliability of service and to the relative ease of obtaining selectivity and high speed of the relay protective system the growth of the use of parallel lines (usually in pairs) has been rapid. Back-up protection against through short circuits or failures of relays or breakers at the succeeding stations is growing in use and the necessary relays are being added unless the scheme adopted inherently has this covering protection.*

*Due to its fundamental advantages of the detection of a fault in its incipient stage thereby reducing the voltage disturbance to the system, minimizing the damage at the fault, and reducing the stress on the circuit breakers ground protection is approaching the importance of becoming the first line of defense. The increased spacing of high-tension open wire lines, and the use of the H cable and the segregated phase installations should greatly increase the preponderance of ground faults and consequently the protective system should be able to recognize such faults and remove them before phase-to-phase action results.*

*The purpose of this paper has been to indicate briefly the relay practises at the present time and to endeavor to point out what appear to be the necessities of the immediate future.*

* * * * *

## Introduction

In 1919 a paper[2] was presented before the A. I. E. E. giving a very interesting résumé of the relay protective systems up to that date. This was so well received and proved to be of such value that it was felt that a paper of this type presented from time to time would serve as a review and record of modern relay practises. Part II, which appeared in 1922, met this purpose in an excellent manner, and is still a reliable and instructive guide for the protection engineer.[3]

Since the publication of the last paper, several important developments have been made, and it is now felt that the recent improvements warrant a third paper on this subject.

The title of this paper has been changed somewhat from the previous papers to permit the addition of notes on the protective practise for the main items of equipment in a transmission system.

Probably the greatest change in the design of a protective system has been the realization of the importance of shortening the time for removing a fault. With the large quantities of power involved in the present generating and transmission systems, it is very important to disconnect faulty equipment as soon as possible to preserve the system stability, insure continuity of service through other circuits, prevent synchronous apparatus from dropping out of step, minimize the spread of the disturbance to adjacent phases or lines and to remove the fault before much material damage has occurred. This requirement overshadows the former method of purposely introducing time delay so as to reduce the required interrupting capacity of the oil circuit breaker. The modern tendency is to disregard this decrement and to install breakers with a sufficient factor of safety to handle the present and future maximum fault currents, so that full advantage of rapid relay and breaker operation may be utilized to the ultimate.

In conjunction with this minimum operating time, there has been recently a remarkable development of the high-speed breakers. It is now possible to produce commercially an oil circuit breaker with two or three million kv-a. interrupting capacity which will open the circuit in two to eight cycles from the time of the fault. The relay art has kept pace with these developments.

The cost of a relay protective equipment should not be considered as a deciding factor, since it is only a small percentage of the cost of the system being protected, or of the monetary and good will value of the service. Often a reduction of a few tenths of a second in a relay operation, or the installation of "back-up" protection is well worth considerable complexity and cost.

There is also a tendency in the relay art at this time to adopt types and schemes which have inherent selectivity in operation. Under this category may be included impedance relays, all schemes of balanced or differential relays, split conductor relays, and pilot wire relays or equivalents such as the carrier current schemes.

Another feature affecting the relay art is the tendency toward the simplification of the design of transmission

*(Paper prepared in conjunction with H. P. Sleeper, Chairman, O. C. Traver, R. Cordray, L. N. Crichton, E. A. Childerhose, and H. A. McLaughlin, all members of the Relay Subcommittee of the Committee on Protective Devices.)

1. Station Engg. Dept., Edison Electric Illuminating Co. of Boston, Boston, Mass.

2. *Transmission Line Relay Protection*, by H. R. Woodrow, D. W. Roper, O. C. Traver, and P. MacGahan, A. I. E. E. Trans., Vol. XXXVIII, 1919, p. 795.

3. *Transmission Lines Relay Protection—II*, by E. A. Hester, O. C. Traver, R. N. Conwell, and L. N. Crichton, A. I. E. E. Trans., Vol. XLI, 1922, p. 670.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

systems. Formerly transmission design had as its sole object the supplying of sufficient load to the stations with a reasonable amount of reserve and diversity. This type of planning frequently imposed severe hardships on the protective schemes. It is now commonly recognized by operating engineers that the design of the transmission and of the relay systems must be considered together. The design of both is, of course, ultimately decided by economics, but as long as the problems are considered mutually, the best protective scheme will invariably result. The importance of this procedure cannot be overemphasized.

In preparing this paper, reference has been made to the various papers presented before the A. I. E. E., to the N. E. L. A. relay handbook, and to data furnished last year by various operating companies to the Relay Subcommittee of the A. I. E. E.

In general, relays and schemes described in the previous papers, and which are still applicable, will not be discussed here in detail, as reference may be made to the preceding papers.

Relay symbols also will not be repeated here, as they have been standardized by the A. I. E. E. and N. E. L. A.

Standards and definitions for relays are now in the hands of a working committee of the Standards Committee of the A. I. E. E., and it is expected that a report will soon be available.

## Phase-To-Phase Protection of Transmission Lines

*Radial Feeders.* This heading includes such radial feeders as are independent of each other, have no sources of back-feed, and are not divided into successive sections. In general, the only protection given them is for overcurrent, the relays being instantaneous or with a small time delay, depending on the type of load or service, and on the interrupting capacity of some of the older types of breakers.

*Single Line Networks.* Feeders having a possible back-feed, or with more than one source of power, and those which are divided into sections, require a more complicated protective scheme, as special consideration must be given to insure that only the element in trouble shall be disconnected, the others being kept in service. As a means of convenience, they may be discussed in the following order:

*Selective Timing Between Stations.* When there are several stations in succession, it is desirable to trip the breaker closest to the fault, thereby permitting the stations toward the source to remain in service.

Graduated definite time settings will insure that proper selectivity will be obtained between successive stations, independent of the value of fault current. The stations nearer the generator are inherently "back-ups" for the more remote stations.

Discrimination between successive breakers may also be met by setting the remote relays at lower current values than the nearby ones, if the reactance of the line is sufficiently high to cause the fault current to taper off as the distance from the source increases. Usually, however, this differential in current is too small to insure correct discrimination, but this principle combined with the preceding, is of great value, especially for complicated networks.

Probably three-quarters of the present relay applications include a relay which is a combination of the above

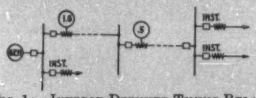


Fig. 1A—Inverse Definite Timing Relays

features. This is the standard inverse definite time relay whose time of operation decreases as the current increases, until the adjusted minimum time setting is reached. This insures selectivity between stations, rapid tripping on heavy faults, and improved discrimination between feeders on one bus by virtue of the per cent increase on a small capacity feeder being many times that of the larger incoming supply circuits. (Fig. 1A.)

Although the above relay has given, and is giving, a very good account of itself, it is often too slow for present day systems, as the relay next to the generating station must be set longer than the more remote stations, and its timing may reach two or three seconds, which, of course, is far from the few cycles which is possible in the breakers.

One of the most interesting developments in recent years has been the production of the so-called "distance" relay. The impedance type consists of an inverse definite timing element similar to the above, with an added feature which automatically decreases the time setting as the line voltage decreases. Thus with a nearby fault, the heavy current and the lowered voltage both tend to decrease the timing of the relay. Such a

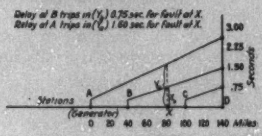


Fig. 1B—Impedance Relays

design permits the relays at the successive stations to be set for the same minimum time, the discrimination between adjacent stations being obtained by this feature. (Fig. 1B.)

This relay has been applied quite widely and has been found particularly useful in the following locations:

Loops having a number of substations so that the total cumulative time is excessive if simple time limit relays should be used.

Systems whose generating stations are frequently cut in or out, and whose connections are changed so often that time limit relays are difficult to adjust.

Interconnected systems which are so closely connected that trouble on one seriously affects the other, thereby requiring that the selectivity on one system should match with the other.

Installations to sectionalize a generating station bus; in this case feeder and bus reactors are used so that the impedance relays can tell when the trouble is on the bus, or when it is on the line side of a reactor.

In order to obtain selectivity between adjacent stations the relay must be adjusted to add the required interval to its minimum time setting, this timing being due to the voltage drop under fault conditions through the line section to the next substation. This means that a fault at the far end of a line section will cause the relay to have a total time setting of 0.7 or 0.8 second, which in certain applications may be too long. A high-resistance fault will materially increase this time setting.

If a breaker should fail to operate, the next nearer station will open at an increased timing. This "back-up" protection is of the utmost importance, but for a short section followed by a long section, this "back-up" timing becomes excessive.

With the present relays, the minimum length of line between stations must be sufficient under minimum short-circuit conditions, to give a voltage drop of approximately 5 per cent of the line voltage. This often prevents their use on short line sections.

Due to the large number of factors to be considered and the accuracy of setting required, it is quite important that the minimum fault currents are fairly accurately known. This may involve considerable calculation and study.

Since the timing is dependent on the voltage applied to the relay, accurate means must be taken to obtain values corresponding to the actual line voltages. The usual method is to install high-tension potential transformers. In cases where this cost is difficult to justify, low-tension potential transformers may be used with compensators which correct for the voltage drops through the power transformer. Such a scheme is quite complicated and may require recalibrating if transformers are added or removed. The use of bushing potential devices on the breaker or power transformer offer an encouraging substitution for high-tension potential transformers.

For systems having a load current relatively large compared to the fault current, the impedance relays may be normally short-circuited, and only brought into service by fault-detector relays during trouble.

One well-known European distance relay is similar to the above except its timing is varied by the line reactance instead of the impedance, thereby tending to eliminate the additional time due to the resistance in the fault.

A new impedance relay is being developed which will have a constant minimum time setting approaching a very few cycles.

Although this new relay has most of the limitations of the standard impedance relay, yet its very high speed for nearly the entire length of line section will offer a solution to many protective problems in connection with interconnected systems, or where stability is a factor. The relay and its use is being described in companion papers.

*Directional Relays.* Faults beyond a substation produce currents and voltage conditions for the incoming line, the same as for the outgoing feeder in trouble. This would tend to operate both relays; therefore it is necessary to add a device which will prevent the relay on the incoming line from operating. This directional feature should be included on all incoming feeders which have a source of power, these elements being connected to operate only when the fault current is away from the substation bus.

Since a potential is generally used as a base to indicate direction, it is necessary to insure that this potential is always available and will at all times approximately correspond to that of the feeder in trouble. It should be noted that, theoretically, it is possible to have an improper operation for certain classes of faults when the potential transformers are connected to the low-tension side of the station power transformers, but this condition is normally disregarded in practise.

There are two types of directional relays, one using three single-phase over-current relays with one polyphase directional relay, the other having three relays each having a current and a single-phase directional element. The choice of systems depends on local conditions such as power and potential transformer connections, ratio of load and fault currents, and in some cases, the remainder of the relay protective system.

The directional feature may be used in conjunction with any of the over-current or impedance relays mentioned above, the individual considerations being the same as described.

The conventional arrangement of placing the contacts of the directional relay and the over-current relay in series, has several shortcomings. The most serious one is, that while trouble is being cleared by the opening of breakers, there may be a reversal of power flow through a breaker on a good section of line, whose over-current relay has already been closed, so that this breaker will be improperly tripped when its directional contacts swing over to the closed position. Another difficulty is that the current setting must be low because of a small supply of outgoing power, yet the relays may be subjected to a frequent heavy, incoming load which will result in the current contacts' being closed. This removes the time element feature if trouble should occur while such a load condition exists. These troubles have been eliminated by arranging the directional relay so that it renders the over-current relay

inoperative when power is flowing into the station. The over-current time line relays will, therefore, not begin to move until power is flowing away from the bus.

An objection to this arrangement is that it introduces an extra time delay, namely, the time required for the directional relay to operate. This may be avoided by using an additional locking relay, which picks up instantaneously, but when deenergized, drops out with a time which can be adjusted to be the same as the minimum definite time of the over-current relay. (See Fig. 1c.)

Another use for a relay combination which will not

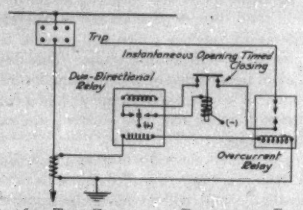


Fig. 1c—Time Controlled Directional Relay

start its timing operation until the directional element allows it to do so, is for the "back-up" protection on balanced lines, which are primarily protected by differential relays. In this arrangement, it is usually desirable to delay the start of the "back-up" timing relays until the differential relays have operated, and the flow of power is in the outward direction.

## Balanced or Differential Schemes

*Split Conductor Method.* Each phase lead is composed of two conductors operating in parallel and

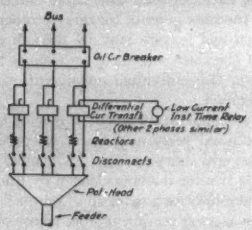


Fig. 2—Split Conductor

normally carrying approximately equal currents. Most faults will initiate on one of the wires, thereby causing an unbalance in the pair. This differential is determined by means of cross-connected current transformers. The relays can safely be set very fast, and for quite small current. Reactors are inserted in one leg to provide the necessary unbalance when both wires fail. The experience with this protection has been excellent, but the system is decreasing in use, due to the cost and inconvenience of obtaining and stocking the special cable and apparatus. (Fig. 2.)

*Pilot Wires.* Schemes using pilot wires to balance conditions at one end of a line section against the other end, are very much in use in Europe, but have not received much favor in America, due to the high cost and the technical difficulties involved in the use of pilot wires over the long distances common to our lines.

For short sections of lines or for important tie lines in extensive and complicated networks, pilot wire protection offers the best prospects and their use may increase, unless new relay schemes are developed.

There are many types of pilot wire schemes, some using current and other voltage balancing. In some installations current is circulated through the pilot wires, but the tendency is towards the zero or opposed voltage methods. (Fig. 3.)

*Carrier Current.* A very ingenious system has been devised which balances the instantaneous polarities of the current waves at the two ends of a line section, by means of carrier current superimposed on the line itself.

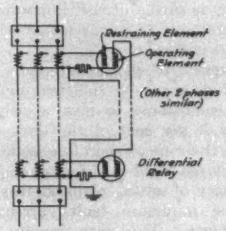


Fig. 3—Pilot Wires

Under normal conditions, the instantaneous direction of current flow at each end of the transmission line is the same, but at the time of fault, one end generally reverses or else becomes zero. The line current is used to supply plate and grid voltages for three-electrode tube oscillators. Since plate current flows only when the alternating plate voltage is on its positive half-cycle, it is possible to transmit from one end of the line and receive the impulse at the other end, for the one-half cycle durations. Similarly, this is repeated for the other end of the line, which will be transmitting during the other half-cycle duration.

Under these conditions, carrier-current is flowing first from one end of the line to the other, and vice versa, changing every half-cycle. The plate current is smoothed out with capacitors and is used to hold open the contacts of an induction over-current relay by means of a restraining coil.

In order to trip the breaker, it is necessary that there be sufficient over-current flow in the lines to close the over-current relays, and that the instantaneous direction

of current flow be different at the two ends of the line, or that either becomes zero.

It is possible either to operate the tubes continuously, or to have the tubes begin to operate as the over-current approaches the setting of the over-current relay. The over-current relay used is of the induction type, having a time delay of less than 0.1 second.

The reports on the operation of this system have been good.

### Parallel Lines

The growth of the use of parallel lines (usually in pairs) has been rapid due to the increased reliability of service and to the relative ease of obtaining selectivity and high speed of the relay protective system.

In general, the schemes used may be divided into the following classifications:

*Individual Lines.* Each line may be treated individually and equipped with the directional overcurrent or impedance relays discussed above. The systems involved in this first general method will not be gone into as they are generally well-known, but there are some limitations which should be considered.

If standard directional relays with graded time settings are used on a pair of parallel lines, a fault on one line near the station with the longer time setting, may trip both breakers on the other end of the section, since both will have fault currents of the same value and direction. On the other hand, if the fault occurs near the station with the shorter time setting, both breakers on this end may be tripped, due to the fault current through the good line after the first breaker has opened.

These conditions can usually be taken care of by proper settings, interlocks, the so-called directional controlled relay, or by a combination of these methods.

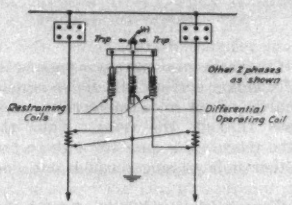


Fig. 4—Parallel Lines—Mechanical Unbalancing

These contingencies may not exist, due to the distribution of current in a particular circuit, especially if there is another source of back-feed, but they should be checked carefully.

Directional impedance relays overcome these objections and are operating satisfactorily for installations having any number of lines.

*Balanced Current Schemes.* The various balanced current schemes have several important advantages, such as fast operation, simplicity of connections, omission of potential transformers, etc., but there are certain limitations which must be considered. Thus they cannot be used on the substation end of a pair of lines if the station has no other source of supply. In this case there would be no unbalance if the fault current is large compared with the load current. On the other hand, if the load current is appreciable, the wrong line may be tripped.

In general, these relays have an operating coil and a restraining coil. The windings are so proportioned that the operating current must exceed the restraining

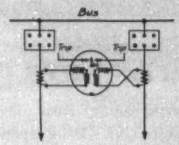


Fig. 5—Parallel Lines—Magnetic Balancing

current by 25 per cent before the element will close its contacts. As the restraining current decreases to zero, the operating current decreases to the minimum operating current for which the relay is set.

When applying these types of relays, their individual characteristics should be carefully studied in connection with the characteristics of the system involved, and the operating conditions which will exist. The manufacturer's recommendations regarding connections should be followed, especially with the last type mentioned, as a change in the connection causes a difference in the differential current required to trip.

One of these schemes uses a mechanical balancing relay, as described in the previous 1922 paper. (Fig. 4.) A recent modification of this relay includes a potential restraining coil, thereby automatically reducing the required operating differential current, if the fault is nearby, and the line voltage is affected. This relay is being discussed in a companion paper.

A second type has two induction elements, each having an operating and a restraining coil. The action is similar to the above mechanical or plunger type.

In another type the currents from the two lines are connected to two sets of coils on the same magnetic circuit, the balancing being accomplished magnetically. The relay is provided with double-throw contacts and an unbalance causes the relay disk to operate and trip the breaker carrying the greater current. (Fig. 5.)

On solidly grounded systems, phase protection of the above types would also clear ground faults. However, there usually is an advantage in using ground protection of the same balanced types. In general, the phase relays must be set high in current to avoid trouble due to switching. The ground relays are not subject to this limitation, and can be given a low current setting.

Since the majority of faults involve ground the over-all sensitivity is increased.

*Cross-Connected Directional Schemes.* The simplest and most general arrangement consists of two sets of directional over-current relays with their current coils connected in series across the cross-connected current transformers of the two lines. The potential connections to the relays are reversed so that only the trip circuit of the breaker carrying the greater current will be closed by the unbalanced current.

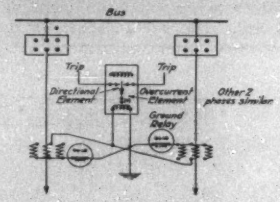


FIG. 6—PARALLEL LINES—DUO-DIRECTIONAL RELAYS

The same results can be obtained by using one set of duo-directional over-current relays or by means of one set of over-current relays and two uni- or one duo-directional relay. (Fig. 6.)

If the time and current settings will allow, the same relay may be used for single line operation, although it is generally necessary to use additional relays for this purpose. It is also necessary to add other relays for simultaneous faults on the two lines, and for through faults.

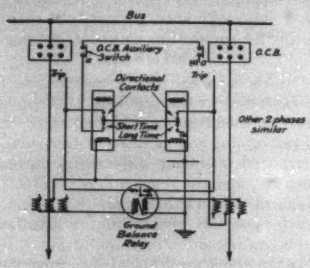


FIG. 7—PARALLEL LINES—CROSS-CONNECTED DIRECTIONAL RELAYS

A second method sometimes known as the short and long time schemes used two sets of directional relays, but the over-current and directional contacts are interconnected so that each directional contact is associated with an individual line, while the over-current contacts are common.

One of these current elements has a short time setting and the other a long time setting. The first is arranged to be cut out by auxiliary switches on the circuit breakers when either line is open, thus leaving the long time setting in service for single line operation. (Fig. 7.)

This scheme also requires additional relays for simultaneous and bus faults.

A scheme which gives short time protection for double-line operation, and long time protection for single-line operation, and which also offers protection against simultaneous line and through faults has recently been developed and appears to meet most situations.

The current transformers of the two lines are cross-connected through an auto-current transformer, across which is an over-current relay. The directional relay is connected to the midpoint of this auto-transformer.

The "back-up" protection for through faults has the same pick-up, whether one line or both lines are in service. This will readily be understood if it is kept in mind that the auto transformer has a high impedance compared to the relay. Thus for equal current in each line, the total circulating current passes through the over-current relay connected across the auto-transformer. If the same total current is passing through one line, the secondary current will divide equally through the two halves of the auto-transformer, and only one-half passes through the relay. Thus the current through the relay is the same for a given primary current, whether it is passing through one line or both. (Fig. 8.)

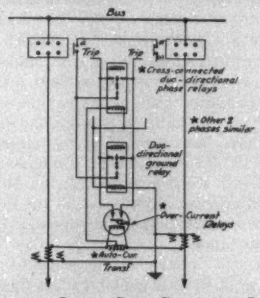


FIG. 8—PARALLEL LINES—CROSS-CONNECTED RELAYS WITH AUTO-CURRENT-TRANSFORMER

In all these balance schemes, careful thought and study should be given to the matter of back-up protection, for simultaneous faults on both lines and for bus faults, not as a duplicate system of protection, but as additional protection to take care of special conditions which may arise at any time.

These schemes should be carefully studied as to the effect of switching in or out the second of a pair of balanced lines, since it is impossible to close or open both ends simultaneously. Incorrect relay operations may result unless the current settings are higher than any normal load or surge carried on one line, or unless special interlocks are included.

The comments given in connection with ground protection by the use of current differential schemes, apply equally well to the balanced directional schemes.

Occasionally balanced lines are connected to different sections of a bus, which may operate with the sectionalizing switch open. In this case some provision must be made for cutting the balanced protection out of service, either manually or by auxiliary switches on the sectionalizing breaker.

In applying differential protection to more than two parallel lines, it is now considered better practise to protect them by pairs. Thus in the case of three lines, Nos. 1 and 2, 2 and 3, and 3 and 1, would be balanced using the regular schemes for pairs of lines.

In general, balanced line schemes are giving satisfaction, and their use is increasing.

### Ground Protection

Present-day transmission systems are generally grounded at one or more points. Experience has shown that most faults on these systems start as a flashover or failure to ground; therefore, on a grounded system, the flow of ground current is a positive sign of trouble. Because of this, ground fault protection is of extreme importance, and is gradually becoming recognized as a front line of defense against damage caused by fault currents.

Zero phase-sequence component currents flow only during ground faults. They may readily be isolated from the positive and negative phase-sequence components by means of a simple network. Three star-connected current transformers will permit only the zero phase-sequence component currents to flow through their common or residual circuit. This connection is in common use and the zero phase-sequence or ground relays are connected in this residual circuit.

Since ground currents are not present during normal operation, no consideration need be given to load currents when considering the zero phase-sequence relays. They may be set to operate on very small currents so that in many cases they will isolate the faulty section or piece of apparatus while the trouble is still in an incipient stage.

*Solidly Grounded Systems.* Frequently the ground fault currents exceed the load values and the line phase-to-phase relays will also give ground protection. However, ground fault currents decrease in value, as the point of fault moves away from the grounded source much more rapidly than phase-to-phase fault currents, and on long lines it is necessary to use zero phase-sequence relays to give protection against ground faults remote from the relay.

*Residual Current Protection.* Over-current relays used as ground relays may be installed in the residual circuits of current transformers. This system is applicable to radial or stub-end feeders. Selectivity is obtained in the same manner as over-current phase-to-phase protection on similar systems. (Fig. 6.)

*Current Differential Protection.* Current differential relays may be connected in the residual circuits of the current transformers on parallel feeders. The application is the same as the phase current differential relays on parallel feeders, as previously explained. (Fig. 7.) Quite frequently parallel feeders to a substation have taps to supply customer loads, and under these circumstances, it is not always practical to obtain phase-to-phase protection by means of differential relays. The flow of ground current, however, in either feeder indicates trouble on that feeder, and advantage may be taken of this fact and current differential ground relays installed on the feeder.

*Directional Residual Current.* Directional ground protection may be obtained with directional over-current relays potential element being connected in one corner of the secondary delta of three star-delta connected potential transformers.

Directional over-current ground protection may also be obtained by use of a relay whose directional element is polarized by a current transformer in the neutral of the main power transformers. Ground fault currents

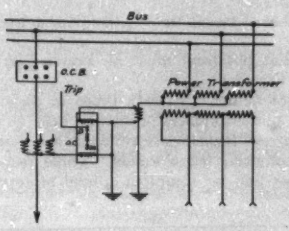


Fig. 9A—Directional Ground Relay

always flow in the same direction in this ground connection, and advantage is taken of this fact. This method eliminates high-tension potential transformers. (Fig. 9A.)

*Power Type Residual Relays.* Protection against ground faults may be obtained by using a power type relay with its potential element connected in the secondary delta of star-delta potential transformers and the current coil in the residual circuit of the current transformers. It has a theoretical advantage of quick operation for nearby faults, but quite frequently its use is limited because the voltages do not unbalance sufficiently to give enough residual voltage to operate the relay. When this relay is used at a station which is not a point of grounding, special care should be exercised with the connection to insure that resonance shall not occur between the inductance of the potential transformers and the capacity of the line, if the protected section of the line should be left grounded only through the potential transformers by the opening of a circuit breaker. Such an occurrence might displace the electric neutral of the lines to such an extent that

destructive potentials would appear on the lines. (Fig. 9B.)

A power relay with its current coil operated by the residual current of the current transformers and its other coil in the ground connection of the power transformer, is directional, quite sensitive, and has the desired inverse time characteristics. (Fig. 9C.)

*Balanced Directional Residual Current Relays.* Directional over-current relays may be balanced to give protection against ground faults in manners similar to those for protection against phase-to-phase faults,

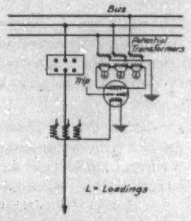


Fig. 9B—Power Directional Ground Relays

except that potential must be supplied as described above. (Fig. 8.)

*Distance Relays.* Various types of distance relays used for phase-to-phase protection may be connected to the current transformer residuals and star-star connected potential transformers. Three relays are required per line for complete ground protection. The

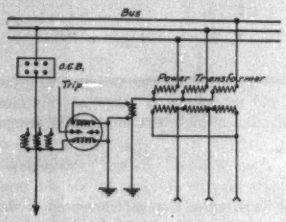


Fig. 9C—Power Ground Relay

wiring is complicated and operation is sluggish for small fault currents.

*Pilot Wire Protection.* Any of the split conductor or pilot wire schemes inherently give ground protection, though for small ground fault currents, it may be preferable to add a sensitive relay in the current transformer neutral circuit.

*Isolated Neutral or Delta Connected Systems.* A ground on one phase is not followed by a power current, and in itself is not particularly dangerous. It, however, increases the potential strain on the two ungrounded phases on all parts of the system and, if not removed, may develop into a phase-to-phase short-circuit. An arcing ground may set up surges which cause dangerous voltages to appear.

*Voltage Relay.* Overvoltage relays connected in the corner of the delta of three star-delta connected potential transformers may be used to indicate these unbalanced voltage conditions. Under normal operating conditions there is no current flowing in the delta, and the relay potential is zero. In case of a ground on the line, this voltage becomes quite large. Harmonics and large charging currents may seriously upset such a scheme, but their effect can usually be eliminated by adding a load across the secondary of each potential transformer. This arrangement only indicates a ground fault, but does not locate it. It is applicable, then, for tripping breakers only on single feeders, or a series of radial feeders, where selective timing may be used. (Fig. 10.)

*Charging Currents.* When one phase of the system is grounded, there immediately appears on all conductors a charging current to ground. On a large system, this charging current is of sufficient magnitude

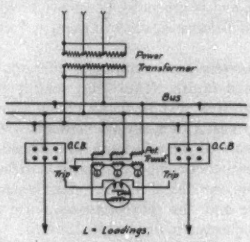


Fig. 10—Voltage Ground Relay

to operate relays. It increases in magnitude as the point of fault is approached. It appears in the residual circuit of three star-connected current transformers, and may be used to operate directional over-current relays. The potential for the relays is usually taken from the corner of star-delta connected potential transformers as described above, if high-tension potential transformers are present, but potential may be supplied from the low tension side of the power transformers if necessary.

*High-Impedance Grounded Systems.* The ground protection of high-voltage systems using a relatively high-impedance ground presents a difficult relay problem. It is particularly pertinent that such faults be relieved, since dynamic current actually flows to ground and not as in the case of isolated systems only a charging current which passes to ground. Moreover, high voltages may appear on the system during such a ground fault, and simultaneous faults may be avoided if the ground fault is relieved quickly.

The ground relay system must obviously operate on a

small amount of current to ground, thus requiring sensitive relays.

Current transformer circuits connected to such relays must be accurately balanced, as an improper unbalanced secondary loading will pass load current through the sensitive ground relays and operate them incorrectly. Ordinarily the relay volt-ampere burden is high and care must be taken that the current transformers are not over-burdened. The particular problem giving directional operation to such relays, and the use of inside delta potential has been found most satisfactory for this, since the relays operate when so connected with a power-factor close to unity.

Another problem of such relays is to take care of simultaneous faults on opposite phases on separate parts of the system. Power-factor conditions over an extreme range may be presented to the relays, and it is impossible for the relays to detect current operating conditions from incorrect, under such circumstances, at certain locations on the system. The most practical solution for such a condition has been to lock out the ground relays during simultaneous faults and allow phase relays to function to relieve the disturbance.

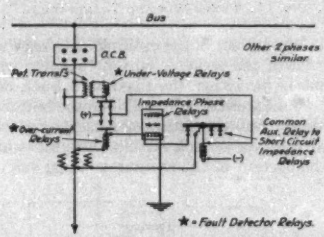


Fig. 11—Impedance Relays for Small Fault Currents

This is accomplished by utilizing the short-circuit current which flows in the neutrals under these conditions to operate lockout relays which render the directional ground relays non-operative.

If the ground current is sufficient to produce a difference in voltage drop between stations, impedance ground relays may be used which are introduced by fault detector relays during a disturbance. These fault detectors are usually a combination of over-current and undervoltage relays. (Fig. 11.)

## Apparatus Protection

*Bus Sections.* In the past it has not been the general practise to provide relay protection for the main bus sections in a station, as bus faults are seldom experienced, due to the method of construction and design of the bus installation. In recent years, however, there is a tendency to install some type of protection due to the large amounts of connected kv-a. capacity, especially since most of the protective schemes for the rest of the system exclude the bus.

Balanced protection of each phase where all the current transformers (using auto-balance transformers if of unequal ratio) are connected together to an over-current or differential relay, is commonly used and offers accurate and fast protection. It has the disadvantages of tripping the bus in case any of these current connections fail, or if any of the current transformer ratio curves are not similar on heavy external short circuits.

A modification of the above connects only the secondary neutrals together. This is safer in many ways,

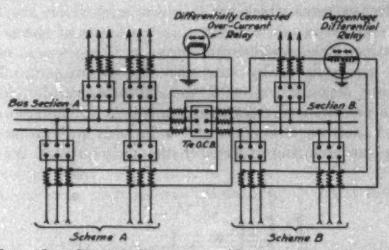


Fig. 12a—Ground Protection Neutral Differential

but it only gives protection against ground faults. This protection is sometimes considered all that is necessary, as most faults occur initially to ground, especially in isolated phase and outdoor installations. (Fig. 12a.)

Over-current protection, especially if combined with undervoltage relays, may sometimes be applied. The impedance relay may safely be used for bus installations having feeder reactors.

Several installations have been made using sections of

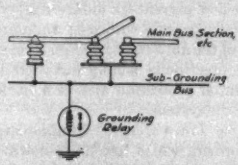


Fig. 12b—Ground Protection

ground bus connected to insulator bases, circuit breaker tanks, supports, etc., with relays inserted in the ground connections from these busses. The action is rapid and satisfactory as long as the ground bus and structure are well insulated from the building steel. (Fig. 12b.)

*Power Transformers.* Since the input and output of the transformers are very nearly equal, it is a relatively simple matter to balance one against the other and consider any unbalance to be due to a fault within the transformer. Care must be taken that these balancing or differential relays are not too sensitive, as there is

some unbalance due to the variation in ratios of the current transformers on the two sides of the transformer. This is particularly true during an external short-circuit or due to the inrush of magnetizing current when the transformer is first energized.

There are now available current differential relays which operate on the percentage of the unbalanced current with respect to the load current, instead of on a fixed value of unbalance. Such relays will detect a minor fault at normal loads, yet will not operate improperly during an external short circuit.

In applying either type of relay, it is necessary to select currents which are in phase and which are approximately equal or are within the limits of the relay setting. This equalizing of currents, if necessary, may be accomplished by auto-current transformers. For power transformers with tap changing under load equipment, if differentially connected over-current relays are used, it is necessary to provide a corresponding tap changing switch for the auto-current transformer. The new percentage differential type of relay, however, usually permits sufficient unbalance to allow the omission of the auto-balance transformer.

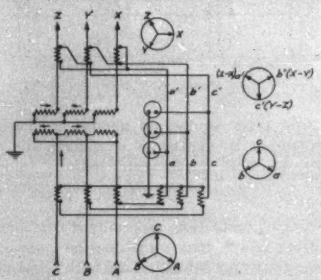


Fig. 13—Two-Winding Transformer Differential Protection

Overload protection is usually included as a back-up to the differential protection and as a back-up feature for the rest of the system.

*Two-Winding Transformers.* Single-phase or three-phase transformers which are delta-delta or star-star connected offer no complexity as the corresponding phase leads are balanced together. A delta-star combination, however, requires the current transformer on one of the phases of the delta side to be balanced with the two current transformers of the star winding. (Fig. 13.) A Scott connected transformer should be treated in a similar manner, that is, the path or paths of one phase of the load current should be traced through the various windings and the current transformers selected accordingly.

*Three-Winding Transformers.* The same principles as above apply, with the added requirement that the primary winding should be balanced against both of the two secondaries. (Fig. 14.) If the system connections require it, it may be necessary to balance the two secondaries against each other.

*Regulating Transformer.* A regulating transformer used as tap-changing-under-load equipment for a power transformer performs in a similar manner to an induction voltage regulator. Protection is obtained by balancing the current of the exciting or voltage winding against that of the series or current winding when the equipment is on either the maximum buck or boost position. An external fault will increase both currents several times, but the ratio remains nearly constant. A ground fault or a fault within the unit which increases the current of the exciting winding will operate the relay. The setting must be sufficiently high to prevent operation on the initial heavy inrush of magnetizing current. For the zero position where there is no current in the exciting winding, an additional percentage differential relay is necessary. (Fig. 15.)

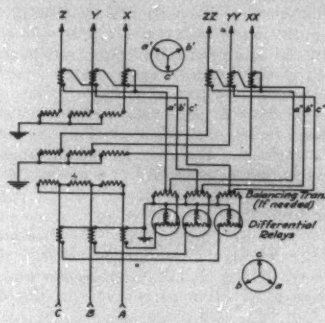


Fig. 14—Three-Winding Transformer

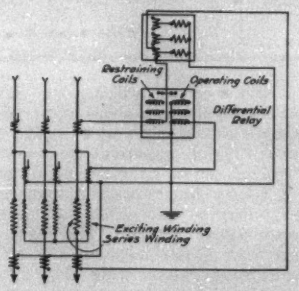


Fig. 15—Differential Protection Regulating Transformer

*Generators.* Generators are normally not protected against overload, as it is desirable to maintain service

as long as possible and to permit the fault to be isolated by the circuit breakers of the line in trouble. On the other hand, the value and importance of the generator necessitates that it be removed immediately in case of internal trouble. This is best met by providing some type of balanced or differential protection.

The usual method has been to balance the current transformers in the main leads against those in the neutral. An internal fault would cause an unbalance

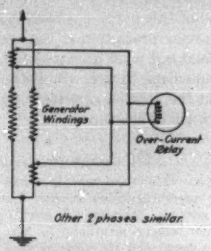


Fig. 16A—Parallel-Winding Generator Differential Protection

and the differential relays would operate. Since the current transformers may all have similar ratio characteristics, these relays may have a very sensitive setting. (Fig. 16A.)

The percentage differential relay can be set even closer as its action is proportional to the load current, and the relay will be restrained from opening on a

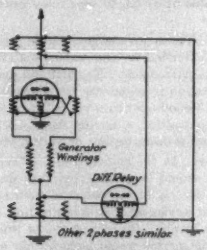


Fig. 16B—Parallel-Winding Generator Differential Relays

through short-circuit, even with some unbalance of the current transformers. (Fig. 16B.)

Parallel winding generators may have balanced protection between the windings, in addition to the overall differential protection, or may have these two functions combined into one set of relays. (Fig. 16B.) Another scheme uses a current transformer and relay connected between the mid-points of the two windings. These relays operate on grounds and on faults between turns or phases, but the scheme may be difficult to apply, as the mid-points are often difficult to locate. (Fig. 17.)

Automatic shut down of the generator should include tripping the main breakers, neutral breaker, field breaker, throttle, ventilating system, and fire protective scheme as applicable.

Generators, especially water wheel units, may develop dangerous overvoltages when the load is suddenly dropped. This condition may be prevented by overvoltage relays which reduce or trip the field or shut down the set.

## Conclusions

We have endeavored in this paper to point out that the trend of the relay art at this time is toward the use of relays which operate in much shorter times than heretofore practised. It is believed that the use of relays which may be called high speed, operating in a very few cycles, will hereafter supplant many installations heretofore protected by relays operating with a time delay up to an accepted maximum of two seconds. Time element relays will, of course, still find many applications such as the protection of radial feeds,

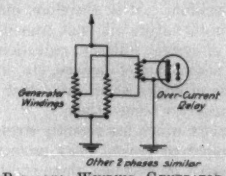


Fig. 17—Parallel Winding Generator Mid-Point Protective Scheme

small machines, back-up protection of lines and apparatus, etc.

One of the greatest needs of the protection engineer at this time is that of improved types of ground relay protection. This requirement will become increasingly apparent as time progresses due to the changing character of power system transmission. Today the base transmission of a system consists of lines or cables operating usually at voltages between 66,000 and 220,000 volts. There is a secondary step in the transmission system consisting of a network of lines and substations operating at voltages of between 13,000 and 33,000 volts. The power is finally transmitted to the customer at voltages of 4000 to 6600, where a local reduction in voltage may occur. The present trend in transmission system design seems to indicate that some of these intermediate steps will soon disappear. Hence the system of tomorrow may consist of only the high-tension base lines and one secondary high-voltage network bus at the customer's voltage only. Such a system could be relayed almost entirely by means of secondary network switches on the customer's end, and ground relays only at the service end. All recent new developments have been along the line of phase pro-

tection. Ground relays are needed that are instantaneous in operation and inherently selective. The fundamental advantages of ground relaying are detection of the fault in the incipient stage, reduction in voltage disturbance to the system, minimizing of damage at fault, and reduced stress on circuit breakers. The increased spacing of high-tension open wire lines and the use of type H cable should greatly increase the preponderance on ground faults and consequently the protective relays should be able to recognize such faults and remove them before phase-to-phase action results. The importance of this is paramount.

Another factor which demonstrates the necessity for improved ground relay protection is the advent of current limiting devices in system neutrals. This practise has a limited application in this country at the present time, but the effects of its use are receiving favorable attention, and this fact should not be over-looked by manufacturers of protective equipment. All of the desirable effects of single-phase faults versus phase-to-phase faults are enhanced by the use of impedances in system neutrals, and many of the objections to such installations have either been removed or are now recognized as being non-existent. It is, therefore, quite possible that systems in the future will limit ground currents in the necessity of system stability, reduction of system disturbances, minimizing of damage, etc., and this will require the use of relays which can detect such faults and operate quickly to remove them.

A further factor which has recently stressed the importance of improved ground relay protection, is the absolute necessity of avoiding three-phase faults on interconnection tie lines. It is frequently the case that such a fault which exists longer than a very few cycles, almost less than the time of opening of the fastest designed breaker at this time, is sure to result in instability. However, practically all faults on such lines start as single-phase or two-phase-to-ground faults, and if they are removed as such within a short time, they will not produce instability. It would therefore appear that ground relays which can be made to operate at all times in a very few cycles would be a distinct contribution to the stability of interconnected systems.

Therefore it seems that the field of improved ground relay protection is one that offers further room for improvement. Much has been done along this line recently, and one of the papers presented at this time demonstrates some excellent work done by one of the operating companies. With the cooperation of the manufacturing companies, the improvement of ground relays should present no serious defects, and it is hoped that the proper attention will be given to this phase of the situation.

The need of accurate operating data on the performance of relays has long been recognized. Such records have, of course, been kept individually by most operating companies, but there has been a lack of uniformity in the methods of doing so, particularly as no common base of comparison had been established. Some excellent work in this direction was done by the Southeastern Division of the Electrical Apparatus Committee, N. E. L. A., under the chairmanship of Mr. E. E. George and published as a serial report in April 1929. It is hoped that all operating companies will be guided by the principles established by that committee, so that comparative records may be used in the future between different companies on relay performance.

The purpose of this paper has been to present standard practise in relay protection at the moment, and to endeavor to point out what appeared to be the necessities of the immediate future. It is the hope of this committee that the practise of presenting such a paper every few years will be continued.

## Discussion

**W. H. Colburn:** One of the needs in relays or relay protective systems—is something which will anticipate the fault and clear it before it occurs. The nearest to anything of this kind is the split-conductor scheme mentioned in Mr. Edson's paper. This particular scheme and its corresponding split-conductor protection schemes were thoroughly covered in a paper by Mr. W. H. Cole of The Edison Electric Illuminating Co. of Boston in 1918, on record in the TRANSACTIONS of that year, but so far is applicable to cable protection only. Operating experience as indicated in that paper and extended during the past 12 years shows that this system usually clears the cable fault in its incipient stages without system disturbance and frequently with so little damage to the cable that the fault is not readily discoverable. Originally, as mentioned in that paper, the cable was put back into service over an extended period before failure reoccurred, but since operating experience shows that operation of this protective system almost certainly indicates a fault, current practise calls for examination and tests of a cable upon which such relay operation occurs to locate the fault.

In spite of its obvious advantages in cable protection this system is not being extended for the reasons stated by Mr. Edson and for two additional reasons. The first and more important of these is the limitation in cable size and therefore power transmitted by the split-conductor construction, and the second is the limitation of the protection to the line itself, whereas some other schemes provide some desirable bus or station protection as well.

**H. H. Spencer:** In the balanced current schemes discussed by Mr. Edson it should be pointed out that the usual schemes involve opening the trip of the balanced current relays when a line is returned to service after an interruption; otherwise, upon reclosing the first breaker, the corresponding breaker of the line which remained in service would immediately open. The new balanced current relay presented by Messrs. Traver and Kennedy has a voltage restraining coil which completely avoids this difficulty. Staged tests have been made on our system with this relay and it appears to be highly satisfactory both from the point of view of sensitivity and from the point of view of voltage restraint.

**R. E. Hellmund:** The merits of circuit interruption at various time intervals of from one-half to several cycles and the complications justifiable in order to accomplish such results have been discussed. In this connection it may be of interest to know that the commercial demand for such short periods as one-half to one cycle first originated for reasons outside of the power system proper. In single-phase railway systems short circuits or grounds on the trolley wire lasting several cycles caused considerable trouble in telephone systems, resulting in the so-called "acoustic shock" to telephone operators. It was for the

purpose of eliminating this condition that the first real high-speed a-c. circuit breaker and relay systems were developed. The use of these was subsequently found to have various advantages for the power system proper, among which may be mentioned less contamination of the oil in the breakers, and greater system reliability.

**W. W. Edson:** It is quite evident from the discussions on this paper as well as on the others of this group that the tendency is towards high speed relay operation with selectivity obtained by means of some type of balancing rather than by timing or current selection. Ground protection is also being emphasized.

This rapid growth of the relay art will require numerous relays to be developed and it is very necessary that the manufacturers use care in the mechanical design of such relays.

A relay may be theoretically and electrically correct but an otherwise satisfactory protective system may be thrown into disfavor if the relay fails from some mechanical reason.

From the standpoint of the relay application engineer it appears that more standardization is required in vector representations, in relay testing and records, and in data for current transformers under short circuit conditions.

There are several special situations which are not being satisfactorily met at the present time, one being the protection of parallel lines having bus sectionalizing breakers at the stations or having taps out on the lines between stations.

The writers of this paper wish to take this opportunity to thank the many engineers who contributed data and information used in its preparation.

# Modern Requirements for Protective Relays
## on Important System Interconnections

BY O. C. TRAVER[1] and L. F. KENNEDY[1]
Member, A. I. E. E. Non-member

### Introductory

THE usual methods of relaying are becoming inadequate for tie line application. The need for limiting the duration of faults on lines of major importance is unquestioned. The possibility of maintaining stability by quicker operation of protective equipment is well recognized. These considerations have resulted in the development of the high-speed relays and oil circuit breakers as steps in the over-all reduction of short-circuit duration.

Besides limiting the duration of short circuits, it is frequently necessary that the protective equipment function correctly at current values below rated load. On some important interconnections, the range in capacity is such that the minimum short-circuit current is but a fraction of the full load value. It is a requisite, therefore, that the new protective relay types and methods should give rapid, selective action, even at low current values.

It is obvious that the use of cumulative or graded settings will not produce the desired results. Preferably, therefore, the relay equipment should make no attempt to operate except when a fault occurs on the circuit protected or as back-up for disorders in a contiguous line. Furthermore, excepting where the through current is limited chiefly by the impedance of the protected line alone, its absolute magnitude is of little value in determining where a fault exists.

### Comparison—The Modern Foundation

Time having been excluded in the concept of our problems, and current magnitude, or any other single quantity, being too variable to be trustworthy, an immediate comparison of two or more electrical quantities is needed, as a prompt means of discriminating between good and bad. These comparisons may be listed as:

| | |
|---|---|
| Series Balance..... | Comparison of currents at the two ends of a circuit. |
| Parallel Balance.... | Comparison of currents at one end of two parallel circuits. |
| Balance of Dissimilar Quantities..... | *e. g.* current and voltage. |

The speed of operation of the directional relays is of unusual importance. They must be fast under all expected voltage and phase angle conditions. A tardy relay may impair otherwise excellent protection.

Though quick action of the relay nearest the fault is a highly desirable feature, it does not necessarily rid the system of the disturbance. The opposite end is sometimes obliged to wait and thereby double the time to completely clear. The various means dealt with in this paper range from about 60 per cent to 100 per cent of effective simultaneous and complete isolation.

### Series Balance

The series balance method gives a comparison of the relative magnitude of current values at two points in the same circuit. It is the best method of obtaining selective action. This is the familiar differential protection, in which an instantaneous comparison is easily made between currents, normally equal, at two points reasonably close to each other. A fault is indicated by an inequality between the two current values. For line protection, such methods involve the use of pilot wires with their attendant expense and technical problems, in proportion to their length. Quick action is secured with simultaneous tripping of both ends of the line, for faults over its entire length.

Related to the foregoing is the carrier current pilot protective system which provides a comparison of relative direction of the currents at the two ends of a line. The breakers at both ends of the line can be simultaneously tripped in 0.1 second or less. For a description of this method, see paper by Mr. A. S. Fitzgerald.[2]

### Parallel Balance

A comparison between currents in two lines which normally bear a definite relation, constitutes a parallel balance.

Split conductor cables fall in this class. Although with them excellent results might be obtained, nevertheless on account of their first cost and more difficult installation and maintenance, they have not found favor on American systems. On the other hand, balancing the currents in pairs of completely equipped lines has become a general practise.

On account of the simplicity, reliability, and speed of this equipment, two similar parallel lines should be protected by balanced relays which will operate to trip one line when its current is a certain percentage above that in the other line. The percentage unbalance is chosen high enough to prevent false operation on small differences, such as may be due to variation in current transformer or transmission line characteristics, unequal mutual inductance, and similar causes. The usually

1. General Electric Company, Philadelphia, Pa.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.*

2. *A Carrier Current Pilot System of Transmission Line Protection*, A. I. E. E. Quarterly Trans., Vol. 47, Jan. 1928, p. 22.

accepted value is 25 per cent unbalance on outgoing lines.

For faults close to one end of a pair of parallel lines, the current will flow in opposite directions in the two circuits. Since the direction of current flow in two parallel lines is always the same, unless one of them is at fault, it is permissible to operate on a 10 per cent unbalance when the currents are in opposite directions. Such a characteristic makes for wider application of the

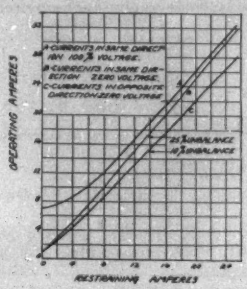


FIG. 1—OPERATING CHARACTERISTICS OF BALANCED CURRENT RELAY USING VOLTAGE RESTRAINT

parallel balance methods. In cases where the generating capacity at the end nearest the fault is very low and where there may not be 25 per cent unbalance, with relays operating in the order of one cycle it is possible to obtain action on current fed from synchronous condensers or induction motors. This combination

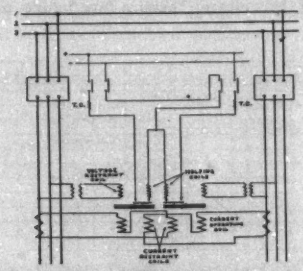

FIG. 2—SCHEMATIC CONNECTIONS FOR BALANCED CURRENT RELAY USING VOLTAGE RESTRAINT

makes balanced current relays almost universally applicable for parallel trunk lines.

Balanced relays should have a straight line percentage characteristic at the higher current values, as shown in Fig. 1. In order to cover the entire range, including low-current faults, it is necessary that the curve continue on down below the normal load. Such a curve with a minimum operating point of 1 ampere is shown in Fig. 1, Curve *B*.

Where balanced relays are used, they are prevented from tripping the second line after one opens, by means of auxiliary switches on the breakers. With the characteristic referred to above, however, the relay would be ready to trip the line carrying load if an attempt were made to close the associated circuit. To prevent this, a voltage restraining feature is added to the current balance relay, modifying its characteristic at 100 per cent voltage, as shown on Fig. 1, Curve *A*. This novel feature adds an impedance factor and normally raises the minimum operating point above full load, thereby permitting switching in the open line without special operating requirements. Under short-circuit conditions, a family of curves between *A* and *B* is obtained, Curve *B* being the zero voltage characteristic and *A* the full voltage characteristic.

Fig. 1, Curve *C* shows the effect of reversing current in one line, automatically reducing to the 10 per cent unbalance characteristic previously discussed.

This balanced current relay is immediately discriminating, without cascading over an average of at least 80

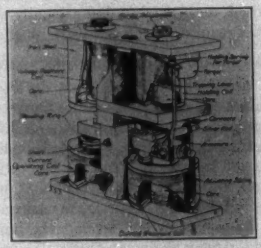

FIG. 3—UNIT OF BALANCED CURRENT RELAY

per cent of the length of the lines. In this regard it occupies the place next to the 100 per cent pilot wire schemes.

The schematic connections of this relay for one phase are shown in Fig. 2. The relay is composed of two units each with its separate circuit-closing contacts for opening one line. Each unit has current operating and restraining coils interconnected, as shown. The voltage restraining coils may be energized from potential transformers associated with the phase which supplies the current coils.

The construction of one unit of the relay is illustrated in Fig. 3, and the complete relay in Fig. 4. Small travel and relatively large forces are used to obtain fast operating time with assurance against false operation from shock or vibration. The current cores and voltage restraining cores are shaded to quiet the operation of the relay under normal conditions and to make it less sensitive to surges.

A holding coil is provided as shown in Fig. 3. This coil seals the contacts closed until the breaker has

opened. The trip circuit is interrupted to both breakers by auxiliary contacts on either breaker, in accordance with long established practise.

A time characteristic, Fig. 5, shows the extremely low values obtained. It is to be noted that at 20 amperes the time is 0.004 second and, in general, is less than 0.016 second (1 cycle on a 60-cycle basis).

In the application of these to two parallel lines, four

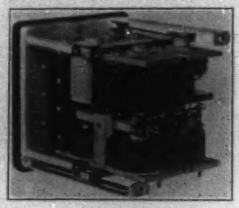

Fig. 4—Balanced Current Relay

relays are used, one in each phase, and one in the residual circuit for ground faults. Usually the residual relay will not require the voltage restraining feature.

## Comparison of Dissimilar Quantities

In any circuit there is a distinct difference in the relative values of current and voltage between load and fault conditions. A relay operating on the ratio of these quantities is, therefore, valuable in indicating the occurrence and location of a fault. The ratio between voltage and current is impedance, and impedance, neglecting the fault component, is a measure of distance.

On any transmission line section the impedance is known and if a relay having an ohmic pick-up is set at a lower value than that of the line its operation will result only in case the section considered is at fault. Such an arrangement needs very little time delay and,

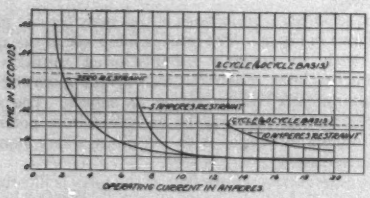


Fig. 5—Time-Current Curves of Balanced Current Relay

therefore, approximates the methods which employ a comparison of currents in parallel circuits.

Since it is not practical to set a relay with an impedance pick-up to cover 100 per cent of a given section, it is necessary to provide some means of protection for the far end of the section as well as the bus to which it connects. This protection can be provided by a second similar impedance unit, operating at a higher ohmic value and giving the desired time delay.[3]

An efficient type of protection using an ohmic relay is indicated on Fig. 6. This "step characteristic" protects Line *A* in the minimum time up to about 80 per cent of its length. At this point, time is introduced for the protection of the last 20 per cent of the line and the bus, overlapping well into the next line. The relay on Line *B* would have a similar characteristic. Provision can also be made to give back-up proteciton at *A*

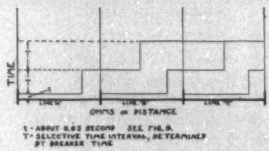


Fig. 6—Stepped Time Characteristics for Distance Relay

for faults in Line *B*, in case of failure of its circuit breaker to clear. This unit requires still higher ohm and time settings.

Three time steps can thus be provided, one as low as practical and operating for faults up to 80 per cent of the line ohms; a second step, higher than the first by the selective time interval required by the breaker and operating up to a value including about half the next line; and a third step for back-up only.

A time characteristic of this kind may be secured by a group of units functioning on ohms and on time. In an elemental form, the ohm unit is operated by current and restrained by voltage, thereby functioning on impe-

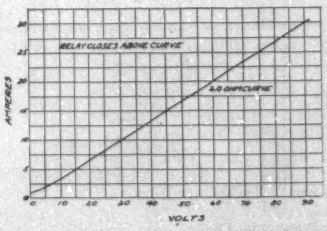


Fig. 7—Operating Characteristic of Impedance Relay

dance, as shown in Fig. 7. The time desired is measured with precision by an escapement mechanism.

The impedance units shown in Fig. 8 make use of induction elements having shaded poles working through a "disk" cut away at all but the active areas to reduce weight and hasten the action. This construction also provides the needed unstable point which

3. A. I. E. E. Trans., Vol. XLII, 1923, p. 532—Discussion by P. Ackerman.

permits the "disk" once started to continue to contact for a reasonable increase in impedance. This feature tends to correct for the impedance rise due to a lengthening arc but cannot compensate for a high initial value caused by low current.

The induction type impedance unit shown in Fig. 8 has the time characteristic illustrated in Fig. 9. This time is fast enough to match the associated directional

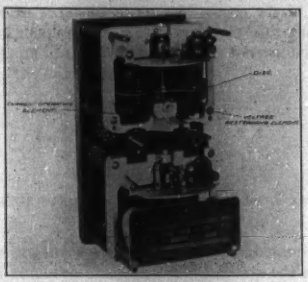

Fig. 8—Impedance Relay

unit and, at the same time, deliberate enough to avoid false action on transients, etc.

The operation of the third step, or back-up, is simple in the case illustrated, involving single lines in tandem. When several circuits, which are sources of power, connect to the bus that feeds a faulted line, the subdivision of the total current produces a corresponding increase in the ohms indicated at each of them. For example, if there are two pairs of parallel lines as in Fig.

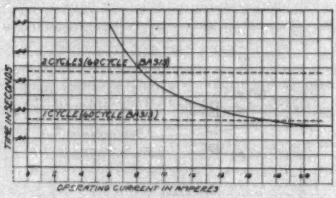


Fig. 9—Time Current Curve of Impedance Relay when Operating below 90 Per Cent Ohmic Setting

10, all of the same length and construction, a short at $X$ would indicate $W$ ohms at $D^1$. If then, in the extreme case, lines $A$, $B$, and $C$ all feed equal currents, the ohms indicated at $A^1$, $B^1$, and $C^1$ would be 3 $W$ and at $A$, $B$, and $C$, the ohms indicated would be 4 $W$ and not 2 $W$.

In setting impedance relays, arc resistance must be taken into account. In fact, on short lines, the arc may have a higher impedance than the line. See composite effect illustrated in Fig. 11. It should be noted that this illustrates a simple mathematical computation based on the assumption that there is no reactance in the arc. It is even more optimistic, therefore, than actual test values indicate. As either metallic or arcing faults are possible, it may be difficult to obtain the proper setting of impedance relays. Even if one were to disregard metallic faults, because of the lesser chance of their occurring, the arc itself is extremely

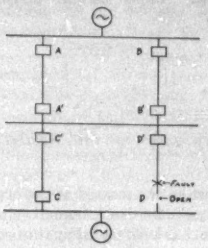


Fig. 10

variable due to changing current and length, as discussed later under field tests. The effect of the arc is, of course, proportionately less as the line increases in length.

## Reactance Relays

The chief component of an arc is resistive although, contrary to a general belief, it also has a very pro-

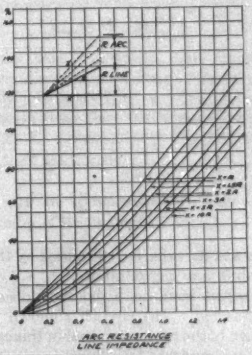


Fig. 11—Effect of Arc Resistance in Increasing Impedance of Faulty Line

nounced reactive effect which may appear in proportions approximating the resistance. This reactive tendency is largely fictitious and becomes decreasingly effective as it is added to line impedance. Furthermore, by the proper choice of instruments, even this fictitious effect can be practically discounted.

Under these conditions, it is submitted that the ohm

unit, most reliable for a distance relay, will work on the inductive reactance component, rather than on impedance.

### Directional Action

A distance relay can operate no faster than the directional unit which is a part of it. The shortest time is desired when the voltage and, accordingly, the torque is the lowest. Ample torque under short-circuit

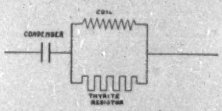


Fig. 12—Connections of the Amplifying Potential Circuit

conditions must not be secured at the expense of excessive temperature or burden at normal voltage.

This problem has been solved by the use of a potential circuit which is resonant at low voltage but not so at full voltage.

This very useful principle can be put to work by tuning the potential coil with a series condenser at low values and detuning at high values by saturation, thereby limiting the current flow by the condenser capacity. This method causes a considerable shift in

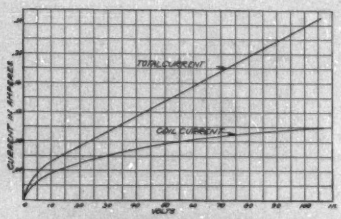


Fig. 13—Current Characteristics of the Amplifying Potential Circuit

phase angle and its value is determined by the extent to which this shift may help or hinder.

In the present instance, a modification of the foregoing is preferred. The circuit is shown in Fig. 12. No saturation of the core is required in this case, and the detuning is accomplished by a thyrite resistor connected in parallel with the coil. Thyrite has the valuable property of changing its resistance to suit the need.[4]

At low voltage the thyrite resistance is so high that practically no current flows through it, leaving the coil and condenser in resonance, and the current through the coil limited only by its own resistance. As the voltage increases the thyrite resistance decreases rapidly (exponentially) until resonance is destroyed. The total current through this circuit and the current through the coil are plotted against secondary volts in Fig. 13.

With thyrite in parallel with the coil and no saturation, the angular relation between the line voltage and the coil voltage is nearly constant as shown in Fig. 14.

A polyphase relay embodying this feature will give speeds of the same order as the distance relay. By providing this relay with a voltage restraining element it can be given a characteristic which will prevent the

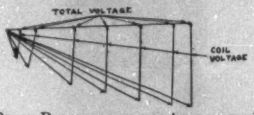


Fig. 14—Phase Relations of the Amplifying Potential Circuit

relay from closing its contacts except when there is a fault on the system. This restraint is secured by the use of a watt element with two potential coils arranged to produce a torque equal to the product of the voltages times the sine of the angle between. If these are excited from two adjacent delta voltages, obtained from the line being protected, the torque will be proportional to the area of the voltage triangle.

This feature insures return of the relay to the contact open position immediately after the fault is cleared and prevents false operation due to surges.

The time current curves for a three-phase fault with five volts, at 60 deg. and 10 deg., are shown in Fig. 15,

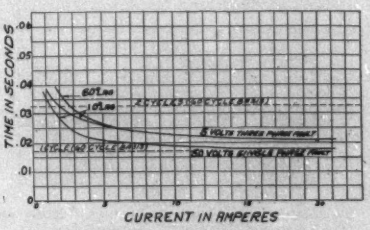


Fig. 15—Polyphase Directional Relay with Voltage Restraint

also for a single-phase metallic short. The relay is illustrated in Fig. 16.

### Simultaneous Tripping at Both Ends vs. Cascading

To require that the breaker most distant from the fault must delay tripping until the nearer end has opened, means double time for many disturbances before the circuit can be cleared.

Expressed as a percentage of perfection in simultane-

4. *Thyrite—A New Material for Lightning Arresters*, by K. B. McEachron, A. I. E. E. Quarterly Trans., Vol. 49, April 1930, p. 410.

ous tripping without cascading, the various methods discussed earlier stand about as follows:

| | |
|---|---|
| Pilot Wire | 100% |
| Balanced Current | 80% |
| Distance | 60% |

FIG. 16

## TESTS

*Arc Impedance.* In connection with various field tests, the authors have been privileged to secure some data concerning the characteristics of arcs such as occur in case of a flashover of a high-voltage transmission line.

The accuracy of these data is not of a high order since they were obtained in each case as a secondary consideration, without the equipment or preparation which would be needed for a true investigation. The information is included, therefore, in the hope that it will shed its flickering light on a very hazy subject.

It is certain that as the current decreases and approaches an unstable condition, the arc voltage rises rapidly until there is not enough potential in the circuit to support it.

Mr. Paul Ackerman has advanced the theory that an arc will follow the characteristic of an approximately constant value of 400 volts per foot.[5]

Some of the discrepancies in our tests are probably due to the method used to start the arc and to the length of time it has been playing. The presence of the metallic vapor of a fuse wire must have a material effect, particularly at the start. In tests 9 to 12, the arc voltage doubled, on the average, after one-half second, with no appreciable change in current or in arc length.

In another test, the total current in each phase on a three-phase to ground fault was 605 amperes and at the start of the arc the phase to phase voltage was 4500, giving an arc resistance of 7.45 ohms. At the end of 15 cycles of arc, the voltage was 10,280 with practically the same current flow or 16.95 ohms. At the end of 15 cycles, one breaker opened, reducing the current to 322 amperes. The arc lengthened and the voltage continued to rise to a value of 61,000 volts, 40 cycles after the start of the fault.

*Low-Voltage Tests.* The correct setting of distance relays is dependent upon accurate data on the impedance or reactance of the line in question. Usually this is readily obtainable by calculation though it may be sometimes advisable to check this in the field. Such a test is very easily made with the use of a small current (say 10 amperes) secured from the regular test source and supplied directly to the line through a load box. The usual test ammeter, voltmeter, and wattmeter tell the entire story.

## ACKNOWLEDGMENT

The authors wish to express their thanks to the officials of the New England Power Company and the Tennessee Electric Power Company for the opportunity offered to obtain these field test data, and particularly to Messrs. E. E. George, C. F. Powers, and H. H. Spencer, for their assistance.

## Discussion

For discussion of this paper see page 1239.

TABLE I
MISCELLANEOUS ARC DATA

| Test No. | System voltage | Position of arc | Approx. length of arc in ft. | Instruments used | Current | Arc voltage | Volts per foot | Arc impedance ohms | Ohms per foot | Arc kv-a. | Kv-a. per foot | Measurement taken after arc duration of |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 110 kv. | $\phi$ to gr. | 4.25 | Instrument | 960 | 2,040 | 480 | 2.13 | 0.5 | 1,960 | 461 | 2 seconds |
| 2 | 110 kv. | $\phi$ to gr. | 4.25 | Instrument | 640 | 4,000 | 940 | 6.25 | 1.48 | 2,560 | 606 | 2 seconds |
| 3 | 110 kv. | $\phi$ to gr. | 4.25 | Instrument | 640 | 3,740 | 870 | 5.84 | 1.39 | 2,295 | 540 | 1½ seconds |
| 4 | 110 kv. | $\phi$ to gr. | 4.25 | Instrument | 624 | 3,070 | 715 | 4.95 | 1.16 | 1,930 | 453 | 3 seconds |
| 5 | 110 kv. | $\phi$ to gr. | 4.25 | Instrument | 592 | 3,600 | 850 | 6.1 | 1.44 | 2,130 | 500 | 1½ seconds |
| 6 | 110 kv. | $\phi$ to gr. | 4.25 | Instrument | 480 | 4,560 | 1070 | 9.5 | 2.24 | 2,190 | 515 | 2 seconds |
| 7 | 115 kv. | $\phi$ to gr. | 6 | Oscill. | 800 | 1,500 | 250 | 1.8 | 0.3 | 1,200 | 200 | 0.1 seconds |
| 8 | 115 kv. | $\phi$ to gr. | 6 | Oscill. | 605 | 2,600 | 433 | 4.32 | 0.72 | 1,570 | 261 | 0.05 seconds |
| 9 | 154 kv. | $\phi$ to $\phi$ | 12 | Oscill. | 405 | 23,100 | 1916 | 57 | 4.75 | 9,350 | 779 | 0.5 seconds |
| 10 | 154 kv. | $\phi$ to $\phi$ | 30 | Oscill. | 385 | 30,700 | 1023 | 78.7 | 2.6 | 11,830 | 394 | 0.5 seconds |
| 11 | 154 kv. | $\phi$ to $\phi$ | 40 | Oscill. | 385 | 35,000 | 875 | 90.8 | 2.27 | 13,500 | 337 | 0.5 seconds |
| 12 | 154 kv. | $\phi$ to $\phi$ | 40 | Oscill. | 135 | 58,500 | 1462 | 433. | 10.8 | 7,900 | 197 | 0.7 seconds |

5. "A Study of Transmission Line Power-Areas," by Paul Ackerman, *The Engineering Journal*, (Canada) May, 1928, p. 309.

# High-Speed Protective Relays

BY L. N. CRICHTON[1]
Member, A. I. E. E.

*Synopsis.—During the past year or so, studies of stability have been made, to determine methods of preventing loss of synchronism upon the occurrence of faults. Of the several methods found, the most obvious and effective is the high speed isolation of the faulty section of the line; and this, of course, means high speed relays and high speed breakers. Investigation so far has indicated that the time required depends upon the type of fault. Since a three-phase short circuit prevents the flow of synchronizing power, it is the most serious type, and must be cleared in from 6 to 10 cycles. This demands the use of relays which will operate instantaneously.*

*Recent suggestions have been numerous and these are discussed. This paper covers relays operating at normal frequency and those which have been operated or suggested for operation at higher superimposed frequencies.*

*While there is a number of difficulties attendant on the design of high-speed relays, (these troubles depending on the type and construction of the relay), high speed relays may still be made to operate on any of the present well known principles such as, impedance principle, current balance principle, etc. They may employ either a mechanical structure or they may make use of thermionic or gas-filled tubes.*

*Attention is given to a mechanical relay of the impedance type operating with a speed of one cycle or less. Some discussion is also given of the reactance type relay with mention of its limitations, particularly that of the extra time required for its initiating element to operate.*

*The effect of resistance at the point of fault (arc resistance) is discussed and the conclusion drawn that, for extremely high speed operation, it does not interfere with satisfactory relay performance. This is because of the time required for the arc resistance to increase to an appreciable value.*

* * * * *

DURING the past year or so, studies of system stability have been made with the view of determining the conditions under which large amounts of power can be transmitted without danger of the equipment falling out of step under fault conditions. As a result of these studies, a number of ways of preventing loss of synchronism have been found. The most obvious and effective method of accomplishing this result is the high-speed isolation of the faulty section of the line. While other methods may be employed to increase the stability limit the maximum results cannot be attained on successful interconnections unless high-speed breakers and relays are employed. The necessary speed of clearing faults will depend upon the type of fault. Investigation so far has indicated that a very narrow time zone is available for fault clearing. The most serious conditions occur with the three-phase short circuit because no synchronizing power can flow past the fault. In order to maintain synchronism, faults of this nature must be cleared in 6 to 10 cycles. The double ground fault is not as severe as the three-phase fault and the clearing time may be of the order of 8 to 12 cycles. Next in the order of decreasing severity comes the two-phase fault with clearing times of 15 to 20 cycles. The single-phase-to-ground fault is the least severe and the clearing time may be 20 to 26 cycles. The maximum permissible clearing times for the various types of faults may vary considerably on different systems but the above values indicate the general degree of severity of the different faults and enable one to compare the speed requirements of high-speed relays and breakers with the requirements of the present slow speed equipment.

With high-speed breaker operation, more power can be sent over a transmission line without losing synchronsim on faults; insulator damage due to flashovers will be negligible; the damage to conductors will be practically eliminated and interference with communication circuits reduced.

High-speed circuit breaker operation requires the use of high-speed, selective relays, and these may operate at normal frequency or at a higher frequency.

## Normal Frequency Systems

Since high-speed breakers require from 4 to 8 cycles to open the circuit, high-speed relays must operate in 1 cycle or less on a 60-cycle system, in order to keep the total clearing time within the required limits. Many relay operations will be less than 1 cycle, possibly even below ¼ cycle. Some of them will be slower, but, in general, the more severe the trouble the faster should be the relay performance.

High-speed relays may be constructed to operate on any of the present well known principles, such as the impedance principle, the current balance principle, etc., and may employ either a mechanical structure or may make use of thermionic or gas filled tubes.

There is a number of difficulties which present themselves in the design of high-speed relays. The difficulty which will cause the most trouble will depend upon the type and construction of the relay.

One of the most annoying difficulties is that any device which will work at high speed in case of trouble is likely to vibrate badly under load conditions. Another difficulty is that the transient values of short-circuit current may vary through a wide range depending upon the point on the voltage wave at which the trouble occurs.

For any given location of short circuit and condition of connected generator capacity there will be a normal,

1. Meter Engg. Dept., Westinghouse E. & M. Co., Newark, N. J.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*



30-140

symmetrical value of short-circuit current. A short circuit may be started at such a point that the peak value of its first alternation may be anywhere from near zero up to, say, 175 per cent of the normal. This effect is more pronounced on systems having a highly inductive circuit. Examples can be seen in oscillograms of almost any high-voltage short-circuit test.

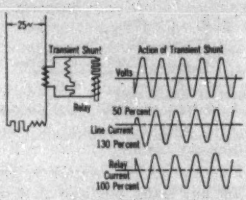


FIG. 1—TRANSIENT SHUNT AND LABORATORY TEST RESULTS

Showing that the shunt diverts the d-c. component from the over-current relay so that the first half cycle of current is the same value as the sustained current

Simple over-current relay may be compensated by means of a "transient shunt," shown in Fig. 1, so that its performance will be uniform no matter at what point of the voltage wave the short circuit occurs. This shunt is made up of resistance and reactance and is so proportioned that it carries the d-c. component of the unsymmetrical current and allows the normal symmetrical current to flow through the relay.

Where the high-speed relay requires a directional element, a further difficulty is introduced and a more or less definite limitation is placed upon the speed of operation.

It is necessary to make sure that a directional relay integrates the conditions existing in the power circuit over a considerable period of time. Except at unity power factor, the flow of power is always alternating so that the direction of trouble cannot be instantaneously determined. The oscillograms in Fig. 12 show some of the conditions which exist when the current is suddenly reversed in a transmission line. These curves were made in the laboratory and do not represent the

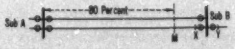


FIG. 2—ILLUSTRATING THE DIFFICULTY THAT THE RELAYS AT SUB *A* WILL HAVE IN DISTINGUISHING BETWEEN TROUBLE AT *X* AND *Y* AND IN DETERMINING WHETHER THE POINT *X* IS ON THE TOP OR BOTTOM LINE

usual condition because the reversed current is smaller than the normal current. It is, however, a common occurrence. Three examples are given showing the reversal at different points in the current wave and the transient current is clearly shown under two of these conditions. Particular attention should be paid to the power wave in order that a better appreciation may be had of the difficulties under which a directional element must operate. At first glance, it appears that one-half cycle of current must be integrated before a determination of the direction can be made but, by manipulation, this may be brought down to one-quarter cycle.

## DIFFERENTIAL RELAYS

On parallel lines, differential relays might be used and can easily clear the majority of troubles by opening the breakers simultaneously at each end of the line. However, it is well recognized that when trouble is close to one bus (*X* Fig. 2) the relays at the other bus cannot tell which is the bad line and must wait until the closer relay has operated before they can operate. This is what has been called "sequential" operation.

This type of protection requires the addition of some other relays to be used when one of the parallel lines is not in service. Also, most operators believe that some form of "back-up" protection should be used to care for a possible balanced fault on both lines or for a quite probable fault on the neighboring bus, both of which troubles could not be distinguished by balanced relays. It therefore seems most reasonable to use relays of the distance type and let them care for all kinds of trouble. Distance relays, either of the impedance or reactance

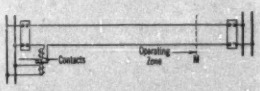


FIG. 3—THE SIMPLE, HIGH-SPEED, IMPEDANCE RELAY

type can be connected to their respective circuit breakers without any provision for changing connections or changing adjustments when line conditions are changed.

## IMPEDANCE RELAYS

The impedance relay will not eliminate sequential operation because (refer to Fig. 2) the two impedance relays at substation *A* cannot distinguish trouble at *X* any better than differential relays can. Furthermore, a relay at substation *A* cannot distinguish between a short circuit at *X* and one at *Y* if these two points are both close to the bus bars. It is therefore necessary to limit the operation of relays at substation *A* to a zone extending from the relay to *M*. This zone will be approximately 80 per cent of the length of the line section but it will vary depending upon the nature of the fault and the accuracy of the relay. Theoretically, if the zone has a length of 75 per cent for a short circuit between two wires it will have a value of 83.6 per cent for a three-wire short circuit. Double grounds will be practically the same as the two-wire short circuit, if there is no extra resistance at the point of fault.

The fundamental design of this type of relay, Fig. 3, is simple. A current coil attempts to close the contacts but is restrained by the voltage coil. The two coils are so proportioned that they balance each other when

a short circuit occurs at the point $M$. If the trouble is closer than that point the relay will operate, if it is farther away the relay will not operate. This device is instantaneous in the usual meaning of the term but, of course, it will operate faster when the trouble is close to it. Fig. 4 shows a characteristic time curve of the high-speed element as it is at present developed.

In order to care for the section of the line beyond the instantaneous zone, it has been proposed to use a definite time relay whose operation is initiated by a

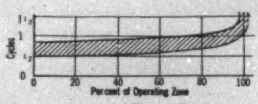


Fig. 4—A Characteristic Time Curve of an Impedance Relay Adjusted for Operation on a Line of Moderate Length.

When used on a short section the time may be slightly greater

second impedance relay set to operate over a longer zone. This should be sufficient protection but, to satisfy a frequent requirement, a second longer time relay operated by a third impedance element has been added for back-up protection to operate in case the breaker at the next station should fail to open as expected. Several sections of transmission line representing part of a network are shown in Fig. 5 with the relay time steps superimposed on top of the line. The setting of one relay operating in the reverse direction is shown below the line in order to emphasize the overlapping of the two operating zones.

It will be observed that if trouble occurs between the points $M$ and $N$, which represents about 60 per cent of the length of the section, both breakers will open at high speed. When the trouble is outside this zone, only the nearest breaker will open rapidly.

The distance elements and also the time relays are so

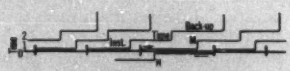


Fig. 5—A Section of Transmission Line Having Several Substations

Showing the method of adjusting the instantaneous and time element impedance relay

designed that they will restore themselves instantly if the trouble is cleared by the opening of other breakers.

## Directional Element

Conventional induction type directional elements would be too slow for high-speed relays but a modification has been made which will do fairly well if the voltage can always be kept above 20 per cent of normal. For unbalanced short circuits this is satisfactory if the customary connection is used which permits at least one relay of a set to obtain its voltage from an unaffected phase. For three-phase faults this type of directional element will not be satisfactory, particularly because three-phase faults are most serious and must be cleared with the highest possible speed. One of several methods which has been suggested for overcoming this trouble is to drive continuously a small synchronous motor having a sufficient flywheel effect so that it can keep its proper phase position during the line dis-

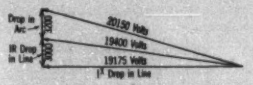


Fig. 6—Effect of Resistance of an 8-Ft. Arc on the Impedance of 50 Mi. of Short-Circuited 220-Kv. Line

Insulators on all three phases assumed to have flashed over simultaneously

turbance. (Fig. 8.) Of course this motor will not stay in step for any great length of time but we are concerned with only the first few cycles. This scheme has another characteristic which has occasionally been wanted in the past. Some power systems are equipped with grounding switches, and relays are desired which will properly select and cut out the proper line when this switch is accidentally closed. Of course, under

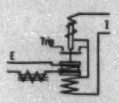


Fig. 7—Simple Reactance Relay

The balance point is where $I^2 = E\,I \sin\phi$ which, simplified, is $I = E \sin\phi$

this condition there is no voltage available for operating the ordinary directional relay. This scheme has not been useful in the past when power directional relays required an appreciable time to operate, but it should work beautifully for high-speed relays which are expected to operate immediately after the start of the trouble. This voltage-sustaining motor need not be considered a part of any individual relay. Rather, it

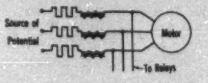


Fig. 8—Motor so Connected that it will Maintain Voltage on the Power Directional Coils of a Relay Even Though the Potential on the Line May be Reduced to Zero

should be connected to the relay potential bus and might better be considered an adjunct to the potential transformers.

## Reactance Relays

The effect of resistance at the point of fault in shortening the operating zone is frequently mentioned, but a number of years experience with relays of the impedance type indicates that this is not serious, at least for short circuits. In a short circuit, as distinguished from a

ground, the only resistance can be that of an arc. A remarkable set of tests made by Mr. P. Ackerman several years ago showed that long arcs of heavy current values have a potential across them of about 400 volts per foot. Some unpublished tests made in Germany gave a potential of 360 volts per foot. This does not indicate that impedance relays will be adversely affected by the arc, provided they work fast enough. As an illustration assume that a 220-kv. line has an arc formed between two line conductors. This arc will be about 25 ft. long and, at 400 volts per foot, will have a total drop of 10,000 volts across it which is about 4.5 per cent of normal. This arc voltage has been depended upon for years to operate power directional relays but it is not of sufficient magnitude to affect adversely the operation of distance relays. If the short circuit is close to the relay this arc voltage will be too small to prevent the relay from operating and if the trouble is near the far end of the operating zone its vectorial relation at right angles to the reactance of the line, will be such that it will not seriously change the length of this zone. Fig. 5 is a simple vector diagram for a 50-mile 220-kv. line wherein a short circuit current of 500 amperes has been assumed. Although the voltage across the arc is 15 per cent of the total voltage, this total is only 4 per cent more than what it would have been for a metallic short circuit. This represents the same, decrease 4 per cent, in the operating zone length.

Of course, if the arc is not interrupted promptly, it will increase in length with a consequent increase in the voltage across its terminals. This increase in arc voltage will reduce the current somewhat and this current reduction may, in turn, increase the resistance of the arc, this circle of effects continuing until the arc voltage becomes a large fraction of the normal line voltage. But this requires time. Tests on two different power systems have shown that the arc remains stable and of low resistance for 5 or 6 cycles. It is therefore reasonable to assert that the effect of the arc resistance can be ignored in the operation of high-speed relays except possibly on very short section of line or on systems where the short-circuit current is small. Neither of these limitations will ordinarily apply to the large systems which are under discussion.

The same argument cannot be so easily applied to ground faults because it is conceivable that the earth has considerable resistance at the point where the fault occurs. It is unlikely that a 220-kv. conductor will ever fall to the ground but some object could be brought into contact with it. Under such conditions the ground resistance might amount to several hundred ohms. Even the flashover of an insulator might have a high resistance if there were no overhead ground wires, because the tower ground might be poor. It is possible to construct a reactance relay for ground protection, which will nullify the effect of the fault resistance to a large extent. A relay utilizing the reactance principle can be made in a manner similar to the impedance relay except that the restraining coil, instead of being operated by voltage, should be constructed as a wattless component indicator (Fig. 7). For a single-phase system, this is easy to apply, but difficulty is encountered on a three-phase system because of the different kind of faults which occur. Where an impedance relay is used it is customary to have one set of relays to care for short circuits between wires and another set to care for grounds. The relay having the least restraining voltage is the one which should operate. In a reactance type of relay the phase relations are different for different classes of faults, and therefore the reactive components are different. If then, a relay is so connected that it will operate properly when one wire is grounded it may operate backwards when two wires are grounded because, although the voltages are about the same, the currents are in a different phase position. In order to correct this difficulty, lock-out relays can be used which will cut-out the ground protection relays whenever there is excessive current in more than one of the line wires. Because of the additional complication of the reactance relay, it may be preferable to use impedance relays on systems having overhead ground wires and good soil conditions.

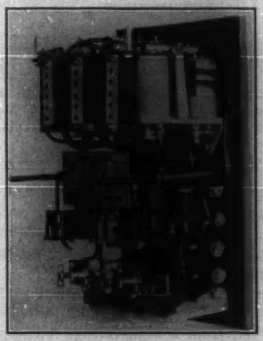

Fig. 9—High-Speed Impedance Relay with Directional Element and with Short-Time and Back-Up Time Elements

The preceding discussion considers the various elements which go to make up a high-speed relay operating at normal frequency. The complete device having all the necessary elements contained in one case are shown in Fig. 9 which illustrates a single-phase high-speed directional impedance relay. It has a high speed, distance time limit, and time limit back-up protection as shown in Fig. 5. To protect completely a three-phase line, three of these relays are used to take care of short circuits between wires and three other relays to care for grounds. If the ground relays are of the reactance type, each is so connected that it uses line

current and the corresponding star voltage. If of the impedance type, they are connected so that they all make use of residual current in their current coils but each one uses a different star voltage. These ground relays may have no directional elements of their own but may make use of the directional elements which are contained in the line relays.

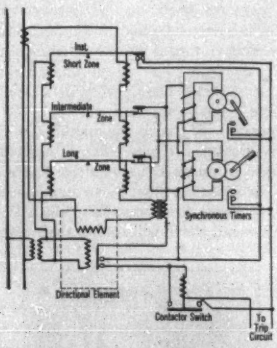


Fig. 10—High-Speed Impedance Relay Showing Directional Element and the Two Small Timing Motors Operated by a Transformer in the Current Circuit

## Example of Impedance Relay Installation

This relay for transmission lines has not, up to the time this paper is written, been placed in actual operating service. However, the principles involved have been quite thoroughly tried out in single-phase railway service for more than a year.

This type of relay has been applied to 11,000-volt trolley wires which are connected to closely spaced substations fed from a high-voltage transmission line. If trouble occurs close to a bus, the voltage may be

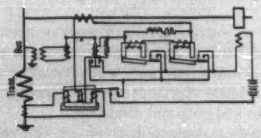

Fig. 11—High-Speed Relay Installation for 11-Kv. Trolley Wires Showing Directional Element, Impedance Element, Instantaneous Over-Current Element, Time Over-Current Element, and Transient Shunts

lowered so much on the high-voltage transmission line that comparatively little current is supplied by the neighboring substations. Then, as soon as the breaker opens at the near station a current much heavier than any load will usually flow in from the other end. Hence, for this location of fault, proper selectivity will be obtained by the use of high-speed over-current relays at both breakers. But for faults between substations, impedance relays are used so that simultaneous operation is obtained.

This relay arrangement shown in Fig. 11, consists of a high-speed impedance element backed up by a high-speed over-current element. Additional back-up protection to care for the failure of the proper breaker to open and to care for some unusual line conditions consists of an over-current relay set to operate after a short period of time. The directional element is polarized by the neutral current of the power transformers, an excellent arrangement on a system of this kind.

This relay when applied to a 25-cycle system will operate in an average time of less than 0.25 cycle.

## The Use of Thermionic and Gas-Filled Tubes

The use of devices of these types has been suggested by many engineers because of some of their obvious advantages. Work along this line is progressing rapidly and there is no reason why impedance relays, including directional elements, should not be constructed of such material. Many engineers are surprised that tubes have not been used before this time and a few general observations regarding them may be of interest.

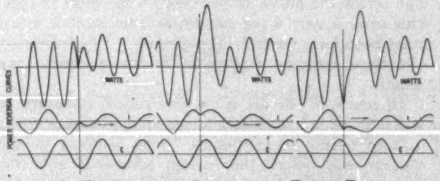


Fig. 12—Reversal of Current at Three Different Points in the Voltage Wave of a Transmission Line

Showing the transient effects in current and power flow

The tube is faster than any mechanical device having the same burden on the current and potential transformers. It will probably be difficult to obtain the extremely high speeds which might be expected, because of the time constants of the various electrical circuits. But then, speeds much below 0.3 cycle appear difficult to attain because of the necessary time required by the directional element.

Some objection has been raised against the use of tubes having hot cathodes but this should not be considered too seriously if other compensating advantages are obtained. It is likely that a life of one or two years may be attained and, in any case, the filament circuits can be supervised so that an alarm will be given if any tube burns out.

Because of the high values of trip currents which high-speed breakers will probably require, any tube type of relay must be especially made to carry a much greater load than is customary in radio receiving equipment. This will probably require the use of tubes containing gas to assist in carrying the current.

This use of gas in the tubes has brought out two unexpected short-comings. Since the action of these tubes involves ionization of the gas, some time is required for the operation to be completed and it has been found that, near the critical point of discrimination, the tubes are neither fast nor accurate. Some tests which were made on a tube type of relay showed that it was no more accurate than a mechanical device. The fault was possibly in the circuits and further work will, no doubt, result in considerable improvement.

### High-Frequency Schemes

In order to overcome sequential operation and thus increase the speed of clearing troubles, two solutions

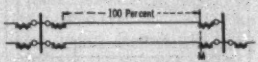


Fig. 13—Illustrating the Use of Reactors to Overcome the Difficulties Shown in Fig. 2

have been proposed. Both of them are expensive. One is the use of a reactor in the transmission line where it connects to the bus. This, in effect, insures that a line fault always occurs some distance away from the bus, so that the trouble will be within the operating zone of impedance relays, or the current in the two lines at the other end of a parallel section will be so unbalanced that differential relays can operate simultaneously. A simple illustration of this arrangement is shown in Fig. 13. In order to secure proper selectivity

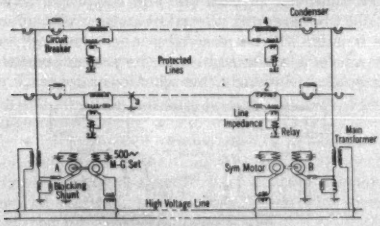


Fig. 14—Superimposed High Frequency (500 Cycle) as it Might be Applied to the Trolley Wires of an 11-Kv. Single-Phase Railroad System

this reactor should be equivalent to about 10 per cent of the reactance of the line, so it is obvious that such a device will cost a considerable amount, particularly when used on high-voltage lines.

The only other apparent methods of securing simultaneous operation is by means of some high-frequency scheme.

Some of the high-frequency schemes which have been suggested will increase the speed of relay operation, others will simply make sure that the breakers at both ends of the line will be opened simultaneously at the speed which may be attained by normal frequency relays. A superimposed scheme has been suggested, carrier current is in use, and several proposed schemes are being investigated. Consideration has been given to the use of both moderate frequencies of the order of 500 cycles and carrier current frequencies of from, say, 20 to 100 kilocycles.

### Superimposed High Frequency

The superimposed high-frequency scheme described by Mr. L. R. Ludwig before the Institute June 25, 1928, promises to become of considerable importance. The method is to superimpose a high frequency on the power system at various points, probably at every place where there is a power transformer, and depend upon the short-circuiting of this high-frequency circuit to sectionalize the transmission line. The reason for using the high frequency is that it can be more cheaply blocked out of line sections than can the normal frequency. Instead of the simple but expensive reactors

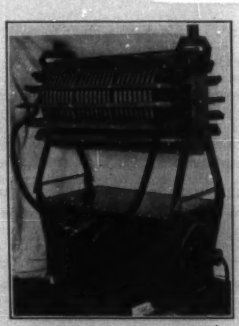

Fig. 15—An Anti-Resonant Shunt for Blocking the Current in the 500 Cycle System Shown in Fig. 14.

shown in Fig. 13, the high frequency can be impeded by anti-resonant shunts composed of small reactors and capacitors as shown in Fig. 14. An anti-resonant shunt intended for an 11,000-volt railway system and capable of withstanding 50,000 amperes short-circuit current at 25 cycles is shown in Fig. 15 and is obviously not too expensive. It is intended to be hung from the bus structure by suspension insulators and will not require any particularly heavy structure to support it.

It is of interest to note that, although the anti-resonant shunt can be designed to have a high impedance to the flow of the high-frequency current, this acts as a resistance and is at right angles to the reactance of the line so that it is not as effective as might at first be expected.

For a three-phase system, a three-phase generator may be used so that short circuits between wires as well as short circuits to ground can be isolated. Directional relays can easily be provided on such a system although they will not usually be required.

## Carrier Current Schemes

All of the carrier current schemes that have been suggested, make use of some characteristic of the fundamental current for their operation or else they depend upon normal frequency relays which send out a high-frequency impulse to the other end of the section. They are all equivalent to the use of pilot wires. Various frequencies have been suggested ranging from 500 cycles to 100 kilocycles but the difference in frequency does not materially affect the principles involved; neither does it appear that any particular range of frequency is less likely to be interfered with by the power arc disturbance which occurs during the trouble. The advantage of a higher frequency seems to be that it is somewhat easier to block it out of circuits where it is not desired.

The method which has been installed on at least two power systems in this country and which has been

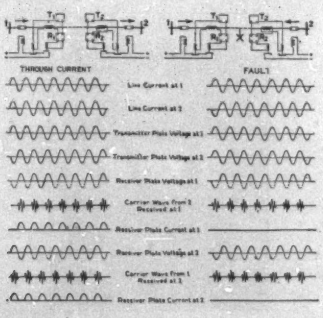


Fig. 16—Fitzgerald's Carrier-Current Scheme

Normal frequency over-current relays operate to trip the breaker. If the instantaneous currents at each end of the line have the same direction, indicating that the line itself is sound, a carrier signal is received preventing the over-current relays from tripping the breakers

described by Mr. A. S. Fitzgerald, of the General Electric Company, makes use of the effect that, when trouble occurs in a section, the current in the two ends of the wire is flowing to the fault in opposite directions. A sending set and a receiving set at each end of the line are both polarized by these currents so that an impulse will be sent out from one end when the current is in a certain direction and it can only be received by the receiver at the other end when the current is in the opposite direction. A simplified diagram is shown in Fig. 16 which is taken from Mr. Fitzgerald's paper.

Another scheme is based upon the fact that at least one end of the line section can always be opened simultaneously by normal frequency relays no matter where trouble occurs. The idea is to have this relay not only open its own breaker but to send an impulse to the other end of the line and open the other breaker. An advantage of this arrangement is that the high frequency is not actually used in the majority of cases of trouble and if it should fail the effect would not be so serious as would be the case if it were always depended upon. Even if it should fail on a case of trouble near one end of the line, the result would be sequential operation, not a total failure to clear trouble. Of course, all carrier current schemes can readily be interlocked with normal frequency relays so that false operation when there is no trouble, can be prevented.

A 500-cycle carrier current scheme of this type

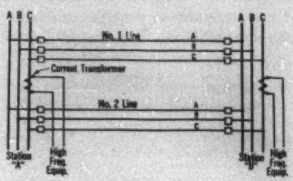


Fig. 17—A 500-Cycle Carrier Current Scheme Applicable to Parallel Lines or Loops

When an instantaneous relay at either end of a line operates it opens its own breaker and sends an impulse to the other end of the line to open the other breaker

which is applicable to parallel lines is shown in Fig. 17. Two frequencies, say 480 cycles and 600 cycles, will be introduced when desired, one frequency to trip the breakers on No. 1 line and the other frequency to trip the breakers on No. 2 line. Two generators will be run continuously at each end and the proper impulses sent out whenever any normal frequency relay operates. This impulse will be received at the other end by the relay which is tuned to it, and the proper breaker will be tripped. Obviously this scheme cannot work when

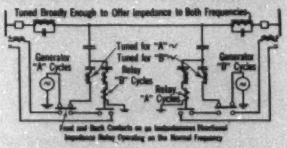


Fig. 18—Suggested High-Frequency Carrier-Current Scheme

The carrier is sent continuously. The operation of any normal frequency relay will interrupt the carrier and thus transmit an operating impulse to the breaker at the other end of the line

one of the lines is cut out of service. However, it can be applied to loops of any reasonable number of sections in which case there must be as many frequencies used as there are sections of line.

Another scheme which can be applied to any form of network is to use a carrier current to send the tripping impulses from one end of the section to the other and to put anti-resonant shunts in the line so as to keep each carrier impulse within its own section. This is one of the most likely schemes which has been suggested

because of its flexibility. One method of accomplishing this is shown in Fig. 18 with the interlocking connections between the high-frequency and the normal frequency relays.

### Power Arc Disturbances

There is no doubt but that the arc which occurs at the point of faults must be given serious consideration when considering the questions of high-frequency relay. Often there is no way to send a carrier impulse to the next station except over the line which is in trouble. It is conceivable that this arc may send a false signal. The difficulty is that any shock to a tuned circuit will cause it to oscillate and this shock may be applied to the tuned circuits of receiving sets over a large part of the power system. This may result in a tripping impulse being improperly given. It will not help much to have the carrier running continuously and interrupt it as a signal because the arc disturbance may be of such a nature that the stoppage of the carrier will not be detected.

The answer to this difficulty is, apparently, to raise the power level. By this is meant to increase the amount of power used by the carrier equipment to such a point that it will not be seriously influenced by the disturbance set-up at the point of fault.

### Summary

Present day developments in the central station industry demand high-speed protective relays in order that the systems may be kept stable.

Suitable designs are now available and a single-phase installation has received a thorough test in exacting service for the past eighteen months.

Improvements are now being made so that the relay art will keep pace with the circuit breaker development.

Normal frequency relays of the distance type are recommended.

The shortcoming of these relays is in the frequent troubles which can only be cleared sequentially by them.

High-frequency protection must be used to overcome sequential operation on long lines where pilot wires are out of the question.

The use of high frequency is largely an economic problem. If the lines have sufficient capacity, if the breakers are fast enough, and if the excitation response is quick enough, simultaneous breaker operation will not be necessary. But where all these factors or a sufficient weight of them cannot be economically attained, then high-frequency methods should be used.

### Acknowledgment

In addition to the acknowledgments made in the text, the writer is indebted to the following members of the Westinghouse organization whose work has been studied in the preparation of this paper: Messrs. R. C. Bergvall, R. C. Curtis, S. L. Goldsborough, R. D. Evans, and H. A. McLaughlin, who is now with the Central Hudson Gas & Electric Company.

## Discussion

### MODERN REQUIREMENTS FOR PROTECTIVE RELAYS ON IMPORTANT SYSTEM INTERCONNECTIONS

(Traver and Kennedy)

### HIGH SPEED PROTECTIVE RELAYS

(Crichton)

**H. H. Spencer:** There appears to be a real limit below which it is unwise to carry the operating times of reactance or impedance relays such as described in the papers by Messrs. Crichton, Traver and Kennedy. In general these relays consist of element operated by current and restrained by voltage. A fixed ratio between these two determines the operating point and the ratio is commonly referred to as impedance. It should be pointed out, however, that the operating point of the relay is only an apparent impedance and is equal to

$$\text{“}Z\text{”} = \frac{R\,i + L\dfrac{d\,i}{d\,t}}{i}$$

Only in steady state does this become a true impedance $R + j\,X$. Since the predominating transient in alternating-current short circuits is a decrement $\dfrac{d\,i}{d\,t}$ is less than $j\,\omega\,I$ and the apparent impedance is less than the vector sum of resistance and steady-state reactance. The unfortunate thing is that the difference between the apparent impedance and the true impedance is a function of the decrement and therefore of the connected capacity which is the thing we are trying to avoid in all these relay schemes. Possibly a transient shunt such as Mr. Crichton has described but with taps to take care of the various values of connected capacity might eliminate this difficulty, but it appears to the writer that it would be better to make the minimum time of impedance or reactance relays long enough to allow the worst of the decrement to expire. Dependence upon other relays, as for example, balanced current, can be placed for extremely high-speed operation.

**A. S. Fitzgerald:** Since in two of the papers as well as in the discussion, there have been references to the carrier current relay scheme you may be interested to have some further information about this system.

It is now several years since this development was first embarked upon. It represented an entirely new departure in relay methods. As such, it was necessarily an undertaking likely to take a considerable time to bring to completion. Indeed, due to the general advancement of ideas with regard to relaying practise, during the last few years, we have had to considerably revise our plans as to what the carrier current system should accomplish. So that in addition to spending time on the development of carrier current methods we have also had to undertake a good deal of development work relating to features of this relay scheme, which are not concerned primarily with carrier current, as such, in order to keep abreast of changes in relay requirements during this time.

For example, when this work was commenced time delay methods of selective protection were still in good standing. Thus the first carrier current relay field tests were made on the basis of a time delay scheme which enabled the tube filaments, on the occurrence of an excess current, to be brought up to operating temperature. The connections also, as described in the original paper,* involved a system of starting, receiver, and tripping relays, operating in sequence. The total time of operation was about one-half second.

This scheme enabled us to develop, and to try out in the field, the carrier current circuits and methods of operation. After this had been done and promising results obtained, it became clear

*Journal A. I. E. E., October 1927.

that the general trend or relaying practise was rapidly moving towards higher speeds of operation. It was therefore found better to keep the tube filaments continuously at operating temperature and to avoid relay connections involving sequence operation. Therefore, an entirely new scheme of relay connections was devised, capable of operating reliably in one-tenth of a second.

As well as higher speeds of operation there has also been a tendency toward lower current settings. In developing the original carrier current relay scheme we were anxious to avoid a multiplicity of auxiliary apparatus, for purposes of power supply. It was found that with direct operation from bushing transformers successful operation could be obtained at currents of two or three hundred amperes. At that date it was felt that this might be of practical use. However, in actual applications of this scheme much lower tripping currents have been required and a great deal of the time spent in developing this scheme has been devoted to this aspect of the problem.

Everyone who has experience of relay development realizes the very limited value of any tests or data other than actual operating records. This is mainly why relay developments take such a long time. However, due to the splendid co-operation of the operating companies, of which I cannot speak too highly, we have now records of at least one hundred short circuits on lines on which the carrier current system has been installed. Many of these have been actual faults. Others have been applied intentionally during field tests and a large number of oscillograph records have been obtained.

With this data available I think you will agree with me that we are beginning to know enough about this scheme to attempt to draw a few conclusions. I believe you will find these rather surprising.

For purposes of discussion, we may conveniently divide this scheme into two separate parts, namely, the power frequency part and the carrier current section. The former includes the relays and the current transformer excitation circuit by means of which the carrier current apparatus is energized and set to work to transmit to the other end of the line a signal indicating the power conditions. The carrier current part includes the vacuum tubes, the carrier current apparatus and circuits, and the transmission and reception of carrier current over the high line under fault conditions.

There is nothing about the power frequency part of this scheme that relay engineers will have any difficulty with, but the carrier current and vacuum tube part of the business is something with which we, as relay engineers, are unfamiliar, and with regard to which very little engineering experience is available. Any feelings of doubt or apprehension which we may entertain as to the success of this scheme very naturally refer to the carrier current feature.

This feeling, which is entirely logical, is to be noted in Mr. Crichton's paper where he raises the question as to the effects which the power arc may have on the carrier current operation. I doubt if there is any one feature of this work with respect to which the engineers following this development felt more concerned. There was absolutely no data to go upon whatever. I remember that plans were made to install a carrier current receiver, and an operation recorder on a high line, and, with no carrier current transmitter at all, see if we could get any data showing operation due to power arcs and similar disturbances. This work, however, was delayed due to other field tests on this scheme. When we came to check up on the records which we were obtaining we did not find a single instance where evidence of interference by the power arc could be traced. Nor have we been able to, up to the present date. Due to this we were unable to justify the expense of the special test referred to.

Indeed the surprising result of the operating record of this scheme is that the carrier current part of it has come through with flying colors. It has never given us any trouble at all. Of course, we have had our difficulties. These must be expected in such an undertaking. But it is a fact that all the troubles we have encountered have been associated with the 60-cycle circuits and not with the high-frequency apparatus. We have changed our relay design and connections to get higher speeds. And we have had a number of failures to operate because the fault current was too low to furnish enough excitation. But we have not found it necessary to make any substantial modification in the design of the carrier apparatus.

As you may know this system is installed on one of the Big Creek lines on the Southern California Edison system*. The power company feels that the carrier current scheme has proven successful and recently I learned that during March heavy sleet conditions caused eight faults on this line in two days and that correct operation was obtained, every time.

**P. Ackerman:** I am very gratified to see the profession in general gradually come around and accept the need of the basic principle of instantaneous protection for which I have been fighting for the last fifteen years.

In particular I am pleased to see both large manufacturing companies accept finally, for fast line protection, the same basic principle of multi distance range protection as I have developed and successfully applied for the past ten years. As has been pointed out in my paper, this principle of protection for long transmission lines, along with the differential principle for station apparatus must be considered the key to the universal solution toward 100 per cent system protection which could only be still further improved in effectiveness by a carrier current pilot protection or a similar arrangement, which would clear all line short circuits simultaneously at both ends.

I note from the two papers that great strides are being made to obtain as low as half a cycle or even shorter relay clearance, based on 60-cycle current. The impedance relay has inherently this characteristic, but the directional relay doubtlessly offers decided obstacles for different reasons. It is very doubtful as to whether such short timing, with its complications, is warranted, at least at this instant. One- to two-cycle relay time would appear sufficient at present, as this would present only a small fraction of the proposed circuit breaker timing of six to eight cycles, which latter appears to be the present limitation.

I believe that the successful and universal solution of the stability problem will have to be sought in an effective system layout rather than in the solution of excessively fast breakers, as has been pointed out in my paper.

**H. W. Haberl:** With all new relays pointing toward instantaneous operation and possibly simultaneous clearance, I wish to point out a few important points and a method by which they can be overcome, even by using the older style of distance relay and its distance proportional time curve.

The new style distance relay time curves, as shown in the papers presented by Messrs. Traver and Kennedy, and also by Mr. Crichton, are represented by the step principle in which the instantaneous feature reaches only to about 80 per cent of the line length. This is not objectionable on single lines but, where two or more lines are on the same tower (assuming the fault to be 20 per cent line distance from either station) the trouble is cleared at one end after a predetermined time during which period the arc is very liable to communicate to the good line.

The scheme I wish to present is an instantaneous clearance to 100 per cent line length, provided both lines are in service. One line being out of service the time for the remaining line is either the distance proportional or the newer step principle, depending on the style of relays used. With one line out of service the disadvantage of having the line clear at one end by definite time is not objectionable here because the power arc cannot communicate trouble to another circuit.

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* *Electrical World*, March 22, 1930.

Fig. 1 shows a combination distance relay and balanced relay scheme. Under normal conditions or under through faults the duo-directional relay is in the mid-position and therefore the circuit opening auxiliary relays are short-circuiting the resistors. All relays have full voltage, therefore standard back up protection is in force, but with the trouble occurring on one line the duo-directional relay contacts towards the faulty line, operating the auxiliary relay on the faulty line which inserts the 3000-ohm resistor in the voltage coils of the faulty line relays which, in turn, operate instantaneously. The auxiliary switch of the oil breaker makes the instantaneous feature inoperative on the remaining line.

**C. Litchtenberg:** Protective relays are now recognized as an essential part of every electricity generation, transmission and distribution system. Their characteristics are requiring marked changes from time to time as interconnections are increased and improved service continuity is demanded.

Initially a protective relay was just an auxiliary trip for a circuit interrupter. It was first just an overload trip. Two or more of these were set far enough apart so that some degree of selection was obtained when faults occurred. As the number of circuits increased, however, the limit of this type of selectivity was soon reached. About this time there was introduced the time delay feature to obtain greater selectivity. It inaugurated what may be called the second phase of development. It

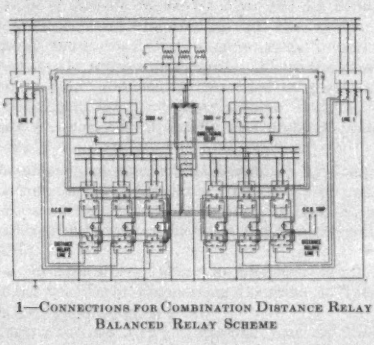

Fig. 1—Connections for Combination Distance Relay and Balanced Relay Scheme

brought first the definite time delay dash pots and air bellows. Then came the inverse time delay with air bellows. These, however, had inherent limitations. They did not permit accurate setting or accurate repetitive operation. They were replaced for more exacting service by the induction disk time delay relays.

The common method of obtaining selectivity with all of the time delay features was by suitable settings of the pick up or starting current and the time delay. One of these is electrical in its performance. It depends upon circuit conditions. The other is mechanical or magnetic in its operation. It is relatively independent of circuit conditions. In addition the minimum time obtainable with reasonable accuracy for any of these is in the order of 0.1 second, or 6 cycles on a 60-cycle circuit. Consequently, where a number of circuits is to be protected and the time settings are additive, the last relay in the chain had to be set at from 0.5 second to 1.0 second, that is, from 30 cycles to 60 cycles, on a 60-cycle circuit.

For simple radial feeder systems with few series relay steps such settings permit excellent performance. However, when the number of series steps of relaying exceeds three or four, the maximum time delay becomes an important item. If it is too long it may result in low-voltage conditions during system disturbances and may even cause further system disturbances, resulting in unnecessary interruptions.

Many years of experience have shown that the induction disk time delay relay is almost as good as can be expected when all conditions are considered. Therefore, it became imperative to find new ways of meeting service requirements for protective relays which would more promptly and accurately clear faulty sections from the system.

Studies led to the third phase of the development. This is the present stage which employs circuit currents and circuit characteristics for not only starting the operation of the protective relay, but also for selecting the most effective circuit interrupter to trip.

Several of the newer developments in relays to meet these changed conditions have been described in the papers presented by Messrs. Traver and Kennedy, and Crichton. These indicate that while a minimum of 0.1 second was to be expected with the induction disk form of relay, the newer distance and balanced circuit relays can be expected to complete their performance in somewhat less than 0.01 second. This is in about ½ cycle on a 60-cycle circuit. The improved performance is accomplished by utilizing resistance, reactance and capacity, in combination with circuit current changes. It brings the protective relay development well up to the development of circuit interrupting devices, which now permit clearing disturbances on circuits up to and including those operating on 220 kilovolts within 8 cycles of the appearance of the disturbance at the protected point.

The fourth phase of protective relay development is about to begin. It will probably tend to a closer realization of the "anticipatory relay" which engineers have hoped to secure from time to time. It will no doubt utilize vacuum tubes and vacuum tube circuits for following circuit current wave shape and magnitude changes. As a result, it may be expected that the minimum time of operation of relays may be reduced from 0.5 cycle as at present, to the order of 0.05 cycle or even less on a 60-cycle basis. The further advances will no doubt be made available as soon as the circuit interrupting requirements are such as to warrent removing faults more promptly to improve service continuity.

**O. C. Traver—L. F. Kennedy:** We agree with Mr. Ackerman concerning the difficulty in determining the length of an arc, and in order to overcome this the majority of those referred to in Table I of our paper were drawn in still air, between electrodes spaced a definite distance. Photographs of these arcs indicated no material tendency to rise and lengthen before interrupted.

Answering Mr. Ackerman's question as to the speed of the carrier current pilot protective equipment, the present installation operates in 0.1 second and there is prospect of cutting this to approximately one-half. In general, this action is simultaneous at the two ends, without cascading, for faults over the entire length.

Reference has been made by several of the speakers to the limit in speed for directional distance equipment. Operation in two or three cycles seems quite in keeping with the circuit breaker time and offers a very distinct and reasonable reduction. This two or three cycles is based not on operation under favorable conditions, but upon severe faults close by which leave practically no potential and, accordingly, aggravate the likelihood of instability.

We do not consider this speed to be an ultimate but rather a logical step for the present. We have secured much lower time but consider it unwise to tempt inaccurate results through premature action. Further reductions will be forthcoming to match the inevitable increase in circuit breaker speed.

**L. N. Crichton:** Mr. Spencer's remarks concerning the effect of the transient current on the performance of high speed impedance relays, are pertinent and deserve consideration. If the system is highly reactive the effect of the transient is notice-

able for several alternations. An example of this is on railway trolley circuits where the spacing between wire and return conductors (rails) is large and the reactance consequently high. But the usual high voltage system has a sufficiently high short-circuit power factor so that the transient is not appreciable after, say, two alternations. This can result in an error only when the trouble is near the balance point of the impedance relay. Because the forces are nearly balanced, the resultant effect on the moving parts is slight. Hence the inertia of these parts makes the relay act in a sluggish manner as shown in Fig. 14 of the paper. The requirement of Mr. Spencer's analysis is, therefore, satisfied without any particular effort on the part of the relay designer. Tests which have recently been made on a large power system prove that the transient shunt is not necessary with the 60-cycle relay shown in Fig. 9.

Where the shunt is really needed is on 25-cycle railway systems where only ¼ cycle is allowed for the relay operation. Here the shunt is necessary for accuracy. The transient is not always larger than the steady state current. Sometimes the first alternation is smaller. The shunt equalizes all these conditions.

Referring to Mr. Fitzgerald's description of the carrier current systems, the industry is indebted to him for the splendid work he has done and to the power companies for their cooperation. But the question still remains, is it worth what it costs? Probably it will be justified on some important and heavily loaded lines.

One- to two-cycle relay time, as suggested by Mr. Ackerman should be satisfactory for present day applications. But we wanted our relay to be suitable for any demand which may occur during the next few years.

The scheme suggested by Mr. Haberl is clever and is illustrative of the resourcefulness which operating men must employ in order to harmonize the operating conditions with the lines and equipment which they have available.

Many engineers have dreamed of the anticipatory relay mentioned by Mr. Lichtenberg and when it is discovered it may perform a function which is different from our present relays. Perhaps it will anticipate trouble and remove it from the circuit before the circuit has broken down. For some troubles this seems absurd but not so absurd for the most frequent trouble of all, lightning. However, this is some time in the future. In the meantime, progress is continuing along conventional paths with the principal objects of maintaining stability and preventing power lines from being burned down by the arc which follows a flashover.

# Directional Ground Relays

BY E. E. GEORGE[1] and R. H. BENNETT, Jr.[2]

Member, A. I. E. E. Associate, A. I. E. E.

***Synopsis.***—*This paper deals with the paramount importance of ground protection on transmission systems which has been demonstrated by experience over the past few years. It presents the advantages of ground relays and shows that the disadvantages sometimes attributed to them are not well founded or have been overcome.*

*A number of standard and special applications of relays for directional ground protection are described and illustrated by sketches showing connections. The application of these schemes is discussed and their desirability and feasibility supported by records of operating experience.*

*Attention is called to the point that high-speed relaying will soon be an accomplished fact. High-speed relaying will be needed in both phase and ground protection to take full advantage of high breaker speed.*

*In the testing of relays adequate test facilities are necessary to save time and to insure correct test results. Attention is called to the desirability of making staged tests at system voltage to insure correct relay operation and for their experimental value in developing improved forms of protection.*

* * * * *

LESS than four years ago, there appeared the following summary of protective relay practise for transmission systems.

"Electrical faults on a transmission or distribution system consist mainly of short circuits and grounds. The protective scheme is primarily designed to operate on values of current caused by short circuits between phases. . . . If the neutral of the system is grounded, the method of grounding has an important bearing on the protective scheme. Where the neutral system is dead grounded, or grounded by means of a low resistance, the protective scheme designed to operate on short circuit usually also protects against grounds."

The above quotation will be recognized by many as taken from the Relay Handbook which was prepared by a joint committee of the N. E. L. A. and A. I. E. E., and undoubtedly represented the latest and best thought as of 1926.

Late in December, 1929, the *Electrical World*, in reporting the World Engineering Congress at Tokyo, made the following statements:

"During the past five and one-half years of 220-kv. operation on one system there have been 148 cases of trouble and in all cases a flow of ground current was recorded. Even though the trouble resulted from widely varying causes, such as birds, fires, floods, lightning, sleet, contact with telephone wires and contact with trees, etc., ground current is always indicated. Accordingly, on one system the decision has been made to rely for protection solely upon residual or ground current relays. . . . Phase relays are retained on most systems, but many engineers are agreed that phase to ground protection is the most essential for 220-kv. operation."

With such a remarkable evolution in transmission relay practise so recently accomplished, it may be desirable to point out some of the developments that have come about more or less unheralded. For instance, the argument as to whether high-tension neutrals should be grounded or ungrounded is a thing of the past, and the industry has come to accept grounded neutral operation as economically advantageous and technically indispensable. The only related argument left is as to the extent of grounding,—whether it is to be solid, resistance, reactance, or resonant grounding. If we make liberal allowance for the wide variety of conditions to be met, it may be unreasonable to assume that any one of these varieties will ever be generally accepted as standard.

Fundamentally, neutral grounding operates to facilitate protection by providing at the switching station a circuit for fault current independent of the load current. Overload protection utilizes common circuits for fault and load currents and can distinguish fault current from load current only when the former is large compared with the latter. This requirement was generally met a few years ago. Voltages were lower, systems smaller, and interconnections practically unknown. Charging currents and arcing grounds were of academic interest only.

Relay protection has kept pace fully with the increase in voltage, in length of lines, and in growth of regional networks. The past few years have been times of history making, rather than history writing; and although ground protection has been the chief development utilized in meeting the requirements of modern transmission systems, nowhere in technical literature today does there seem to be any adequate presentation of the importance of ground relaying. Nevertheless, it is a matter of common verbal admission among relay engineers of transmission companies that ground protection is more important than phase protection, and that with most types of transmission construction above 66 kv., phase protection is of very questionable value, excepting, of course, a few promising recent developments. Only recently has there been available a sufficient knowledge of fault phenomena to justify on

1. Superintendent Electrical Operation, The Tennessee Electric Power Company, Chattanooga, Tennessee.

2. Asst. Superintendent Electrical Operation, The Tennessee Electric Power Company, Chattanooga, Tennessee.

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30-132

a theoretical basis the general opinion that ground relaying becomes of more importance as transmission voltages go higher, and that at voltages of 66 kv. and above, ground protection is of more importance than phase protection. The efficiency of ground relay protection which has resulted in its popularity of late years is largely due to the following factors.

### Advantages of Ground Relays

1. Ground relays are independent for all practical purposes, of surges due to switching, synchronizing, motor starting, condenser starting, etc.

2. Ground protection is based on the fact that the current flowing in the relay under normal conditions is zero and, therefore, such protection is even more sensitive than differential or balanced protection with phase relays.

3. Ground relays can easily be made to operate at higher speeds. Directional ground relays now operate on some systems as fast as 5 cycles and one type of special induction relay used for initiating the operation of oscillographic equipment operates in 2 cycles.

4. The high attenuation of ground fault current with distance results in automatic selectivity. The zero sequence impedance of lines is usually considered to be 3½ to 4 times the positive sequence impedance, which means that distance provides several times as much discrimination on ground faults as it does on phase faults. The application of inverse time characteristic relays to ground protection is thus fairly easy.

5. Ground relays are applicable to systems either solidly grounded or grounded through impedance, although they are applied more easily and more satisfactorily to solidly grounded systems.

6. Ground relays are applicable to multi-grounded systems. With the increasing number of interconnections, such systems will soon result, even though we started out originally with each system grounded at one central point.

7. Ground relays are applicable to networks and to intercompany tie lines because they are independent of the location of generation, and thereby afford dispatchers maximum freedom in allocating power supply. This point has often been overlooked. Relay schemes should avoid unnecessary restrictions on the location and amount of generation, and ground relaying does this much more thoroughly than any available form of phase protection.

8. Ground currents can now be calculated with sufficient precision to enable ground relays to be set correctly.

9. Equipment is now available to check ground current and the tripping time of ground relays under actual fault operation on the power system.

10. Ground relays operate fast enough to clear up faults with a minimum amount of damage to insulators, bushings, and windings. Most high-tension line failures can be cleared quickly enough by ground relays to prevent burning the line down, except in cases of direct lightning strokes.

11. Ground relays usually clear up lightning flashovers, wires swinging into trees or structures, etc., before the arc has time to spread into adjacent phases. Single-phase-to-ground faults seldom result in instability, and fast clearing of such troubles therefore prevents out of step conditions and loss of synchronous load. In the case of horizontal construction, lightning very frequently causes two phases to flash over to ground simultaneously, but ground relays will clear a double ground fault about as fast as a single ground fault, under most conditions. Ground relays give no protection against three phases shorted or grounded, but such faults are rare except with closely spaced horizontal construction and high insulation to ground.

12. Ground relays prevent lines down on the ground from remaining energized and endangering lives and property. A single damage suit may cost more than providing grounded star-connected transformers and ground relays for several substations.

13. Phase protection has to be proportioned to the maximum carrying capacity of the largest section of a circuit in order not to limit the economic capacity of the circuit. Small branches connected to heavy circuits cannot be protected by such maximum settings of phase relays, but ground relays may be set low enough to protect small transformers or small conductors.

14. Very frequently it is difficult or impossible to install differential protection on transformers or rotating equipment, but in practically all such cases ground relays can be used to give satisfactory protection, especially if the transformer or generator windings are not grounded. This is usually the case on step-down transformer stations and on large motors and synchronous condensers. Of course, the system neutral must be grounded at some other point.

15. In general, systems of different voltage will not intercharge ground current except when coupled by auto-transformers or by three-winding transformers with two-grounded $Y$ windings. It is, therefore, possible to set ground relays on one voltage system independently of those on another voltage system. This is not true of phase protection, and in most high-tension systems it is necessary to coordinate the phase relay settings even when switches are separated by transformation.

### Advantages of Directional Ground Relays

1. Directional ground relays do not necessarily require potential connections.

2. Directional ground relays may be made independent of fault power factor for all practical purposes.

3. The direction of normal power flow and reactive flow have no effect on directional ground relays.

4. It is unnecessary to interlock phase and ground relays when directional ground relays are used.

5. Directional ground relays have more highly

inverse characteristics than any other type of relay. Their characteristic curves are almost rectangular hyperbolas, which are, of course, the theoretically perfect form of inverse characteristic.

### Disadvantages of Ground Relays

Any discussion of the merits of plain ground relays and directional ground relays would not be complete without reference to the objections raised against such relays by those who are not using them.

1. "Ground relays often operate too fast and trip out a line on remote trouble."

This is entirely a matter of setting. Many systems operate with less than one per cent of incorrect operations due to such causes. Ground relays with low-current taps and fast time settings cannot be used indiscriminately on networks any more than could phase relays with similar current and time settings. However, on radial feeders it is often possible to use ground relay settings of five to 15 per cent of the phase settings and considerably shorter time. The increased zone of protection is readily apparent. Nothing but ground protection has ever been devised that will protect 11-kv. rural distribution lines 50 miles long and of small conductor size, as we frequently have today.

2. "Ground currents are difficult to calculate."

This has been substantially true until within the last year or two. Much progress has been made recently. Several companies use direct current calculating tables to determine ground currents. Long-hand calculation can be used without especial difficulty by making use of several assumptions justified by field test during the last year and described in the serial report of the South-eastern Division, Electrical Apparatus Committee entitled, "Calculation of Ground Currents."

3. "Ground currents are difficult to measure."

This is no more true of ground fault current than of phase fault current. Any comment on either should take note of recent developments and improvements in high-speed graphic ammeters and the oscillographic equipment.

4. "Ground relays are unnecessary if a system is grounded at every supply transformer, as every ground fault will take enough current to operate phase relays."

This may be true on short lines and at the lower voltages but it is well known that even phase fault currents at higher voltages may be less than maximum load currents, in which case, phase protection of any ordinary overload or reverse power type is unreliable and hazardous.

It is very interesting to note that the new distance relays now available for phase protection measure reactance or other circuit characteristics, rather than phase current. The successful use of distance relays lends more weight to our conclusion that any successful protection for high-voltage transmission systems must be independent of load current.

### Non-Directional Ground Protection

As an introduction to directional relay protection, a non-directional ground or residual relay connected in the neutral of three line current transformers is shown in Fig. 1. This connection is well known and very generally used. Where bushing current transformers are used it is desirable in all ground relay applications to use relays with fairly low volt ampere burden so that the current transformer ratio will not be effected.

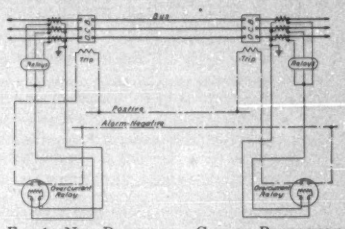


Fig. 1—Non Directional Ground Protection

In order to follow better any of the complicated or unusual directional ground relay schemes, reference may be made first to a non-directional standard hookup for directional ground relays shown in Fig. 2. This scheme may be applied to one or more lines whether they are tie lines or feeders. It is applicable to loops or networks only if the faulty line carries substantially all of the outgoing ground current from the station in question. This scheme is, therefore, not generally applicable to short parallel lines or to a short loop of

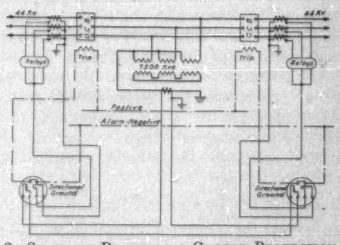


Fig. 2—Standard Directional Ground Protection (A)

only two links, as both lines will tend to relay simultaneously on far end trouble, and inverse time characteristics must be utilized to clear the far end first.

Directional ground relays wired as shown in Fig. 1 are used instead of plain ground relays in the following cases:

1. On tie lines which may carry incoming ground current from other grounded points.

2. On short lines or intercompany tie lines where highly inverse selectivity with distance is necessary.

3. On radial feeders where the far end step-down transformer is grounded on the high side for any reason. An outfeed directional ground relay may be set fast to protect the line and transformer, but its directional characteristic will prevent tripping out the line when feeding back through the bus to a fault on some other line.

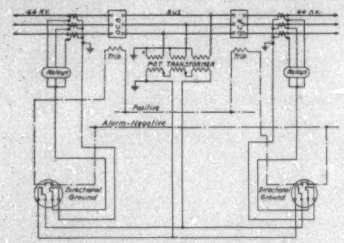


Fig. 3—Standard Directional Ground Protection (B)

4. To get a more satisfactory current setting than is possible with the line current transformers (usually bushing type). As one element of the directional ground relays is connected to a bus type current transformer in the neutral ground lead of the power transformer, any ratio from 1:1 to 1000:1 may be used for the bus type current transformer. The effective ratio between primary and secondary currents will be the square root of the sum of the squares of the line and neutral current transformer ratios.

## Standard Directional Ground Protection

Another scheme of plain directional ground protection is shown in Fig. 3 in which the relay is polarized by potential rather than current. For this purpose it uses an inside delta potential obtained from the secondary of three potential transformers *Y* connected and grounded. In general the application of this scheme parallels that of Fig. 2, the only fundamental difference between the two schemes being the means of polarizing the ground relay, one using residual current and the other residual voltage.

## Directional Ground Protection of Loops

Fig. 4 shows the scheme of directional ground protection used on a 110-kv. loop. The fundamental feature of this scheme is the cross connection. This is shown here as completed through an auxiliary current transformer, but this is required only on unsymmetrical loops. On symmetrical loops and on parallel lines the auto-current transformer may be omitted, since equal primary currents in the same direction in each line will neutralize each other in the secondary circuit. When the auto-current transformer is required, it should be connected so that both secondary currents will neutralize each other on trouble on the far end bus, and thus prevent tripping either line. The ground current supplied by the home and grounding transformer is used chiefly for directional discrimination and not for time selectivity; therefore, a small grounding bank can be used if necessary, particularly at the receiving end of the loop.

The standard wiring scheme for Fig. 4 is as follows: The secondary of the neutral current transformers goes through the upper elements of two directional ground relays in series. The lower elements of both relays are in series and are connected to the bushing current transformer secondary neutrals in multiple. These bushing current transformers and relays have symmetrical polarity but are reversed at the common or multiple connection so that the lower elements of the relays receive the difference of the residual line currents when ground current is going out of both lines. When ground current is feeding through, the residual currents in both lines add in the relay circuit. The characteristics of this connection are as follows:

With both lines in service and either line in trouble, and the loop open at the far end, the bad line trips correctly and very quickly. With both lines in service and the loop closed at the far end, the line carrying the heaviest fault current trips correctly but very slowly, giving opportunity for the other end to clear and relieve the fault current on the good line. If both lines are in service and in trouble and the fault current is balanced, neither switch will operate. If the home bus is in trouble and the line fault currents are balanced, neither switch will trip. If the home bus is in trouble and the line fault currents are unbalanced, the line carrying the smallest current will trip slowly. The other line will not trip. With only one line in service and in trouble, this line will relay satisfactorily unless the trip circuits

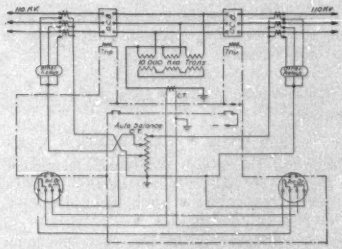


Fig. 4—Directional Ground Protection on Loops

are interlocked. If the bus goes in trouble with only one line in service, this line will not trip at that end.

This connection will not operate correctly if there are other lines off of the bus at the home end unless some means is provided for making both lines directional. This can be done by standard directional ground relays used as locking relays on the trip circuits.

This scheme may require series "A" switches or

standard locking relays if used on a loop of three or more links so as to prevent the second line tripping too quickly after the first. However, series "A" switches are not desirable at the power supply end of a loop as they do not give single line protection except on back up relays. For such installations, locking relays are better as they will restore directional ground protection on the second line in a few seconds. If one end of the balanced lines is without power supply, protection on the second line for single line operation is usually immaterial.

### Directional Ground Protection on Auto-Transformer Ties

Fig. 5 shows an application of directional ground relays to auto-transformer stations or other stations, where the grounding transformer neutral is not brought out but is grounded inside the transformer case. In general this scheme is applicable only to stations with only two transmission lines. It is particularly suitable for auto-transformers with high reactance windings and wide difference between high and intermediate voltages, especially if the intermediate voltage ties closely into a heavily grounded system.

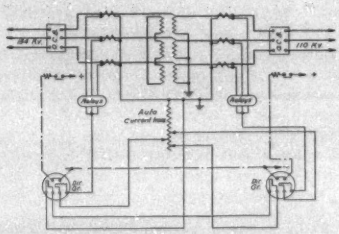


Fig. 5—Directional Ground Protection on Auto-Transformer Ties

In case of a fault on the high-voltage side, such an installation may result in zero or reversed ground current in the auto-transformer neutral, due to the large amount of ground current put out by the intermediate voltage system. The neutral current is, therefore, not suitable for directional discrimination and some other references current must be obtained. Delta current is difficult to get, especially if the auto-transformer is used to supply a load from the delta winding.

The scheme of connections shown in Fig. 5 provides excellent bus protection. No neutral current transformer is required. The scheme is applicable to auto-transformers regardless of ratio. It is very similar in operation to the balanced ground relay scheme for auto-transformers. The line bushing current transformers are connected with symmetrical polarity and are connected symmetrically to the lower elements of their respective directional ground relays. The bushing current transformer neutral circuits are then connected totalizing so that the upper coil would receive the sum of the line currents if both lines were feeding out. On through feed, the upper coil receives the difference of the line currents, which is the ground current put out by the station. In case of auto-transformers, it is necessary to install an auto-current transformer in one current transformer secondary before the multiple connection is made. If there is no reversal of neutral current, this auto-current transformer can be set in the ratio of voltage transformation of the power transformer so as to cancel out the through ground current.

This scheme operates correctly with either line in trouble. It also gives perfect bus protection with one or both lines in service, whether they are balanced or not. This is a disadvantage on loop circuits and this scheme should not be used in place of balanced relays on a loop or parallel lines. It is satisfactory where the outgoing circuits are not connected together at any other point for any appreciable interchange of ground current. This scheme, naturally, will not operate if there is no supply or fault current at the station, but it functions satisfactorily with one line out of service and will trip on either bus or line trouble. The relays work rapidly when current is going in the same direction in the two lines and as fast as ordinary directional ground relays connected in the ordinary manner using a current transformer in the transformer neutral. This plan provides the same current in the upper element of the relay on single line faults and in the same direction as a neutral current transformer does. However, in case of both lines being in trouble, the sum of the two line currents flows in the lower elements providing very fast operation. If the bus goes in trouble, the current is in the opposite direction to that provided by a neutral current transformer, resulting in very fast bus protection.

This scheme is particularly useful where the power transformer neutral is not brought out, or where a proper ratio neutral current transformer cannot be obtained, or where the direction of current in the neutral is indeterminate. In the last case it has the same advantage of using circulating current in the delta for polarizing directional relays, but is independent of the delta load current and has the same other advantages mentioned above. Since the line current transformers are usually of considerably lower ratio than neutral current transformers, it provides much more current for the directional ground relays and may require special relays to get high enough settings. It is particularly advantageous on an auto power bank because auto-current transformers can be used to step up the current on one side enough to prevent a net reversal.

If there are additional lines off of the bus besides those from auto transformers, some sort of locking scheme must be used, as a fault on a third line is similar to a fault on the bus.

### Balanced Ground Protection on Auto-Transformer Ties

By using a balanced ground relay of the *C D* or *I J* type in place of the two directional ground relays described above, there results a very simple and effective protection for auto-transformers having only one line from each of the two auto windings. This is shown in Fig. 6. An auxiliary auto-current transformer may be used in the current-transformer secondaries on either

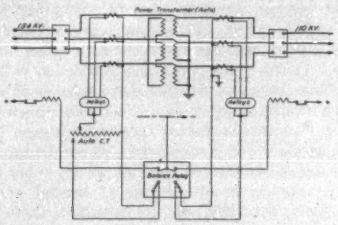


Fig. 6—Balanced Ground Protection

side of the balanced ground relay, so as to compensate for the ratio of transformation of the auto-transformer and also for any difference in current transformer ratios. This results in the flow of ground current through the auto-transformer balancing out in the relay circuit, leaving only the fault current put out by the auto-transformers to operate the balanced ground relay. The current will appear in the side of the relay toward the fault, thus making the balanced relay directional for

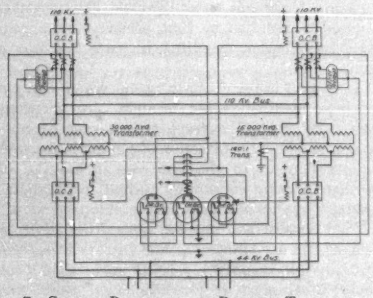


Fig. 7—Ground Protection of Bus and Transformers

ground protection. Although this scheme provides very little in the way of bus protection, it is very simple and effective for directional ground protection of outgoing lines tied through an auto-transformer.

### Ground Protection of Bus and Transformers

Fig. 7 shows a scheme for securing fast ground protection on a high-tension bus and high-tension transformer windings without differential protection. Such a scheme is in use at one of our substations where there are two high-tension lines. Three-directional ground relays have the upper coils connected in series to a 15,000-volt current transformer in the neutral of the 110-kv. grounding bank. Two of these directional ground relays are wired as in Fig. 2 and are used as directional ground relays on the two outgoing lines. After going through these relays the neutral of the bushing current transformers are commoned in such a way that the ground currents will add on an infeed to the bus from each line. This common connection is taken through a third directional ground relay which operates through an auxiliary relay to open the line switches and the low side switches on the transformer bank.

This scheme provides fast protection against failures to ground on the bus or high-tension windings of the transformer. It assumes that a source of ground current is available at the other end of each outgoing line. Combined with low side ground relays as shown on Fig. 8 it provides a very satisfactory substitute for

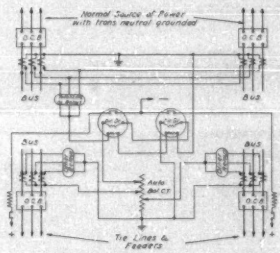


Fig. 8—Directional Ground Protection Without Grounding Transformers

differential protection since practically all bus and transformer troubles either start with failure to ground or develop into such almost immediately.

### Directional Ground Relay Protection without Grounding Transformer

In Fig. 8 the ground current fed into the station from the two parallel lines is used to polarize ground relays on two other outgoing lines. Current transformer neutrals from the two incoming lines are connected in parallel and taken through the upper coils of the directional ground relays. In the simple case the neutral of each outgoing line is taken through a directional relay on that line. In Fig. 8 the two outgoing lines form a non-symmetrical loop between four stations, and a scheme of cross connection together with a balancing auto-transformer as shown in Fig. 4 is used. The polarizing of directional ground relays by this scheme requires that a supply of ground current be available at the far end of the two incoming lines and that at least one of these lines be in service at all times. As a substitute for a grounding

bank the scheme has the objections that current transformer ratios are fixed by requirements of metering, other relays, etc., and also that with one incoming line out of service the amount of polarizing current may be small and relay operating time correspondingly increased.

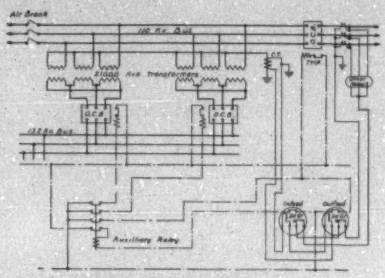


Fig. 9—Directional Ground Protection on Two Lines with One Oil Circuit Breaker

## Directional Ground Protection on Two Lines with Only One Line Breaker

Such protection as shown in Fig. 9 is possible through connections similar to those in Fig. 7. Two directional ground relays are used with the upper coils connected in series to a current transformer in the neutral of the power bank. The neutral circuit from the bushing current transformers on the line breaker is taken through the lower coil of these two relays in series in opposite directions. This scheme considers the section

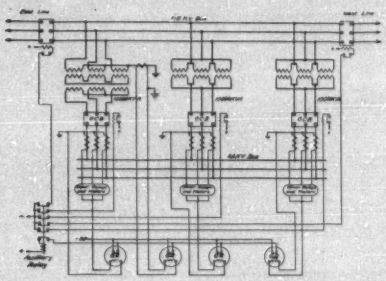

Fig. 10—Ground Protection of Transformers and High Side Bus

of line tied to the bus through the air break switch as part of the bus. As in Fig. 7 this scheme requires a source of ground current at the other end of the line which is equipped with a breaker. The scheme is not as fast on bus or transformer trouble as Fig. 7 since there is no totalizing of ground current. Of course it does not afford transformer protection against power fed in on the line which has no breaker.

Potential operated directional ground relays can also be utilized, instead of current operated directional ground relays as suggested.

## Transformer and Bus Protection

Fig. 10 shows how plain ground relays may be used to secure the equivalent of differential protection. A ground relay is connected in the neutral current transformer secondary in the high side neutral ground lead. Ground relays are also connected in the neutral of the current transformers on the low side. Trip circuits of all of these relays operate an auxiliary relay to trip all sources of power to the high-tension bus and transformers.

This scheme requires that the low side bus be supplied by generators with grounded neutral or some other source of ground current. Relays can be set very fast for grounds on the low-tension windings. The protec-

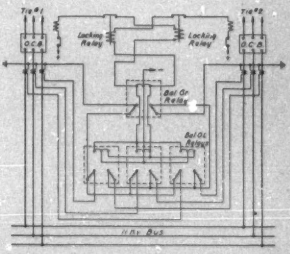


Fig. 11—Locking Relays for Balanced Line Protection

tion afforded on the high tension windings is necessarily slow since the ground relay must be selective with line relays. In this installation at Great Falls only one transformer has its neutral grounded. This scheme therefore requires that this transformer be kept in service at all times. The high-tension ground relay also affords back-up protection for the line relays in case the breaker is by-passed or the relays fail to function.

## Locking Relays for Balanced Line Protection

Where balanced relays without interlocking are used on parallel tie-lines or double-circuit lines many cases have occurred where both lines would relay when only one line was in trouble due either to mechanical back lash in relays or to difference in speed of relay or breaker operation on the two ends of one line. To overcome these troubles it is necessary to interlock the trip circuits so that when one line opens the other line cannot open at the same station for a second or two. Fig. 11 shows

how this can be accomplished by use of locking relays. These relays prevent false operation and at the same time restore protection on the second line in a few seconds. The trip circuits may be interlocked through *A* switches on the breakers, in which case protection is not restored until both lines are in service. In this case some kind of back up protection is needed for single line operation.

Interlocking on loops can be obtained with directional ground relays as described in Fig. 2 with additional advantages. They prevent operation on surges and on backfeed into trouble on a third line when the infeed current will not necessarily be balanced.

### Ground Protection without 11-Kv. Breaker or Current Transformers

In Fig. 12 a current transformer and ground relay in the neutral of a small 11-kv. grounding bank furnishes ground protection for a rural feeder fed from the delta power bank. As long as there is only one 11-kv. line a circuit breaker on the 11,000-volt side of the power bank is not required. This scheme illustrates a relatively inexpensive method of ground protection on rural

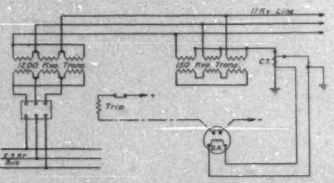


Fig. 12—Ground Protection to 11-Kv. System Without 11-Kv. Oil Circuit Breaker or Current Transformers

feeders. Schemes of this and a similar nature have been used in a number of instances where the load was small and more expensive installations could not be justified. As the mileage of connected 11-kv. line increases the scheme becomes less satisfactory due to the small capacity of the ground bank and its inability to maintain the entire system with balanced voltage to ground.

### High Speed Relaying

With the advent of circuit breakers which are intended to clear faults in from 3 to 10 cycles compared with 20 to 60 cycles heretofore, it is very evident that some marked changes in relay protection will have to be worked out immediately. In so far as the necessary changes to get high-speed relaying can be applied to existing relay installations, there will be a marked saving to the industry and a much more prompt adoption of high-speed switching. A high-speed breaker is of little use unless it is operated by high-speed relays, so as to decrease the total time of duration of the fault. In systems where cascaded time settings are used extensively, high-speed breakers and relays cannot be used in certain locations without seriously imparing the protection at other points. Immediate study should therefore be given to the effect of high speed relaying at certain locations and to the possibility of speeding up relay operation at all possible points. It will be found that ground relays are much more susceptible to improvement in this regard than are phase relays. In some locations, the minimum settings of phase relays are determined by starting currents on large motors and cannot be materially lowered.

For nearly a year the authors have been experimenting with faster ground relay settings, and have found the following limitations in present equipment:

1. Back lash is the most serious design defect in directional ground relays. In some cases directional ground relays will close whenever several times pick-up current is sent through their windings in the opening direction and suddenly cut off. This is due to spring and back lash in the various portions of the mechanism which return energy to the disk when released. A special design of mechanism has already been brought out by one manufacturer to eliminate this trouble.

2. The closing adjustment of the three poles of oil circuit breakers is a very important point in connection with high-speed relaying. On a multi-grounded neutral system, the closing of any loaded circuit on only one or two of the three phases will circulate ground current. It is manifestly impossible to adjust circuit breakers so that all three poles will close at the same instant. Frequently breakers get out of adjustment between poles as much as several cycles and this results in heavy ground currents during the closing operation. This factor will always prevent the application of instantaneous relays to high-speed switching.

3. Synchronizing surges. Even with automatic equipment it is impossible to prevent heavy surges of a few cycles duration when paralleling machines and systems. Ground relays are not affected appreciably by synchronizing except in connection with breaker adjustment as noted above.

4. Most present relays have enough inertia in their moving parts that it is difficult to close them in less than 5 to 10 cycles regardless of the time lever setting. At low time settings there is no proportionality between time setting and actual time of operation and it is difficult to get an inverse time lever characteristic with current.

5. Rebound or chattering of the contacts may occur if very high torque is used to get fast operation.

It would be fairly easy to design and use high-speed relays and high-speed breakers if a whole system could be changed over to this equipment at once, but in many cases it is going to be extremely difficult to use high-speed switching and relaying on one part of a system and the present day types on the rest of the system. It would therefore be advantageous to speed up the relays as much as possible on all present installations so

that the gradual changeover to high-speed switching will not mean so much revision in the protective system as a whole.

### Records of Fault Current

No matter how well relays are designed and how carefully they are installed and tested and no matter how well the settings are chosen, it is impossible to predetermine all the fault conditions that the relays may have to take care of. It is therefore, absolutely essential to watch the operation of relays in service and to know when they operate and how fast they operate, particularly in complicated transmission networks.

Various types of equipment are now available for recording fault current and other electrical data. Records from such equipment have been found to tell considerable about relay settings, breaker performance, fault phenomena, and the operation of the system including the activities of the station personnel.

The most unexpected and valuable information from such equipment has been the approximate location of permanent line trouble on high-voltage transmission lines. In many cases troubles have been located within two or three miles and it is almost always possible to tell which end of the line patrol should start from in order to locate the fault most promptly.

The records from this equipment have also given fairly complete evidence that there are no surges or flashovers or other faults to ground which clear up without relaying at least enough points to materially reduce the voltage across the fault. Those records have also shown that the relays do not work except when there are faults to be cleared. Both of these points have been under discussion during previous years in connection with ground relay protection.

The two general types of equipment for recording fault current are curve drawing ammeters and oscillographs. The outstanding advantages of the high-speed graphic ammeter are its lower cost, and the instant availability of the record. The advantages of the oscillographic equipment are the much more accurate record, response to variations in fault current, and the fact that the oscillographic equipment gets into operation much more rapidly, therefore recording the first portion of the disturbance. Another advantage of multi-element oscillographic equipment is that simultaneous records of current and voltage can be obtained in their proper phase relation, permitting a determination of power factor, etc.

Either type of equipment is well worth while, and the first is probably more suitable for installation at all important stations on the average system. On account of the increased cost and slightly higher grade maintenance required, oscillographic equipment is better suited to the more important high-voltage stations or to stations where unusual trouble has been experienced and accurate records are necessary.

### Staged Tests

As power systems interconnections become more frequent and more complicated, it is likely that some of the simpler and better known relay schemes will prove inadequate. The chief objection to many of the more complicated relay schemes is that they are difficult to test out and to put into operation with the proper connection and settings. It is a difficult problem to phase relays by using low-voltage test current or by using normal load current so that they will operate properly with system voltage fault currents of great magnitude under abnormal conditions. While secondary testing is reasonably adequate for plain overload and ground relays, it is slow and difficult for reverse power and impedance relays, or any other relays having potential connections.

To get away from such difficulties in connecting up and testing out important relay schemes, especially if complicated, several power systems have been checking such installations by actually placing faults on the power system, and having the relay test men watch the operation of the relays, read portable meters, and get oscillographic records. This procedure tells the whole story as to the operation of the protective equipment at all stations involved under actual operating conditions.

The making of such staged tests is one of the most powerful and effective ways of securing the proper operation of relays and other protective equipment. The time and cost involved is usually small and in many cases has been found to be less than the cost of checking out installations by low-voltage tests. Low-voltage tests usually involve a lot of vector diagrams and long arguments as to phase rotation, power factor of the load or interconnection, polarity, correctness of manufacturer's data, etc. Even after low-voltage tests are made in the best manner possible by high grade men, there often result unexplainable errors in connections, and these are usually not detected until the protective equipment fails to operate properly in service. Oftentimes such an installation is then changed radically without much analysis or investigation, and further incorrect operations may result. However, with staged tests, it is generally possible to put the equipment into service with the positive knowledge that it is operating properly, as any errors are almost certain to be discovered on the first staged test and can be corrected and checked on subsequent tests.

Arguments in favor of staged tests have been presented before the A. I. E. E. on several occasions. One of the first articles outlining the advantages of staged system tests was that of Messrs. Sporn and St. Clair, A. I. E. E. Trans., Vol. 46, Feb. 1927, pp. 310, 311, and 314. Those companies which have used such tests for relay work seem to be thoroughly convinced of their value and are now making such tests more frequently than ever before.

Many staged tests for checking relay operation have

been made by the Duquesne Light Company and these have been described in various publications.[3-6]

In some cases it has been found advantageous to check relay connections for the first time by staged tests without making any attempt to determine the proper connections by vector diagrams or by low-voltage tests. In any case the staged test is the final authority, and if a staged test can be made immediately after the new installation, without undue trouble or expense, there is very little reason for men on the drafting board or in the construction department spending the time usually required to figure out the proper connections beforehand.

It should not be assumed that staged tests can be used under all conditions for all relay installations, but it is suggested that considerable benefit may be had by considering every installation as to the possibility of checking by staged tests and making such tests wherever practicable. Where such tests cannot be made, it is of course, necessary to fall back on the usual methods of calculations and low-voltage test.

## Test Facilities

Very shortly after induction relays began to be installed on switchboards there arose a need for a quick and safe way of testing relays and other switchboard instruments without taking high-voltage equipment out of service, without interfering with the operation of the power system, and without removing the protection any longer than absolutely necessary. Various types of test switches, test studs, test jacks and other devices have been used. Any of them are well worth while, but there is a great difference between the various types of such equipment.

## Methods of Testing Ground Relays

Although the connections to plain ground relays can be checked with an ammeter, the use of balanced relays, directional ground relays, etc., makes some more elaborate check of connections necessary. Oftentimes the engineering department will spend considerable time in checking detailed wiring diagrams and attempting to lay out the wiring diagram so that directional relays will be correctly phased when installed. This may save the construction department some time if the drafting room work and construction work is carefully done. However, there is always a doubt as to correctness of the connections until it is definitely proven by the operation of the relays. More reliable results can be obtained by either phantom or staged tests.

A number of years ago the company with which the writers are connected established the practise of checking bushing current transformers, relays, etc., by phantom tests which consisted in clearing the equipment and putting low-voltage test current through it. Originally, sign lighting transformers were used for supplying this current, but special transformers were later bought which were much more flexible and with which currents as high as 1000 amperes could be obtained. This method has been in successful operation for two years.

In phasing directional ground relays by such tests, it is necessary to put test current through the breaker and also through the current transformer in the neutral ground lead. A careful check of all connections is necessary to be sure that the test current is in the proper relative direction in the breaker and in the neutral current transformer. Such tests have been very valuable in phasing relays and checking the breakdown of bushing current transformers, particularly in cases where the transformers were of poor design or the relay burden in the neutral was large. In some cases, we have found the bushing current transformer ratio to ground current was as much as 150 per cent of that to phase current. The data so obtained have been most valuable in obtaining necessary selectivity and coordination of settings.

These phantom tests have been very useful and are still being made on practically all directional ground installations as a check of current transformer ratios, connections, etc. Possibility of mistakes in test connections, the chances of a reversal of current in the transformer neutral in normal operation and other such factors make an actual staged test at normal voltage the most satisfactory check. These tests were begun on this system about four years ago and several hundred such tests both phase-to-ground and phase-to-phase have been made.

Staged tests at normal voltage are made if possible with two breakers in series and with reduced generation or with a switching setup such that the currents obtained are far below the breaker capacity. It is significant that such a large number of short circuits and grounds can be placed on a system with practically no damage to equipment and without serious effect on system load.

Some of the many benefits obtained from these tests are given below.

1. An over-all check is obtained of the correctness of relay wiring and phasing.
2. Any unsuspected characteristics of relays may be discovered by watching their operation under actual fault conditions.
3. The test results furnish a check on the method of calculating fault current.
4. By such tests may be found any unusual distribution or direction of current flow. The tests have explained several supposedly wrong relay operations by

3. *Selective Relay System of the 66-Kv. Ring of the Duquesne Light Company*, by H. P. Sleeper, A. I. E. E. Trans., Vol. 42, p. 513.

4. *Ground Relay Protection for Transmission Systems*, by G. B. Dodds and B. M. Jones, A. I. E. E. Trans., Vol. 46, p. 847.

5. "Field Testing of Relays," by W. M. Evans and R. J. Salsbury, *Electrical World*, March 17, 1928.

6. "Direct Benefits of Field Testing of Relays," by B. M. Jones, *Electrical World*, May 5, 1928.

discovery of new factors which made necessary a change of relay application.

5. Valuable data have been obtained on the effects of arcs on conductors and the consequent necessity for clearing troubles quickly.

6. Many data have been secured on arc and ground resistance. Results so far indicate that these factors may reduce the amount of ground current on distribution lines but apparently do not materially affect relay settings or fault power factor on high voltage lines.

7. The tests have shown that distribution lines may stay in trees with hazard to linemen for considerable time and not take enough ground current to operate the most sensitive ground relays now available.

8. The tests have been used to check the ability of station ground systems to carry sustained ground current.

9. Tests have indicated that a ground chain on a high voltage line does not give adequate protection to workmen if a line is accidently energized.

10. Such tests have been used to determine the performance of various types of insulators under heavy arcs.

11. One of the greatest benefits has been an increase in the morale and efficiency of the dispatching organization. The dispatchers have been present on many tests and become familiar with relay performance, possible troubles, test procedure, etc., and are therefore much better qualified to handle system troubles.

## Operation of Special Relay Schemes

The tabulation herewith shows the operating record of the various relay schemes previously described. This record includes all the installations of the special schemes but includes only two of the many installations of plain directional ground relays.

The incorrect operations for scheme two are due to the following causes. Incorrect connection of the relays caused four incorrect operations, all when the equipment was first installed. Two operations were due to a relay being grounded when the substation was flooded to a depth of several feet. There was one case of bus trouble which caused an incorrect operation, as this scheme does not cover bus protection. There was another case of tripping on through trouble on the 66-kv. system which ties to the 110-kv. system through low-reactance auto-transformers. This scheme does not automatically take care of such a situation, and the settings on the 66-kv. system had to be changed. One incorrect operation was due to a mistake by a relay test man. One operation was due to unusual operating conditions which the scheme was not designed to meet. This particular condition was unnecessary and would not have been used if the relay scheme had been better known by the load dispatcher. One incorrect operation was due to inadequate system planning, as a 150-mile section of transmission line was not provided with a breaker, and the ground current at the far end was too low to operate any relay.

Four incorrect operations of Scheme 4 were due to defective relays. Scale from the magnet lodged between the magnet and the disk, binding the relay disk. Two incorrect operations were due to poor relay settings and three to mistakes on the part of the relay men.

Six incorrect operations of Scheme 7 were due to incorrect relay connections, one to a mistake by a relay test man, one to unnecessary operating conditions, and two to poor system planning.

One incorrect operation of Scheme 9 was due to a mistake in phasing while installing relays. The second

| Figure | Scheme | Station | Voltage | Months in service | Correct operations | Incorrect operations |
|---|---|---|---|---|---|---|
| 1 | Directional ground | Ocoee No. 1 | 66,000 | 37 | 136 | 12 |
| 1 | Directional ground | Great Falls | 44,000 | 19 | 37 | 0 |
| 2 | Cross connected directional ground | Washington | 110,000 | 20 | 101 | 3 |
| 2 | Cross connected directional ground | Arlington | 110,000 | 4 | 28 | 1 |
| 2 | Cross connected directional ground | Great Falls | 110,000 | 5 | 18 | 5 |
| 2 | Cross connected directional ground | Ridgedale | 44,000 | 13 | 8 | 0 |
| 2 | Cross connected directional ground | Ocoee No. 1 | 110,000 | 12 | 43 | 2 |
| 3 | Directional ground for auto transformers | W. Nashville | 154,000 | 5 | 6 | 0 |
| 4 | Balanced ground for auto transformers | Lenoir City | 110,000 | 16 | 132 | 9 |
| 5 | Directional ground bus protection | Ridgedale | 110,000 | 3 | 0 | 0 |
| 6 | Directional ground without star transformer | Carter St. | 44,000 | 7 | 10 | 0 |
| 7 | Directional ground without line breaker | Ridgedale | 110,000 | 28 | 143 | 10 |
| 7 | Directional ground without line breaker | S. Nashville | 110,000 | 5 | 8 | 0 |
| 8 | Bus protection | Great Falls | 110,000 | 11 | 0 | 0 |
| 9 | Locking relays | Ocoee No. 1 | 110,000 | 12 | 43 | 2 |
| 9 | Locking relays | Ridgedale | 44,000 | 13 | 8 | 0 |
| 12 | Low side ground protection | Murfreesboro | 11,000 | 22 | 66 | 2 |
| 12 | Low side ground protection | Cleveland | 11,000 | 12 | 19 | 1 |
| 12 | Low side ground protection | Centerville | 154,000 | 5 | 0 | 0 |
| | | | Total | | 806 | 47 |

was due to 110-kv. bus trouble which the scheme does not protect against.

One incorrect operation of Scheme 12 was due to a defective relay and two were due to inadequate construction work.

The total incorrect operations was 47 and the correct operations 806, giving an accuracy of 94 per cent. The plain directional ground relay operation is, of course, much more accurate as there are very few chances of wrong connections or poor settings, as these relays are relatively easy to install, phase, and set correctly. It is interesting to note that nearly all of the above incorrect operations occurred during the first few months that each scheme was in operation. As soon as incorrect operations occurred staged tests were made, and these usually resulted in finding the relay trouble and clearing it permanently.

In general, incorrect operations occurring after a scheme has been in service during one lightning season are usually due to poor system planning, defective relays, flood conditions, etc., rather than to wrong connections, poor settings, or inadequate types of relays.

## Conclusion

Experience seems to show that ground relay protection is almost paramount on high-voltage transmission systems. On many systems the benefits of ground protection have been extended to lower voltage lines and it is recommended that more general use of ground protection be made on systems of all voltages. Ground relay protection possesses great flexibility of application and can be adapted to the further developments in protection which will undoubtedly occur shortly. The advent of high-speed ground relaying is just around the corner. In developing the relay schemes described above considerable experimental work was done and several of them were modified following tests at system voltage. It is suggested that experimental work of this kind be encouraged on many systems to further the development of protection schemes.

## Discussion

**J. H. Nehler:** It may be well to mention a system of ground relay protection which is being used on the Philadelphia Electric Company's 220-kv. system and on the 220-kv. interconnection with the Pennsylvania Power and Light Co. and the Public Service Electric and Gas Co. The lines are equipped at each end with instantaneous plunger type over-current relays connected in the residual circuits. These relays are given settings slightly higher than the maximum through fault ground currents which can be calculated for the various lines under any possible operating set-ups.

The operation of these relays is similar to that of the first step of the step-by-step impedance relays except that the portion of the line over which instantaneous operation is secured is not constant but varies with the system set-up. Faults occurring beyond the limit of the protection of the relay at one end of the line will fall within the limit of protection of the similar relay at the other end where instantaneous operation will result. In the case of a system solidly grounded at all relay points, the redistribution of the zero phase sequence current after the line has been opened at the distant end, is such that an increased flow of ground currents through the relay under consideration will cause it to operate. In this manner sequential tripping on ground faults at the line ends is secured exactly as in the case of parallel lines equipped with balanced ground relays.

If these relays are non-directional, it is necessary to set the relays at each end of a given line at the same value determined by the maximum through fault ground current possible in either direction. By making them directional it is possible to take advantage of a lower setting at one end of the line. This has been done by introducing the contacts of a directional element into the trip circuit. One operating coil of this element is connected into the residual circuit of the line and the other coil to a current transformer placed in the station neutral. By this means the directional action is obtained.

A high-speed ground relay of this type comprising a directional and an over-current element has been developed which has an operating time of approximately one cycle.

**H. H. Spencer:** In regard to the use of directional ground relays as discussed by Messrs. George and Bennett there are in general two methods of establishing the phase of the ground current in a circuit. The more common method is to use a relay energized through current transformers by the residual current in the circuit protected and the current flowing in the neutral of a grounded-$Y$ bank of transformers located in the substation with the relays. The torque of such a relay is, therefore, determined by the vector product:

$$I_{OL} \cdot I_{OT}$$

where $I_{OL}$ is the zero sequence current in the line and $I_{OT}$ is the zero sequence current in the transformer. The less usual method is to use a similar relay except that instead of being energized from the current in the power transformer neutral the second winding is energized from a wye-delta potential transformer, so that the torque of the relay is dependent upon the vector product:

$$I_{OL} \cdot E_O$$

where $E_O$ is the zero sequence voltage of the system at the point where the relays are installed.

The use of auto-transformers in place of two-winding transformers in the power banks frequently introduce a difficulty. There are two circuits for zero sequence current, one circuit involves the faulted system and the transformer, the other circuit involves the faulted system and the unfaulted system. Now if:

$X_{OA}$ = zero sequence reactance of the unfaulted system including the equivalent reactance of the auto-transformer winding connected to it

$X_{OB}$ = zero sequence reactance of the common portion of the transformer winding.[1]

There is a critical value of $\frac{A_{OB}}{X_{OA}}$ which will result in no current flowing in the auto-transformer neutral. This is when:

$$X_{OA} = X_{OB}\,(a - 1)$$

where $a$ is the ratio of transformation of the auto-transformer. With a lower value of $X_{OB}$ the current of the outer transformer neutral will actually reverse and result in a faulty operation of the relay.

It appears that the use of the other type of relay never results in these difficulties but it has the disadvantage of involving three potential transformers.

**R. H. Bennett:** Mr. Spencer's point regarding zero or reversed ground current in auto transformer neutral has been

1. I. H. Summers and J. B. McClure, *Progress in the Study of System Stability*, A. I. E. E. Transactions, Vol. 49, Page 132.

recognized and encountered by the writers. Fig. 5 in the paper, deals with a method by which this condition can be met using directional ground relays with two current elements. In this case a current transformer in the power transformer neutral is not used. An auto balancing transformer in the neutral of the line current transformers is used to balance out the through feed of zero sequence current leaving the zero sequence current supplied by transformer bank to polarize relay. Such a scheme has been in satisfactory operation on this system for over a year.

The directional ground relay polarized by wye delta potential transformers has been used by many companies. However, this scheme also has its objections due to variations in the power factor of the fault, and variation in power factor in cases of simultaneous faults on different phases.

# Electric Power Consumption for Yard Switching

BY P. H. HATCH[1]
Member, A. I. E. E

***Synopsis.***—*In the application of various types of locomotives to switching service, it is at times quite desirable to have data concerning the energy requirements involved. A convenient figure for expressing such requirements in relation to work done is watt hours per ton-mile.*

*The determination of such a figure involves certain difficulties peculiar to switching service, in that trailing loads and distances moved are continually varying.*

*The electrified Oak Point Yard of the New York, New Haven & Hartford Railroad in New York City offered an excellent opportunity for determining figures of watt hours per ton-mile for different kinds of switching. Accordingly two electric locomotives were equipped with the necessary instruments, and a total of 39¼ hr. of operation was observed and recorded.*

*The paper describes in some detail the entire procedure of the tests and lists in tabulated form the data obtained.*

*Basic figures necessary for calculating watt hours per ton-mile, it was found, could be expanded to give a much broader scope to the results, so that many interesting data became available. Incidentally, the data will permit of even further expansion where certain special figures or factors are desired.*

*Although electric locomotives of different types were used, the results set forth in the paper should be considered without regard to either type.*

*It is hoped that data concerning switching operations on other railroads may become available.*

* * * * *

## I. General

In the case of electric locomotives operating in road, passenger or freight service the problem of determining the power consumption per unit of work done has not been difficult. From one end of a given run to the other train weights undergo few, if any, changes; if they do, such changes are easily accounted for. Distances present no problems of measurement, nor do meter readings necessary for computing total energy. In other words, power consumption per unit of work done or (to use a more familiar expression) watt-hours per ton-mile, present no especial difficulties in such cases.

Where watt-hours per ton-mile are desired for switching service, however, the problem becomes radically different. This is because where the number of cars has changed from the previous move, tonnage and distance must be determined for every individual move that the switch engine makes. It takes little imagination to understand that this makes necessary the calculation of ton-miles practically every time the switcher moves; the frequency of such moves in a busy yard is quite apparent.

A reasonably accurate figure of watt-hours per ton-mile for switching service is of use in many ways. It is, for instance, helpful in figuring battery capacity necessary for a storage battery switching locomotive, where the switching service to be handled by the locomotive is known. Also in the case of the oil or gasoline electric switcher, some idea of fuel quantities necessary for a given service may be obtained. Similarly in the case of applying an electric switcher to a particular location, advance information relative to power requirements can be determined. Still another side of the matter is disclosed when it is considered that watt-hours per ton-mile for a given locomotive in a given service may be taken as an approximate index of performance. Other uses of the watt-hours per ton-mile figure for switching service are readily possible.

It should be emphasized at this point that the tests herein described had for their primary object the determination of energy consumption (based on a sufficient number of hours of service) in terms of watt-hours per ton-mile for various classes of yard switching, without regard to type or types of electric locomotives used.

## II. Description of Test and Apparatus

In order to arrive at definite facts regarding the power consumption per ton-mile for electric switching locomotives, a series of tests was run in the Oak Point Yard of the New York, New Haven and Hartford Railroad in New York City. This yard is devoted primarily to classification work in connection with the interchange business with the Erie, Lehigh Valley, Central New Jersey and Lackawanna Railroads, such business being carried on between the various harbor terminals by means of car floats. There are in general, therefore, two distinct kinds of service performed by the switching locomotives in Oak Point Yard, namely, float loading and unloading and general switching and classifying.

Oak Point Yard is roughly Y-shaped. The foot of the Y is at the north end, the south end branching out to serve the eight float bridges, together with various shop and yard tracks between the farthest bridge track on the east and the six-track Harlem River Branch on the west. Fig. 1 gives a general view of the mid-section of the yard looking south.

The switching locomotives operating in this yard have varied duties. No one locomotive is assigned to a definite class of work. Classifying, float pulling and loading, switching the shop tracks, pushing outgoing trains, etc., are some of the services each engine may be called upon to perform.

1. Engineer of Automotive Equipment, The New York, New Haven and Hartford Railroad Company, New Haven, Conn.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*



30-94

For the purposes of the test, it was decided to equip a locomotive with the necessary test instruments and then have the engine put into normal service, neglecting the test entirely so far as the engine and crew were concerned. It was thought that this would give the most comprehensive results for the test, as well as burden the yard forces and engine crews as little as possible. To the men running the test was left the classification of results according to service.

For measuring watt-hours, the regular locomotive

Fig. 1—General View of Oak Point Yard

(Note curved classifying tracks at left)

watt-hour meter was utilized. It was calibrated both before and after the test. For determining distances moved, a magnetic counter was used in conjunction with dry cells and a contact-making device mounted in

Fig. 2—Electric Switching Locomotive Used in Oak Point Yard

the end of one of the locomotive axles. From readings of the counter the number of revolutions of the wheel was determined, from which were calculated the distances moved.

The contact-making device was home-made, consisting of an automobile timer fitted with a special flange for attaching to the axle hub. Throughout the period of the test, this device functioned satisfactorily and made possible very accurate distance determinations.

The test was run in two periods of three days each. Two different locomotives were used, one for each period. The same test procedures were followed and much the same classes of work were performed by each. Each locomotive operated from the 11,000-volt a-c. single-phase supply. Specifications for the two locomotives follow:

106-Ton Electric Switching Locomotive

| | |
|---|---|
| Classification | B + B |
| Energy supply | 11,000-volt, 25-cycle, single-phase, a-c. |
| Type of conductor | Overhead |
| Total weight of locomotive | 211,500 lb. |
| Total weight on drivers | 211,500 lb. |
| No. of driving wheels | 4 |
| Diameter of driving wheels | 42 in. |
| Total wheel base | 25 ft. 0 in. |
| Rigid wheel base | 8 ft. 3 in. |
| Length over coupler faces | 38 ft. 3 in. |
| Height over pantagraph locked down | 14 ft. 8 in. |
| No. of motors | 4 |
| Type of motors | D-c. series (d-c. from motor-generator set) |
| Drive | Gear |
| Gear ratio | 17:72 |
| Tractive effort, hourly rating | 23,200 lb. |
| Speed at hourly rating | 8.1 mi. per hr. |
| Tractive effort, continuous rating | 14,500 lb. |
| Speed at continuous rating | 11.4 mi. per hr. |

90-Ton Electric Switching Locomotive

| | |
|---|---|
| Classification | B + B |
| Energy supply | 11,000-volt, 25-cycle, single-phase, a-c. |
| Type of conductor | Overhead |
| Total weight of locomotive | 181,000 lb. |
| Total weight on drivers | 181,000 lb. |
| No. of driving wheels | 4 |
| Diameter of driving wheels | 63 in. |
| Total wheel base | 23 ft. 6 in. |
| Rigid wheel base | 7 ft. 0 in. |
| Length over coupler faces | 39 ft. 1 1/8 in. |
| Height over pantagraph locked down | 14 ft. 3 7/8 in. |
| No. of motors | 4 |
| Type of motors | A-c. commutator type series |
| Drive | Gear quill |
| Gear ratio | 17:101 |
| Tractive effort, hourly rating | 23,200 lb. |
| Speed at hourly rating | 8.1 mi. per hr. |
| Tractive effort, continuous rating | 14,500 lb. |
| Speed at continuous rating | 11.4 mi. per hr. |

Weather and rail conditions were good for the greater part of the time in each period. A little rain was experienced in both. Average summer temperatures prevailed.

The personnel of the test consisted of three men. One rode continuously in the cab of the locomotive, and read the watt-hour meter and revolution counter; one was on the ground recording car numbers for each move; the third assisted in this work, obtained car weights from the various sources, endeavored to discover in advance the moves to be made and generally kept track of the test as a whole.

The degree of coordination and sign reading that the man in the cab and the ground man developed between them was remarkable, and resulted in 95 per cent of the

test data taken by the two in widely separated locations being capable of matching up afterward.

Getting the car numbers for each move necessary in loading or unloading a car float presented no particular difficulties after the first two or three floats had been handled. When doing yard switching or classifying, the problem was considerably more complicated; unless the ground man could see both the locomotive and the cars which were picked up or dropped, it was very difficult to coordinate distance readings with number of cars moved. Fortunately the greater part of the classification work was performed on curved track, which made relatively easy the coordination of moves between the ground man and cab man.

It may be of interest to follow the procedure for "shaking out" a string of cars, and to note the method for keeping track of the number of cars and distance each combination moved during the process.

Let it be assumed that the locomotive has "hooked on" to a string of cars, which it will proceed to classify

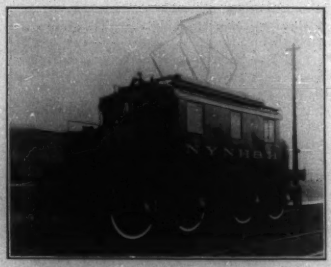

Fig. 3—Electric Switching Locomotive Used in Oak Point Yard

on the different yard tracks according to destination. Classifying in general is done on a fan-shaped set of tracks. The string of cars is hauled out on the lead track and the proper switches thrown. Then a rapid acceleration is made toward the branch tracks. When sufficient speed has been attained, the first cut is made; that is, for instance, three cars bound for track 7 are uncoupled and allowed to coast down to their allotted track, the rest of the string of cars and the locomotive being brought to a stand-still and returning to the lead track. The same procedure is followed until all the cars in the string have been placed on their respective tracks.

In practise, the moves are made as rapidly as the cars can be "kicked off," with the accompanying starts and stops necessary.

The test procedure called for the ground man obtaining in order, the numbers of the cars in the string. Then, standing near the middle of the curve (as previously mentioned the classifying lead tracks are on a curve), he was able to signal to the man in the cab when a new move started and also to determine how many cars were kicked off at a time, so checking off their numbers in his record book.

Following is a sample set of classification moves, taken directly and without change from the notebook of the ground man. As noted, each move was assigned a number, such as A-9, C-6, H-8, etc. The car numbers are noted and the general procedure for getting the tonnage and distance moved during classification moves can easily be deduced, when it is remembered that distance was read at the beginning and end of each numbered move. "X" denotes an empty car.

| | | | |
|---|---|---|---|
| H-1 | Light | | |
| H-2 | 2—Reachers | | |
| H-3 | Light | | |
| H-4 | CNJ | 60248 | 18 cars |
| | CNJ | 62614 | |
| | CNJ | 62874 | |
| | CNJ | 64535 | |
| | CNJ | 64737 | |
| | NH | 51943 X | |
| | NH | 52137 X | |
| | NH | 55065 X | |
| | NH | 54150 X | |
| | BIG 4 | 41120 | |
| | BIG 4 | 58904 | |
| | B & M | 49472 | |
| | SO. | 134985 | |
| | CNJ | 61146 | |
| | CNJ | 61728 | |
| | CNJ | 65130 | |
| | CNJ | 50445 | |
| | CNJ | 61818 | |
| H-5 | H-4 less last 2 cars | | 16 cars |
| H-6 | H-4 less last 3 cars | | 15 cars |
| H-7 | H-4 less last 6 cars | | 12 cars |
| H-8 | 1st 11 cars of H-4 | | |
| H-9 | 1st 9 cars of H-4 | | |
| H-10 | 1st 8 cars of H-4 | | |
| H-11 | 1st 5 cars of H-4 | | |
| H-12 | 1st 4 cars of H-4 | | |
| H-13 | 1st 3 cars of H-4 | | |
| H-14 | 1st 2 cars of H-4 | | |

Translating the above: The locomotive made move H-1 light; coupled on to flat cars used as reachers for float work and moved them to another track (H-2); returned light (H-3) to the string of 18 cars to be classified. These 18 cars were moved to the lead track, stopped, reversed and two cars kicked off (H-4); this left 16 cars for the next move; these 16 cars were moved back to the lead track, stopped, reversed and one car kicked off (H-5); the 15 cars remaining were handled similarly for move (H-6) and three cars kicked off; twelve cars now remained, which were handled as before and one car kicked off (H-7) leaving the first eleven of the string. These were handled similarly, kicking off two cars (H-8), then one car (H-9), then three cars (H-10), then one car (H-11), then one car (H-12), again one car (H-13), which brings us to the last move (H-14) where the last two cars were moved to the lead

track stopped, reversed, and kicked off to a classification track.

## III. Analysis of Test Conditions

The test was of necessity subject to certain errors. Regular engines on their regular runs were used and regular procedures as to switching were followed all through, with the possible exception that the work of the engine under test was not varied quite as much as usual. This did nothing to detract from the test as indicating actual average conditions, and did help some in separating the results according to class of service performed.

Gross weights for loaded cars were taken in round numbers as shown in the various yard records, float lists, etc. Empty car weights were taken as 20 tons. This is the figure used in making up train weights and may be considered as a good average for all empty cars.

Distance readings were accurate to lengths less than

Fig. 4—Electric Locomotive in Float Service—Oak Point Yard

View showing locomotive, reacher cars, and float bridge. Note incline of bridge apron

the circumferences of the driving wheels to which the revolution counter was attached. These circumferences for the two locomotives used were 16½ ft. and 11 ft. Slipping of the drivers to the axle of which the revolution counter was attached was a potential source of error; fortunately, practically no slipping of these particular wheels on the locomotives was noted. (On both locomotives, all axles are driving axles.)

It was first intended to read the locomotive watt-hour meter for each move; this was impossible, however, as the meter, being the regular locomotive type, did not register enough for accurate reading in the case of the shorter moves. The meter readings, therefore, were confined to changes in classes of service, or to other sufficiently long intervals, to insure accurate data.

The meters on both locomotives were calibrated before and after the tests and were accurate to within 1 per cent during the tests. A certain inaccuracy in scheme of meter connections was present; this, however, was considered within the accuracy limits of the tests as a whole.

In any given move where a car or several cars were kicked off, the move with the number of cars as at the start was considered to terminate when the locomotive with its remaining cars had been brought to a standstill. This did not involve great inaccuracy, as the only energy not taken account of was that required to brake the kicked-off cars. In comparison with the energy required for acceleration of the string, this is practically negligible.

Where the locomotive and its load made short moves of less than a car length or two, no record was made. The only effect of this was to increase the watthours per ton-mile figures very slightly.

The test locomotives were in several instances used to push out road freight trains from the yards. The time that the engines first hooked on the rear end until the push-out was completed was deleted from the records of the test. The time spent in returning from the pushing and in traveling to the train to be pushed, was counted, however, as being properly classified as switching service.

In the tabulated summaries for the first period and for the test as a whole, a certain discrepancy may be noted in that the sum of the number of moves, miles, ton-miles, etc., for the different classes of service does not equal the total figures for the entire period or periods. The latter figures take into account five moves totaling 426 ton-miles which were omitted from the records of classes of service as not belonging specifically to either, yet properly belonging to switching service.

As a matter of interest, average speeds for elapsed time for each day were calculated. These took into account the 20-min. lunch period per shift, but omitted time consumed in pushing trains or doing other work of a non-switching variety.

When a rate of energy consumption with respect to work performed is desired, there are two methods of obtaining the final result. In the particular case under discussion, the watt-hours per ton-mile could be calculated for each move and an average taken for as many moves as constitute a certain period or class of service. The other method consists of taking the sum of the ton-miles for a given series of moves and dividing this figure into the sum of the watt-hours for these moves. It was thought the latter method gives the more representative results over a given period, is more accurate, and, as previously pointed out, lends itself more readily to the test procedure as regards meter readings.

In final figures of watt-hours per ton-mile, decimal points are omitted, inasmuch as the accuracy of the test as a whole would not make them particularly significant.

## IV. Tabulations

The tabulations of data obtained in the test show

results for each period, for each class of service, and a composite summary for both periods.

## V. Analysis of Results

Inasmuch as yard switching operations are continually changing—no two days being alike—no unfavorable comparisons are justified as between the locomotives used in the first and second periods. Nor is any comparison intended, as there are too many variables encountered in two three-day periods a month apart to make such a comparison at all significant. The differences which do exist in the results of the two periods serve to illustrate the fact that many hours of switching service must be recorded before a representative figure for watt-hours per ton-mile can be obtained, regardless of the type of locomotive used.

Although figures of watt-hours per ton-mile for the various services were primarily desired, it is interesting to note the extent of the data obtained from basic records of kilowatthours, number of cars, tons, and distances moved.

For purposes of discussion, the first three days of the test in July are referred to as the first period; the second three days of the test in August are referred to as the second period.

In general, each period was similar in classes of service performed, with the exception that the second included considerably more float unloading or "pulling." Comparison of the figures will show that float unloading is the highest in power consumption per ton-mile.

This is no doubt due to the incline of the float bridge apron at low tide, a great number of small moves and considerable waiting time. During the tests, the apron incline was for the most part against movements from the float. At high tide this incline is reversed, but not to the same extent as at low tide. The number of small moves comes in the fact that the floats must be loaded or unloaded in parts; when unloading, the parts are additive; that is, each succeeding move is with a greater tonnage; (in loading, on the other hand, each succeeding move is with a decreasing tonnage). It can readily be understood, therefore, that a low tide will definitely tend to increase the energy consumption for float unloading. Waiting time is another factor which enters into the situation; a certain stipulated time is allowed for unloading, loading, and releasing a car float. Hence a switcher is often dispatched to a float bridge to wait for an approaching float. If the stand-by losses of the locomotive are relatively great, the watt-hours per ton-mile for float unloading are correspondingly increased.

The tests under consideration showed that the general impression that float service is a more severe variety of switching than classifying is in the main correct, though local and tidal conditions may vary this somewhat.

THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD
Electric Power Consumption for Yard Switching
Condensed Summary—Oak Point Yard, New York

| Period of Service | No. of moves | Mileage | Avg. speed (m. p. h.) | Car miles | Trailing ton-miles | Total ton-miles | Trailing tons per move | Kw-hr. | Kw-hr. per mile | Watt-hr. per car mile | Watt-hr. per trailing ton-mile | Watt-hr. per total ton-mile |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **First Period — July 25-27, 1928** | | | | | | | | | | | | |
| July 25, 1928, 6 hr. | 110 | 19.03 | 3.13 | 169.4 | 4180 | 5901 | 214 | 527 | 27.7 | 3111 | 126 | 89 |
| July 26, 1928, 6 hr. | 91 | 17.11 | 2.81 | 149.9 | 5441 | 6987 | 330 | 525 | 30.7 | 3502 | 97 | 75 |
| July 27, 1928, 7 hr. | 129 | 22.71 | 3.28 | 193.4 | 7858 | 9914 | 321 | 711 | 31.3 | 3676 | 91 | 72 |
| Three-day period, 19 hr. | 330 | 58.85 | 3.08 | 512.7 | 17479 | 22802 | 288 | 1763 | 30.0 | 3439 | 101 | 77 |
| Yard classifying | 267 | 47.17 | —— | 427.0 | 14833 | 19102 | 292 | 1480 | 31.4 | 3466 | 100 | 77 |
| Loading car floats | 32 | 5.88 | —— | 45.6 | 1215 | 1 746 | 244 | 131 | 22.3 | 2873 | 108 | 75 |
| Unloading car floats | 26 | 4.37 | —— | 29.0 | 1133 | 1528 | 337 | 130 | 29.8 | 4483 | 115 | 85 |
| Both loading and unloading car floats | 58 | 10.25 | —— | 74.6 | 2348 | 3274 | 286 | 261 | 25.5 | 3500 | 111 | 80 |
| **Second Period — August 13-15, 1928** | | | | | | | | | | | | |
| Aug. 13, 1928, 3 2/3 hr. | 113 | 13.76 | 3.73 | 76.8 | 4070 | 5528 | 314 | 573 | 41.7 | 7457 | 141 | 104 |
| Aug. 14, 1928, 8 1/2 hr. | 115 | 21.63 | 2.55 | 164.2 | 5184 | 7477 | 269 | 1030 | 47.6 | 6272 | 199 | 138 |
| Aug. 15, 1928, 8 hr. | 134 | 24.55 | 3.08 | 202.8 | 8314 | 10966 | 370 | 1131 | 46.1 | 5576 | 136 | 103 |
| Three-day period, 20 1/6 hr. | 362 | 59.94 | 2.99 | 443.9 | 17568 | 23971 | 320 | 2734 | 45.6 | 6159 | 156 | 114 |
| Yard classifying | 277 | 42.93 | —— | 322.6 | 13990 | 18591 | 333 | 1950 | 45.4 | 6045 | 139 | 105 |
| Loading car floats | 25 | 7.14 | —— | 52.7 | 1207 | 1964 | 234 | 249 | 34.9 | 4728 | 206 | 127 |
| Unloading car floats | 60 | 9.86 | —— | 68.6 | 2371 | 3416 | 299 | 535 | 54.2 | 7794 | 226 | 157 |
| Both loading and unloading car floats | 85 | 17.00 | —— | 121.3 | 3578 | 5380 | 280 | 784 | 46.1 | 6364 | 219 | 146 |
| **Both Periods — July 25-27 and August 13-15, 1928** | | | | | | | | | | | | |
| Six-day period, 39 1/6 hr. | 692 | 118.79 | 3.03 | 956.6 | 35047 | 46773 | 305 | 4497 | 37.9 | 4699 | 128 | 96 |
| Yard classifying | 544 | 90.10 | —— | 749.6 | 28823 | 37693 | 313 | 3430 | 38.0 | 4575 | 119 | 91 |
| Loading car floats | 57 | 13.02 | —— | 98.3 | 2422 | 3710 | 240 | 380 | 29.2 | 3865 | 157 | 102 |
| Unloading car floats | 86 | 14.23 | —— | 97.6 | 3504 | 4944 | 310 | 665 | 46.6 | 6810 | 189 | 135 |
| Both loading and unloading car floats | 143 | 27.25 | —— | 195.9 | 5926 | 8654 | 282 | 1045 | 38.4 | 5332 | 176 | 121 |

General yard switching and classification work showed reasonable figures for power consumption per ton-mile. Such figures would, no doubt, vary for different yards, since grades and curves in no two yards would be alike. But Oak Point Yard is large enough so the figures indicated give what is considered a good average figure for flat yard switching. In this connection, it would be extremely interesting if a comparison of watt-hours per ton-mile for flat switching and hump switching could be obtained. Figures for the latter type of switching, of course, should not be considered without due reference to the gradients of the hump approaches.

It will be noted that the figures of watt-hours per ton-mile for each period show a decided difference. This is undoubtedly due in part to the difference in types of locomotives used as regards stand-by losses. Another factor tending to increase this difference between the two periods was that the second included more float work, particularly unloading. Undoubtedly other variables such as different rates of acceleration, different proportions of power-on and power-off time, etc., were present and had their part in the difference noted.

## VI. Conclusion

As previously remarked, extreme accuracy was more or less impossible of attainment under the conditions of the test. Regular operating procedures were followed as closely as possible, as it was considered the results thus obtained would show average every-day conditions and would be of greater value than if laboratory precision of measurements were undertaken at the expense of the test as a whole.

To obtain two three-day periods of switching service exactly alike is well-nigh impossible. In spite of the general similarity of service for the two periods under discussion, there were certain differences between the two which make undesirable any conclusions regarding the types of switching locomotives used. Where comparisons are mentioned, they are simply for explanation of test results, and are not to be considered as reflecting upon either type of locomotive.

It is believed, therefore, that the data herein set forth, represent actual, average conditions of switching service in Oak Point Yard. The various figures obtained for electric power consumption in watt-hours per ton-mile, it is thought, are well within the accuracy range of existing freight car loaded and light tonnage figures. It is felt that an important object will have been gained if this study may lead to similar tests being made under different conditions on other railroads.

In conclusion, thanks are due to all those participating in, or arranging for, the tests. Particular mention is due Mr. W. T. Kelley, Asst. Engineer, and Mr. E. S. McConnell, Mechanical Inspector, for their very able assistance in the running of the test and calculation of results; to the Oak Point Yard forces under Messrs. E. J. Cotter and John Dunford, Assistant Superintendent and Yard Master respectively, for their excellent cooperation; also to Mr. S. Withington, Electrical Engineer, and Mr. A. L. Ralston, Mechanical Superintendent, for their encouragement, and criticism of results.

# Control Systems for Oil and Gasoline Electric Locomotives and Cars

BY N. L. FREEMAN[1]

Associate, A. I. E. E.

*Synopsis:—A review is given of the development of self-propelled railway vehicles which utilize electrical transmission, paying particular attention to the ways and means of regulating the torque demand on the internal combustion engine which serves as the source of power, and the supply of power to the auxiliaries.*

*Two general designs are discussed, and classified as "differential field control" and "torque control." In differentiating between these two systems, two types of differential field control are outlined, giving their major advantages and limitations. The principle of torque control depending upon constant engine speed is discussed, enumerating its advantages over previous schemes. It permits the absorption of the entire engine output for any throttle opening and engine speed selected. The various relays and control devices necessary for proper operation of the scheme are described, together with the use of the auxiliary generator and main generator for compressor operation and battery charging.*

*The appendixes deal with the design of auxiliary generators for differential field control and a short description of the method of limiting the torque required by means of a torque regulator and contactor. The problem of overcoming hunting of the system due to lagging of the field change and its solution are given.*

*The differential field control comprises the minimum amount of apparatus consistent with operation of the car or locomotive and its auxiliaries. It should be noted, however, in connection with this type of control, that battery charging and air compressor operation cannot be obtained at both operating and idling speeds of the engine.*

*Torque control equipment functions to vary automatically the generator voltage inversely as the current in such a way that the full available power of the engine is utilized; it acts directly on the generator field and has proved its superiority over methods of regulation involving the exciter field. The availability of the auxiliary generator for compressor operation and battery charging, when the engine is running under load, represents a marked advance in design. The main generator supplies these auxiliaries during idling. The torque control system meets the requirement of any type of engine.*

* * * * *

## Introduction

SELF-PROPELLED railway vehicles driven by internal combustion engines have a brief history of about 30 years. Those using electrical transmission outnumber all other types. The major portion of their development has been crowded into the period beginning with the year 1924. In this short time, this branch of transportation has grown from a group of low powered gasoline-electric rail cars to embrace many classes of gasoline and oil cars and locomotives with highly effective electrical transmissions.

From the beginning, the electrical transmission for commercial railway vehicles has included a generator and traction motors. Practically all the traction motors have been of the series type, the input to such motors being a function of speed and applied voltage. As overloading an internal combustion engine will cause it to run at a lower speed or stop it entirely, it was necessary to protect against such a condition. In 1924 and 1925 this was done by means of a differential field for reducing the main generator voltage with an increase in current demand. The differential field was placed on the exciter because it produced more favorable characteristics and was a much less expensive winding.

There were two distinct methods of applying this differential winding. One designer distributed the winding to all poles in the exciter and proceeded to charge the battery from the exciter through a field on the main generator. This system supplied the usual drooping characteristic with fairly sharp voltage regulation with respect to engine speed. (See Fig. 1A.) Another designer concentrated the differential winding on two of the exciter's poles. The battery was charged from the exciter, but through an external resistor instead of a field. This concentration of winding gave more than the usual drooping characteristic. Its power requirement was much more uniform over the range of car speeds with less sharp regulation with respect to engine speed. (Fig. 1B.) Both systems were widely used and are still being applied with design improvements. They are more completely discussed in Appendix I.

In all of these equipments, the auxiliaries presented a serious problem. The auxiliaries are the sources of brake air supply, lights, battery charge, and radiator air supply. The brake air supply has been obtained from an electrically driven compressor in the majority of cases. The battery has nearly always been charged from the exciter or its equivalent. The air for the radiator has been supplied by various devices, but the chief source has been an electrically driven fan. Since the auxiliaries were operated from the main generator, their operation was dependent on the engine and car speed simultaneously, and the results were none too satisfactory. This was particularly true when the profile contained grades which required slow, steady pulling in one direction and a long drift in the other. Battery charge and air supply offered the most serious problems under these conditions.

In order to improve the operation of auxiliaries and the loading characteristic in general, a system of torque control was introduced. The equipment using this system had its loading characteristic controlled by a regulator which varied the main generator field.

1. Rwy. Equip. Engg. Dept., Westinghouse Electric & Manufacturing Co., East Pittsburgh, Pa.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

This regulator limited the torque load impressed on the engine to a selected value. The regulator spring had a simple hand lever adjustment for selecting the torque required. In this scheme the exciter became an auxiliary generator and supplied a battery charge under almost any loading condition. A low-voltage compressor operated from this source and, in addition, the battery and compressor were supplied current through the starting connections from the main generator

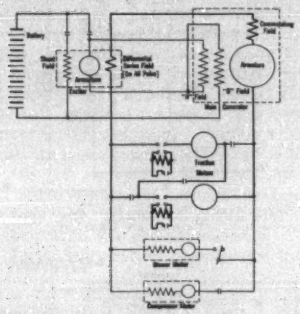

Fig. 1A—Differential Exciter Scheme of Control, Using a Distributed Differential Winding on the Exciter and the "B" Field on the Main Generator

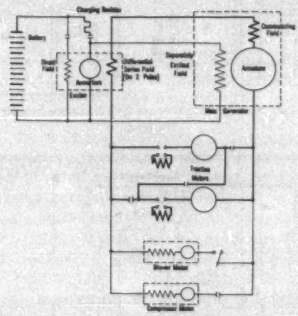

Fig. 1B—Differential Exciter Scheme of Control, Using a Differential Field Concentrated on Two Poles of the Exciter

during idling. This equipment was arranged to use the main generator as a starting motor. All of this is shown in Fig. 2. This equipment with its definite and effective loading characteristic overcame many of the early problems. It was especially effective with the more rugged profiles and irregular schedules and removed several of the natural handicaps under which these cars and locomotives formerly operated.

## Required Fundamentals

The success of the torque control system led to further improvements which enabled it to automatically cope with variation in the output characteristic due to innumerable factors encountered in service. These factors can be classified in general as fuel, mechanical, and atmospheric[2] differences.

Fig. 3 shows a test curve of one engine with respect to its rating. This particular make of engine has been

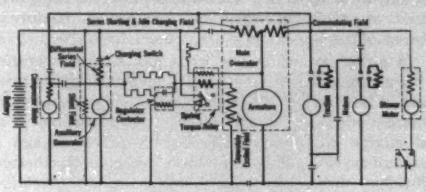

Fig. 2—External Regulator Scheme of Control, Limited Torque System

very dependable in service, yet in the course of 5000 hours service its output has been known to be as low as 85 to 90 per cent of its rating. This fact, in conjunction with the curve of Fig. 3, indicates an output variation for this gasoline engine of 25 per cent to 30 per cent under service conditions. Such a condition is not peculiar to one engine but representative of internal combustion engines in general, since it is a function of the three groups of factors of variation. Similar

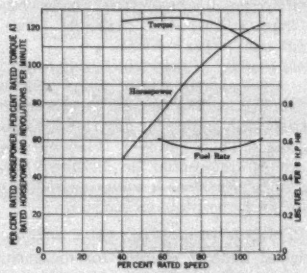


Fig. 3—A Typical Gasoline Engine Performance Curve

variations, probably of different magnitude, have been repeatedly observed with oil engines.

Engines in railway service are frequently called upon to do 2000 hr. or more of full-load duty between major overhauling periods. The total number of hours of operation is considerably greater than the hours of full-load duty for this very exacting service. Such engines

2. "Horsepower Correction for Atmospheric Humidity," by Donald B. Brooks, *S. A. E. Journal.*

are expensive and should be conserved wherever possible, which of course is true of any engine. The length of time between overhaul periods and the life of an engine both depend upon total wear of its parts. An expression of exact relationship between revolutions, load, and wear would be a complicated function. The usual index of engine life, however, is its total number of revolutions.

Obviously, the most economical method of operating an engine is to secure the desired power at the lowest speed at which the engine may be operated to develop that power.

In either an oil engine or a gas engine operating at a given speed the mechanical efficiency at its rated load is better than at lower loads. The corresponding thermal efficiency under variable load conditions in an oil engine partially compensates for the change in mechanical efficiency; while in a gas engine, the thermal efficiency drops appreciably and a severe throttling loss appears with a reduction in load.

Thus, for a gas engine, and to some extent for an oil engine, the best economy appears at the rated load for a given speed.

From definite cylinder charges certain conditions may be expected. These charges produce a torque. If there is an exactly equal opposing torque, the engine's speed will be constant. If the opposing torque is greater than the engine torque, the speed will decrease and vice versa. Obviously, either the engine torque must be matched to its load, or the load to the available engine torque. If the required engine size is to be a minimum, its revolutions conserved, and the economy kept at the most desirable value *the load must be fitted to the torque available.*

The ideal loading is that which, regardless of engine condition, will hold the engine to a selected speed. Such a system of loading permits the absorption of the entire output of an engine for any throttle opening and speed selected. That, however, is beyond the scope of performance of differential or definite characteristic machines, since the ideal loading is predicated on an engine's ability to maintain its speed.

## Torque Regulation from Speed

The original method selected for measuring engine speed was to express the speed in terms of voltage from a small control generator of constant field strength. Because of the constant field strength, this voltage would then be proportional to the generator speed. The control generator was belted to the engine, making its voltage also proportional to engine speed. This voltage was then applied to a sensitive voltage relay which operated a contactor in the main generator field. The contactor gave the minimum field strength required when open and the maximum field strength when closed (See Fig. 4A). Such a system is not stable, since large power surges originate within it. Stability was obtained by recalibrating the voltage relay in step with the regulating switch. This is shown in Fig. 4C. A discussion of this method of stability appears in Appendix II.

It was but a short step from the control generator to an exciter or auxiliary generator for the combined duties of both. Since the regulation was to be for an almost

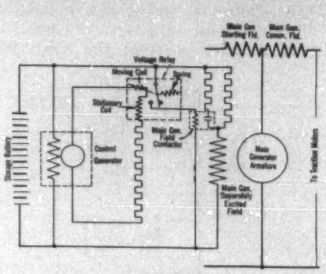


Fig. 4A—Elementary System for Regulating Torque from Speed. (This is an Unstable System)

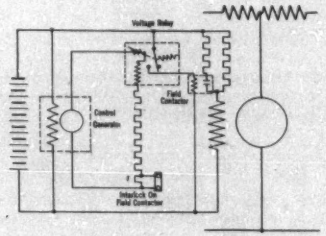


Fig. 4B—Interlock Method of Stabilizing Speed—Torque System

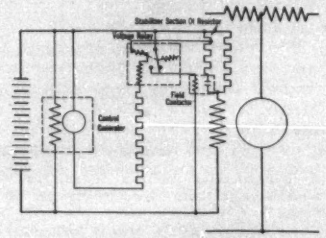


Fig. 4C—Resistor Stabilized System of Regulating Torque from Speed

constant speed, the auxiliary generator volts would be at a nearly constant value for each selected speed. By varying the speed setting over the lower engine speed range, with the resistor in series with the relay, the auxiliary loads were reduced with speed. By making the speed adjustment through the upper speed range in the auxiliary generator field the auxiliary load

was not reduced in this band with respect to engine speed. Thus the auxiliary generator volts are constant in this neighborhood. Therefore, the battery is charged through a ballast or cushion resistor. This is a tapered charging system and commonly known as the modified constant potential system of charging.

The use of this type of charging system permitted the introduction of another feature. The charging resistor is of very low value,—a fraction of an ohm. By connecting the charging switch between this resistor and the auxiliary generator, and the shunt field across the battery through this resistor as shown in Fig. 5, the field is battery-excited, while the charging switch is open. As soon as it closes, the auxiliary generator becomes shunt-excited. This feature has an important result. For all practical purposes, the system is independent of battery condition. Further, the already narrow regulation speed band is further narrowed.

This system of regulation also removes one of the objectionable features of electrical transmissions, which is that the loading characteristic of the electrical equipment changes considerably with temperature. Large temperature changes are frequently

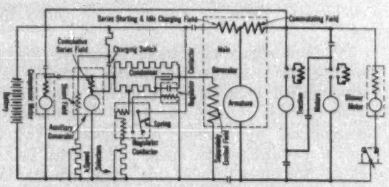


Fig. 5—External Regulator Scheme of Control, Torque Regulation from Speed System

incurred in the electrical equipment at the beginning of service operations. Resistance variation effects due to temperature are reduced in this scheme by the use of near zero temperature coefficient resistors in the two circuits where such changes would produce differences in speed settings. These two circuits are the relay circuit and the auxiliary generator field. Nearly all the heating in these circuits takes place while the engine is warming up and pumping air. In the routine of service, therefore, the effects of temperature do not appear.

The theory of torque control from speed is sound. As developed it is simple. As a result, a simple, effective scheme has been constructed which allows the operator to select the speed at which he desires to operate the engine and the control system insures the engine being effectively loaded at that speed.

### Equipment of Special Significance

Two pieces of apparatus of exceptional merit were used as standard parts of this equipment. These are the "dynamic" voltage relay and the regulator contactor. The voltage relay has been thoroughly described in the May 1929 issue of the *Electric Journal*, under the title of "A Sensitive Roughneck." Briefly, it consists of a powerful magnetic circuit excited by a stationary coil, a moving coil in the air-gap, and a set of carbon contacts. The stationary and moving coils are in series. The moving element is mounted on knife edges and operates against a long camber spring in tension. Fig. 6 consists of a picture and a section of the relay.

The regulator contactor is shown in Fig. 7. It is of the conventional magnetic contactor design, except that it has two sets of silver contacts in series and no blowout.

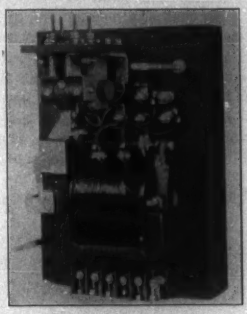

Fig. 6a—Regulator Relay

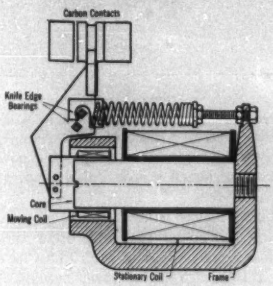


Fig. 6b—Regulator Relay (Section)

It operates with smaller than standard contact travel, does so positively and is, in general, a very fast, sturdy switch.

The operation of this switch is assisted by a small condenser across its contacts. The condenser action momentarily short-circuits the switch at opening. While the condenser is very small with respect to the inductive load of the field, it gives the regulator contactor time enough to open with little contact load. The result is arcless interruption of the circuit. This is an application of the deion principle.

## Special Features

As stated in the beginning, auxiliaries present an important problem. The constant voltage source of the auxiliary generator is almost ideal for the auxiliary power source during running. During idling, the main generator is used through the starting connections for charging the battery and operating the auxiliaries. Being charged through a differential series field, the battery regulates the main generator voltage. This provides a source of auxiliary power for the remainder of the engine operating cycle.

The lighting, control, and field loads on the battery are independent of car or locomotive speed and engine speed. In order that a battery go through a minimum number of charge and discharge cycles it is desirable to carry these loads from the charging sources as much as possible. At the same time, a continuous charge to the battery may be kept within the approved limits. These two features improve battery life, make its capacity available a greater portion of the time, and reduce the voltage fluctuations in the low-voltage circuits.

The compressor supplies air for brakes, signals, and

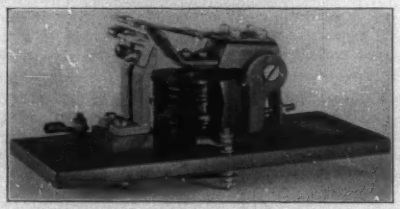

Fig. 7—Regulator Contactor

air-operated control. Most of it is required during periods when the engine is not supplying power to the traction motors; hence, it is desirable to operate it from the charging sources.

The radiator blower is needed more when the engine is delivering full power than any other time. Since the heat losses are highest at such times its operation should be in step with engine power periods. At other times natural ventilation is usually sufficient for the radiators: the radiator blower motors do not generally require a more constant supply of power than furnished by the main generator when delivering traction power.

The measuring of speed by voltage is used to eliminate severe surges in the idle charge system. This is done with the same voltage relay that controls the loading by setting it for a speed slightly above the idle speed when the controller is moved to the "off" or "idle" position. As may be seen in Fig. 6B, the relay is equipped with a moving contact that operates between two stationary contacts. In case the relay current exceeds two amperes, the moving contact is actuated in the direction opposite to the pull of the spring until it touches one of the stationary contacts. The regulator contactor is energized by the closing of the moving contact on this stationary contact. Should the relay current become less than two amperes the spring causes the moving contact to touch the other stationary contact. The circuit thus established is the one used for energizing the starting and idle charg-

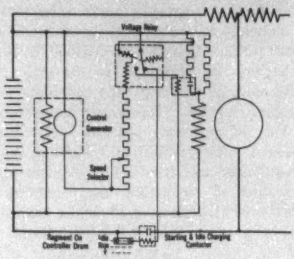


Fig. 8

ing contactors. Refer to Fig. 8, which shows this connection.

In the third regulating system described, Fig. 2, a transition was developed which was distinctly one for self-propelled equipments. It is also used in the new system and is a closed transition. The operation is accomplished by opening the regulator switch, closing one parallel switch, opening the series switch and closing the other parallel switch, all in succession and followed by closing the regulator switch. This

Fig. 9—Test Car

transition is made with no noticeable change in engine speed and without noticeable vehicle surges, thus indicating a continuous accelerating rate.

## Field Tests

After this system had been well tested in the laboratory, a test car was built (Fig. 9) and equipped with a large gasoline engine, generators, control, and motors. Again the system was thoroughly studied and im-

proved as suggested by the tests. As this indicated a successful scheme, arrangements were made with the Baltimore and Ohio Railroad to equip a car with similar control. This car operated over a branch line in West Virginia, and from the beginning, the installation was a decided success. A car which was almost ready for shopping stayed in service for 50 per cent more mileage, and showed a better operating record than ever before.

The chief characteristics of the changed performance were the buoyant operation of the engine and the excellent car accelerating characteristics. With the engine loaded by this scheme, it came up to speed very promptly. There was a smooth continuous flow of power from the time the engine attained the speed selected by the operator until he shut off. There was no complicated handling needed and men unfamiliar with the new equipment had no trouble in operating and maintaining it.

### Summary

Since the beginning of the history of self-propelled cars and locomotives the electrical transmission has been used extensively. All previous systems had their common and special faults. A simple system using speed as an indication of engine torque has now been developed. This system suits the torque applied to the engine to whatever torque the engine is able to develop, at a selected speed and throttle opening, regardless of the condition of the engine at that time. If one cylinder does not fire the load is decreased accordingly, but the speed remains the same. It thus enables the operator to utilize the maximum horsepower the engine can develop at any time. This is of vital importance on a car or locomotive with a limited power plant.

Additional features of continuous power supply for battery charge and compressor operation, and an improved closed transition are used. The scheme has been thoroughly tested with entirely satisfactory results.

## Appendix I

There have been two types of control used extensively on self-propelled railway vehicles which have electrical transmissions. These two types have been those equipments employing differential fields to approximate the proper loading characteristics and those which used external regulators to the same end, together with improved performance in other departments of the equipment. The writer does not consider the hand-operated bus type control employed on small industrial locomotives as in comparable service with these two types of control.

There are two types of differential field control, both having the differential field winding on the exciter. One type, which is shown in Fig. 1A, has a differential winding distributed over all the exciter poles. The other has this winding concentrated on two of the exciter's six poles and is shown in Fig. 1B.

The differential type having the distributed winding uses a main generator having two windings on its main poles. One of these windings, designated as the *A* field, is connected directly across the exciter armature. The other, the *B* field, is so connected that the battery is charged through it. This accomplishes several things, among them, increasing the effect of the differential field and making the unloading due to a drop in speed much more pronounced. The change in field current and loading are due to the current through the *B* field depending upon the difference of potential existing between the exciter and the battery. An example of the regulation of volts with respect to load currents of one of these generator exciter combinations is shown in Fig. 10. The scheme is subject to the usual change of characteristic due to temperature effects. Battery condition will also affect its regulation characteristics. The usual application of this scheme has included series, parallel, and short field operation of the traction motors, so that the part of the regulation curve may be used where the loading is the best.

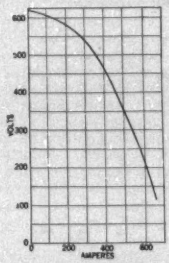


Fig. 10—Performance Curve of a Differential Exciter Equipment Using the "A" and "B" Field on the Main Generator

The differential field type which has the concentrated field on two diametrically opposite poles of the exciter is designed to obtain a good regulation curve by varying the exciter voltage which is applied directly to all the main generator field. The method of producing the required voltage from the exciter is unique. The exciter armature is wave-wound, which makes it two-circuit. The conductors of each of these two circuits are in series and appear under all six poles of the exciter. Then, with constant battery field on all six poles, all conductors produce a voltage in the same direction. The introduction of current into the differential winding on two poles reduces the over-all voltage although the excitation on the other four poles remains constant. This current may be increased to the point that the two poles bearing this winding furnish no excitation; then all the exciter voltage is generated beneath the remaining four poles. A further increase in the differential current will reverse the normal direction of flux under

the two differential poles and their action will then buck that of the other four. The flux in the two poles bearing the differential winding must follow the usual saturation curve. With an increase of current in the differential field, saturation tends to bend the lower part of the curve upward, while with a decrease in the differential current, the maximum voltage of the exciter is limited by the saturation of the two poles. The regulation of the main generator volts with respect to current is then almost hyperbolic through the working range and may be very accurately shaped by the designer to obtain uniform loading.

This equipment is also subject to a change in characteristic due to temperature effects and to some degree, battery condition. With respect to load currents Fig. 11 is a representative regulation curve of main generator volts.

The type of control which employed an external

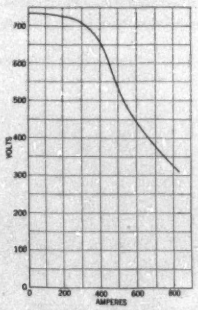


Fig. 11—Performance Curve of a Differential Exciter Equipment which Uses a Differential Series Winding Concentrated on Two Poles of the Exciter

regulator did more than supply a suitable characteristic; it made that characteristic adjustable by a simple device and also simplified the problem of auxiliaries. An internal combustion engine is a producer of torque, and this regulator was arranged to limit the torque to the value that the engine would produce. This arrangement is shown in Fig. 2. The regulator was a special relay, having a field proportional to the main generator field and an armature whose current was proportional to that of the main generator armature. Its saturation characteristics were adjustable as well as the spring tension on the armature. The relay was first adjusted to the power plant and then the percentage of torque for which it was regulated was controlled by a manual adjustment of the spring tension. The relay controlled a regulating contactor, which operated between the minimum and maximum field requirements. In service, it operated in such a manner as to hold the torque imposed upon the engine constant. The torque characteristic was affected by temperature only, as the commutating field of the main generator and regulator armature heated differently under load. The regulator armature was normally shunted around the commutating field.

This external regulator system permitted the use of an auxiliary generator whose voltage was controlled by the battery through a differential field and thus supplied a low voltage for better compressor operation.

The idle charging system and the use of the main generator as a starting motor were begun with this equipment. The idle charging system also furnished power for the air compressor as required.

In general, the external regulator or torque control system was a great improvement over previous equipments. It could be simply and easily adjusted to suit the engine condition, and successful application formed a basis for further improvements.

## Appendix II

A voltage relay across the control generator arranged for operating a contactor in the main generator field presents a problem. This problem is hunting. It was to be expected, since a speed change affected only the voltage of the control generator. This voltage then operated the sensitive voltage relay; next the field contactor opened or closed and the field began to change. Eventually, the field value changed enough to reverse the speed change. In all, considerable time elapsed between the registering of the chosen speed and the final reversal of the speed change causing it. This was confirmed by test. It was apparent that the time lag would need to be overcome by anticipating it, and was accomplished by changing the relay setting as soon as the field contactor closed or opened. An interlock circuit on this switch was first used for this purpose and resulted in the stabilization of the circuit. See Fig. 4B.

The introduction of this method of stabilization altered the character of the regulation, a condition which becomes apparent by considering the resistance value $r$ as varied from zero up to higher values.

At the zero value of $r$, the hunting is at its worst. With each increment of $r$ the system responds in a shorter time. Thus, the circuit operations become more and more self-energized. Such a system can be quickened to the point where it is entirely self-energized and there are no speed pulsations. For its source of energy, however, it depends on speed although it originates its own impulses.

The relation between proper time in and out for the field contactor (or main generator field strength), and the main generator load, would appear to have no connection with the regulating system. This, however, is not true, for if the average field is too low to cause adequate loading, the engine speed will increase. A slight increase in speed increases the voltage on the

control generator. The pulsating system then works between two slightly higher values. The ultimate result is that the regulator switch, or field contactor, stays closed a longer interval of time and open a smaller percentage of time. This will raise the average field value. A raise in field value will increase the loading, and hold the engine to a speed slightly higher than before. Tests have shown that the regulating band thus incurred is narrow.

An interlock on the regulator switch is not desirable. Therefore, the pulsating characteristics of the field circuit were used for the same duty. A resistor in series with the regulator switch results in less current through the switch, and is unaffected by field discharge action. (See Fig. 4c.) Consequently, a small voltage drop from this resistor was used instead of the regulator switch interlock. This again altered the pulsating characteristics of the circuit. They now depend upon two things,—the natural speed that would exist with the interlock system, and the building-up characteristics of the main field. The natural speed of closing determines approximately the time of reclosing of the field contactor, and the rate with which the field current builds up determines the time elapsing before the switch reopens. Since the field responds very slowly to such changes, the system is always exactly in step with it, yet its pulsating rate is greatly reduced. For this connection refer again to Fig. 4c.

## Discussion

**Hermann Lemp:** Mr. Freeman's paper has proven interesting reading to me as it describes another successful way of operating internal combustion engine units with electric transmission for railway traction.

As he well states in his introduction, the year of 1924 proved the starting point of a new development; namely, the introduction of "automatic control" as distinguished from hand control.

The many gas-electric cars built before the war were all hand-controlled, and it required from ten to fourteen days instruction before an engineer could be safely entrusted with the operation of a rail car.

With the advent of what I termed "inherent automatic control," which is referred to by Mr. Freeman as "differential field control," and which was patterned to resemble the control of a steam locomotive as closely as possible, it became possible to turn over the *operation* of a rail car or locomotive to any locomotive engineer with only a brief instruction. This was so well understood that the Committee on Rail Cars of the Electric Railway Association in 1924 officially recommended its adoption.

The *inherent automatic control*, while not perfect, in its practical application to railroad service does not vary from an ideal perfect control by more than from 2 to 5 per cent, and has the great advantage of simplicity, all factors being determined when the generating unit is designed and tested. It is free from adjustable and wearing contacts, relays, delicate governor operated valves, etc. In other words, there is nothing to cause difficulty with regard to adjustment. This was attained by a centrifugal governor of an internal combustion engine acting automatically to vary the admission of fuel and the strength of the generator field.

The method of control, termed *speed control*, makes use of contacts, fluid pressure, valves, etc., and is to keep the speed of the internal combustion engine constant within narrow limits, always giving the maximum horsepower that the engine is capable of giving for the particular speed selected, or as Mr. Freeman says, "Uses speed as an indication of engine torque." It does not attempt to give a constant torque, but on the contrary, in maintaining a constant speed, uses whatever torque the engine is giving at that particular time.

In making this critical analysis the writer does not attempt to minimize the splendid development work achieved by the Westinghouse engineers, but merely wishes to point out that to call the present system a *torque control* seems to be a misnomer.

In connection with the "torque control" described by Mr. Freeman, I believe the variable engine speed settings are obtained by a fluid under pressure passing through a needle valve set at definite positions by the operator through solenoid action. Does not the viscosity of the liquid passing through a fixed opening determine the actual engine speed, and if this is a variable, such as when lubricating oil affected by temperature is used, does not the speed vary with that viscosity? I ask this question because many years ago, when I tried to govern stationary lighting sets by such a control, only water or kerosene could be used for that purpose, and I finally gave it up for centrifugal governor control.

Both the "speed control" and the so-called "torque control" make use of adjustable relays, etc., and time will prove whether it will be as reliable in railroad operation as the "inherent automatic control."

Contrasted to the above, European practise is at variance with the American. The manufacturers of Diesel engines abroad, particularly of the air injected type, objected to the running of the Diesel engines at variable speed, and hence the electrical designers use almost exclusively Ward Leonard Control. In other words, the Diesel engine is preferably run at constant speed under control of a speed governor, and the field strength of the generator is varied by hand. This arrangement furnishes to a certain extent automatic control, except that the engine can be overloaded by a careless operator, and in a Sulzer rail car I inspected this winter on the Swiss Railways *a special visual signal* is placed in front of the operator advising him when he overloads the engine. It has the advantage of giving constant speed for the auxiliary generator from which air compressor, battery charger, fan motor, etc., are operated, but it has the drawback, however, of using more fuel per ton-mile, of wearing out engine parts faster and of producing more vibration in the engine cab.

In my paper read before the Erie Section of the A. I. E. E. on March 31, 1924 (which was printed in abstract in *General Electric Review* of October, 1924) I said that for main line operation the European practise might prove the better. I have, however, changed my views based upon actual observation of locomotives and rail cars operating on both plans, and have come to the conclusion that variable engine speed is the better of the two.

Railway constructor Sueberkrueb has analyzed carefully all methods of control, and summed up his article in Z. d Y. D. I. of April 28, 1928, as follows: (I translate quotation.)

"Controls using *variable engine speed* work in the most economical way. The best characteristics are obtained by the 'Lemp Control' (meaning differential field control). This control by merely changing throttle position results in automatic, shockless, uniform change in tractive effort. At the same time this is obtained at the best engine efficiency and without the necessity of observing measuring instruments. It is also obtained at best efficiencies of generator as well as traction motors."

On the other hand the control described by Mr. Freeman offers a very nice solution of the operation of auxiliaries, particularly the air compressor and battery charging, by alternately operating them from main generator during idling speed and from auxiliary generator during full speed.

In this connection I want to mention another solution of the same problem successfully operating for about one year on a switching locomotive. The engine speed is controlled by a calibrated spring acting against a variable air pressure supplied by the operator through a standard air brake handle, in place of using a mechanical connection between operator's throttle handle and engine governor. The higher the air pressure the higher the engine speed. During idling, when the compressed air governor demands more air pressure for braking purposes, it automatically boosts the engine speed by supplying greater air pressure to control cylinder on governor. Hence, the same air compressor will work at normal speed when needed, and similarly the charging rate of battery will be maintained. This pneumatic control without definite steps furnishes any speeds from idling to full, and proves also a simple means for operating two locomotives from the same operating station on a multiple-unit control basis. A pneumatic interlock causes the engine speed to fall to zero momentarily previous to normal increase when the operator wishes to move locomotive.

For large main line locomotives it is my belief that a separate auxiliary engine unit of constant speed and a battery floating in connection with a main generator with drooping characteristics running at variable speed will prove the most satisfactory all around arrangement.

In conclusion I want to pay a tribute to the late Ward Leonard whose early work, against much opposition, has proven to be the foundation for all successful electric transmission in railroad practise, and I desire also to reiterate my appreciation of the fine engineering skill displayed, as evidenced by Mr. Freeman's paper, to bring to greater perfection the internal combustion engine locomotive and rail car, whose economical position is already accepted as a fact by the railroads.

**R. D. Krape:** It may be inferred from reading this paper that differential field control has become obsolete. Records of locomotive and rail car sales in the United States indicate that in 1929 not less than 85 per cent of all equipments sold used differential regulation.

Each form of control discussed has, of course, certain advantages peculiar to itself and under different conditions of operation, different types of regulation may be required. It is pertinent, however, to point out that differential field control is being used to a large extent today.

In the fourth paragraph of the synopsis of this paper, the statement is made that while differential control requires a minimum amount of equipment, battery charging and air compressor operation cannot be obtained at both operating and idling speeds of the engine. In our opinion at least 90 per cent of the oil electric locomotives in service in the United States today use differential field control and are equipped to supply air and battery charging at idling speeds of the engine. Furthermore, on the rail car, where these features are relatively less important, air and battery charging at idling with differential regulation have been successfully used. The inference may be drawn that the ability to operate the air compressor and charge the battery at idling engine speeds is peculiar to one form of control. Actually this is not the case, as pointed out above.

Any scheme of control depending upon electrical characteristics for engine loading has an inherent variation in characteristic due to temperature changes of apparatus. However these variations may be minimized in any such control scheme by proper design and correct use of materials. Any control scheme depending on mechanical characteristics for loading purposes, is unaffected by temperature variation of allied electrical equipment.

Fig. 10 illustrates the volt-ampere characteristic of a differential field exciter equipment with the *A* and *B* field on the main generator when running at constant speed. When connected to an internal combustion engine, the governor action of the engine regulates the speed to assist in maintaining the load on the engine. As the load decreases the engine increases in speed slightly, thereby permitting the generator to deliver a greater output since its output is very susceptible to a change in speed. The actual output of a generator when connected to an engine is, therefore, considerably closer to the capacity of the engine than that shown in Fig. 10. A more direct comparison between the two different types of differential control discussed might have been shown had Fig. 10 and Fig. 11 both been based on the same engine horsepower. Evidently Fig. 11 is based on an engine output much greater than that obtained under Fig. 10. With a full allowance for the effect of change in speed in each case and if based on the same size of engine, there would be little difference between the two curves over the normal working range.

It must not be overlooked that the field of application of gas-electric and oil-electric locomotives and rail cars is one where expert maintenance is not always to be obtained. It is highly important, therefore, that above all else the equipment be simple, sturdy, reliable and free from apparatus which increases slightly the theoretical engine utilization but in practise as a whole may decrease the availability of the equipment.

**N. L. Freeman:** Mr. Krape states that 85 per cent of the self-propelled equipment sales in 1929 were for equipments using differential control. This has little bearing on torque control since torque control is a very recent development and was in the process of being "road tested" in 1929. Torque control has many advantages, a fact which is not refuted by sales made while it was being developed. It is disappointing that Mr. Krape is not more specific concerning his figure of "90 per cent of the oil electric locomotives in service in the United States today use differential field control and are equipped to supply air and battery charging at idling speeds of the engine," particularly concerning the methods by which the battery and compressor were supplied current during idling.

The "inherent variation in characteristic due to temperature changes of apparatus" spoken of by Mr. Krape is at its worst in the differential equipments.

Mr. Krape's discussion of Figs. 10 and 11 can be answered by comparing Fig. 11 with Fig. 8 of Mr. Dodd's paper on *Electric Transmissions*. Fig. 11 is a "900 r. p. m., 400-hp." curve taken at constant speed and compares to curve *b*, Fig. 8 of Mr. Dodd's paper.

Mr. Lemp has presented a lot of very interesting information. Its substance, as well as the tone, is appreciated. He has, however, confused the torque control system with the oil governor on a well known oil engine. The torque control system is applicable to either oil or gasoline driven power plants. As far as the system is concerned, only overspeed and idle speed governors are required and the idle speed governor is not required on a gasoline engine. In either case the operator selects the desired throttle opening and engine operating speed. The torque control system functions to allow the engine to reach that speed with a light load and to prevent it exceeding speed by proper loading. In case the engine speed drops the load is dropped to permit the speed to rise. If the speed exceeds the assigned speed the load is increased to keep the speed constant.

We believe that time has already justified the use of contactors and relays on self-propelled equipments. Incidentally, there are no relays requiring recalibration as part of their maintenance in the torque control system.

# Electric Transmission and Control of Power
## From Internal Combustion Engines for Transportation

BY S. T. DODD*
Member, A. I. E. E.

***Synopsis.***—*The use of electric transmission is almost a necessity with large internal combustion power plants in transportation service. Furthermore, the interposition of the electric transmission provides a method of obtaining what is the equivalent of a wide change in gear ratio, as well as a cushioning of the characteristic power impulses of the internal combustion engine.*

*In adapting the internal combustion engine to this character of service there has been a number of problems, such as fitting the generator to the engine curve, the question of hand or automatic control, field control arrangements, single vs. multiple motor drive, and arrangement and operation of auxiliaries.*

*The use of the combination generator-battery power plant has recently received considerable attention. This application employs a battery operating in parallel with the engine generator power plant, capable of supplementing the power of the engine for short periods.*

*The characteristics of the engine used in transportation service must be well adapted to the duty required. These characteristics vary somewhat with the size of the unit and the control of the engine throttle is usually adapted to the particular problem in hand.*

*In this paper, the principal problems connected with the operation and design of complete engine generator units are discussed in detail and many typical schemes of connection are diagrammatically shown. No attempt is made to discuss the question of multiple power plant operation, although this would simply mean the addition of the necessary cross connections to operate the two power plants in parallel, unless, as is sometimes the case, the several power plants are operating independently of each other, each engine generator furnishing power to its own motors. In general, a fairly complete summary is given of the operation and design of this equipment as now used in American railway practice.*

* * * * *

TRANSPORTATION service presents certain characteristic demands on the power plant equipment which differentiate it, for example, from marine or industrial service. Such features as high tractive effort required for rapid acceleration, high sustained speeds required for main line train operation, intermittent demand on the power plant required in making up trains or switching cars or any combination of them may be demanded of the same power plant. With this characteristic in view, I have attempted in the following paper to discuss electric transmission as applied to an internal combustion engine for such service, pointing out some of the problems which have come up for solution in such applications and some of the solutions which have been found acceptable.

With any form of motive power there is required some form of transmission between the prime mover and the driving wheels. With an internal combustion engine, in order to meet the requirements of transportation service, there is required a transmission that offers the possibility of what is equivalent to a change in gear ratio. The necessity for this is almost self-evident. The successive impulses in an internal combustion engine are of an explosive character marked by a wide variation between maximum and minimum pressures. For various engine speeds the average torque produced at the engine shaft is approximately uniform. On the other hand, the resistance to be overcome in transportation is due to the movement of trains which develop an approximately uniform resistance at any given speed and cannot well respond to an explosive driving force as produced in an internal combustion engine. The total train resistance, including inertia, grade resistance, and train friction during the accelerating period may easily be ten times that of the same train when running free on the level. Such a train cannot effectively utilize the torque of a prime mover whose average value is approximately uniform at all speeds. In order to meet conditions varying so widely between the driving force on the one hand and the resistance to be overcome on the other, a transmission is required which can deliver at the driven shaft the output of the engine either in the form of high torque at low speeds or low torque at high speeds, the engine shaft in the meantime running at its normal torque and speed.

### A. Various Forms of Transmission

To meet this requirement a number of forms of transmission has been employed. Both hydraulic and pneumatic transmission has been used. In these forms of transmission a pump driven by the engine circulates some form of liquid or gas through appropriate motors on the driven axle. The pressure and volume of the circulating medium are varied by proper arrangement of valves or pump mechanism in order to vary the torque and speed of the driven motor. A description of the various devices has no place in the present paper. We can only say that in general all of these devices require the transmission of liquid or gas under high pressure through flexible pipes. In a locomotive or car such flexible high pressure piping presents a serious problem.

The most evident and simplest form of transmission is mechanical gearing between the engine shaft and the driving wheels. This has been widely used in automobiles and trucks where the problem of change in transmitted torque is solved by changing the gear ratio. When, however, it comes to applying such transmission to engines of the power, and to trains of the weight

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30-84

required in railroad service, the disadvantages of the mechanical solution are more evident.

A simple mechanical connection between the engine and the driven shaft is unquestionably more efficient than any other form of transmission. If the service required only one speed at full output of the engine, no other form of transmission need be considered. The driving of a fan or a rotary pump may be instanced as illustrating the field in which mechanical connection between an internal combustion engine and its driven

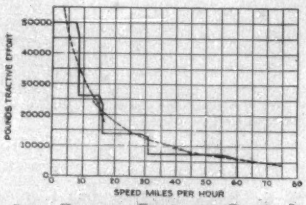


Fig. 1—Speed-Tractive Effort of Diesel Locomotive

Full line—mechanical transmission
Broken line—electric transmission

shaft might be suitable. In this case very little inertia is opposed at the driven shaft and the torque developed at that shaft rises to its full value with the speed. In transportation, on the other hand, where a high inertia is to be overcome, and the power of the prime mover is to be exerted over a wide range of tractive effort and speed, changes in gear ratio are required if mechanical connection is used between the driving and the driven shaft, and this introduces not only the complication and weight of gearing but other operating complications as well.

Fig. 1 shows superposed the speed-tractive effort characteristics of two 1300-hp. oil engine locomotives. The full line is the characteristic of a locomotive with mechanical transmission. The dotted curve is that of an oil-electric locomotive. The difference in operating results is immediately evident. The mechanical transmission is furnished with four different gear ratios. For each of these the locomotive develops an approximately constant tractive effort with speeds varying up to the maximum speed set by the maximum rotative speed of the engine. The result of this is that the curve of the mechanical transmission appears as a series of steps corresponding to the different gear ratios. At each of these the speed of the train is directly proportional to the rotative speed of the engine, the engine shaft and driving wheels being tied together by direct gearing.

a. For each of these gear ratios there is only one point where the engine is developing its normal rated horsepower. Therefore, in the whole of the mechanical transmission characteristic there are only four points where the full normal engine horsepower is utilized. The question of utilization of the full engine horsepower through a wide range of service is one that does not apply to an engine using mechanical transmission.

b. In changing from one gear ratio to the next, it is necessary to throw out the clutch; in other words, to entirely disconnect the engine from the driving mechanism. At the instant of making the change from one gearing to the next, the tractive effort falls to zero. When such a transmission is applied to a locomotive pulling a long train, such a change in tractive effort is certain to cause surges in the train, and from such reports as have been published on the operation of mechanical drive locomotives, it is evident that it is only by careful manipulation that broken couplings are avoided in handling long trains. Apparently no mechanical drive locomotive has been developed up to the present time which avoids this difficulty of losing tractive effort at the instant of making change from one gear ratio to the next.

c. The engine shaft and driving wheel being tied together by a mechanical gearing, the speed of one is fixed and limited by the other as long as the engine is coupled to the transmission gears. The maximum train speed at any gear ratio is fixed by the engine speed. The train cannot run at speeds higher than those corresponding to the engine speed without throwing out the clutch and even when coasting within the allowable limits of engine speed, the engine friction under idling

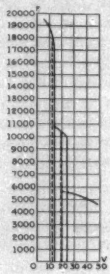


Fig. 2—Speed-Tractive Effort Diesel Locomotive with Mechanical Transmission

throttle will present considerable retardation to the train.

d. The rigidity of the connection between engine and driving wheels transmits road bed shocks and inequalities back to the engine. Engine builders complain of the effect of these shocks and the increased maintenance of engine resulting from them.

Fig. 2 shows the speed tractive effort curve of the Lomonossoff locomotive with mechanical gearing built for the Russian Railways and reported at the World Power Conference in 1928 (Report N-8, pp. 8 to 10). In this connection the report says: "Several breakages

of drawbar couplings occurred at the moment when the change of speed was effected. These breakages never happened later when trains were running on the line, but sometimes the couplings broke when the train was starting." This report appears to confirm the statements made in the preceding paragraphs.

### B. Electric Transmission

No extensive description is required of the electric drive. With this transmission the internal combustion engine drives a generator, and the current generated is utilized in motors connected to the driving wheels. Certain features of this transmission will at once be appreciated by anyone familiar with application of electric power.

a. There is entire freedom of location of apparatus. The position of the engine, for example, is not dependent upon its relations to the driving axles as is the case where mechanical gearing connects the two.

b. The engine is not subjected to road shocks or inequality of road bed reflected back through the transmission.

c. The location of the operator is independent of the engine. By means of remote control the locomotive may be operated from any position that may be selected.

d. Since the power of the engine is developed in the form of current and voltage, the same power may be obtained with a wide variation of values of current and voltage and a correspondingly wide range of tractive effort and speed at the driving motors.

e. This variation of voltage may be gradual through gradually increasing values corresponding to the decreasing values of current, thus obtaining a gradual variation of tractive effort and speed at the driving motors without sudden breaks or fluctuations as illustrated in Figs. 1 and 2.

f. The engine speed is not a rigid function of the speed of the train, so that advantage may be taken of idling the engine or of shutting it down with the train coasting at full speed, or the engine may be driven at normal or even at reduced speed, if more efficient, with the train running at its maximum speed.

While these general features are self-evident to anyone familiar with electric operation, the following sections discuss some of the problems that have presented themselves and the methods which have been used to solve them.

### C. Electric Transmission Problems

We have mentioned above the fact that with mechanical drive it is possible to utilize the engine horsepower only at a few limited points, while with electric drive it is possible to do so through a wide range of speed and tractive effort and with a gradual variation from one value to the next. A great deal of thought has been devoted by electrical engineers to the best method of obtaining this result.

*a. Fitting Generator to Engine Curve.* Fig. 3 presents three curves with amperes and volts as coordinates. Of these, Curve *a* is a rectangular hyperbola. The product of the two coordinates is constant. This represents, therefore, a constant output and may be called the "engine curve" as every point on it represents the same output. The ideal electric drive would require a generator with this characteristic which would develop a current at low voltages limited only by the slipping point of the wheels and a voltage at low currents limited only by the maximum safe locomotive or car speed. Such an ideal generator would fit the engine curve throughout. A practical generator, however, is limited in voltage by the commutating characteristics to a certain maximum voltage, and is limited by the carrying capacity of commutator and brushes to a certain maximum current. The characteristic of such a practical generator is shown in Curve *b* of Fig. 3. Points to the right hand side of the engine curve represent power in excess of the engine and are, therefore, impossible of attainment. For this reason it is necessary to devise some means of reducing the generator voltage for points

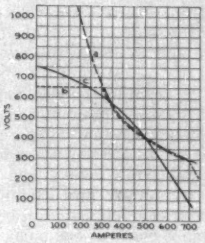


Fig. 3—Electric Transmission Characteristics

a— — — — Engine characteristics
b – – – – – Generator—manual regulation
c———— Generator—inherent regulation

lying between certain limits. Using as an illustration the values given in Fig. 3, when the current reaches 300 amperes the engine is fully loaded and beyond this point, the voltage must be reduced at a rate proportional to the increase of current if the generator curve is to follow the engine curve.

*b. Hand Control.* The most obvious method of obtaining this result is by hand control of the generator field. Fig. 4 shows a method of connection which has been used on a number of the early gas-electric cars in which the operator controlled the strength of the generator field by hand. To take full advantage of this method, it was necessary for the operator to hold the voltage by hand regulation of the field current at a point that would just load the engine to its full capacity and still not overload it. As a matter of fact, the operators soon developed a practical sense to guide them in selecting the proper setting of field strength, and with a skillful and careful operator no more efficient form of control could be devised; but it is evident

that a careless operator could easily hold a field strength which would either overload the engine or underload it. In neither of these conditions would he obtain a power output equal to the full capacity of the equipment.

*c. Automatic Differential Control.* Another method of control which is very widely used and which automatically approximates very closely the desired results is differential control. The results which can be obtained by this control are shown in Curve *c* of Fig. 3. In this the inherent regulation of the generator gives

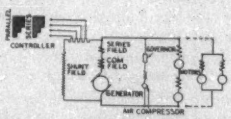


Fig. 4—Connections for Manual Control of Generator Voltage (See Curve B Fig. 3)

it a drooping characteristic so that it does not exceed a maximum given voltage at no-load nor a maximum current at full load, nor does it overrun the engine curve so as to overload the engine. A method of connection which has been used to obtain this result is shown in Fig. 5. In this the excitation of the main generator is obtained from a separate exciter mounted on the engine shaft. This separate excitation by itself would give an approximately constant voltage at all loads for a given engine speed. In addition the generator is wound with a differential series field giving it a drooping characteristic. By proper proportioning of the two fields the generator characteristic can be made to coincide with the engine curve at one point. If the generator curve slightly exceeds the engine curve, the result

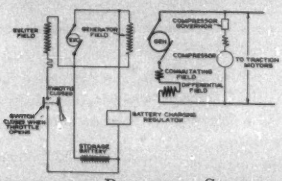


Fig. 5—Connections for Differential Control or Inherent Regulation of Generator Voltage (See Curve *c* Fig. 3)

will be that the engine will slow down, thus reducing the voltage coordinates of the characteristic and giving it a slightly concave shape at this point. In any event, the regulation of the engine governor has an important influence. If the generator curve just touches the engine curve and loads the engine at one point, the engine will carry less than its full load at points to one side and the other of the full load point with the result that in any case the generator characteristic will assume the shape shown in Fig. 6. Incidentally, the curve of Fig. 6 is the average of tests on five 200-kw. engine generator sets and can, therefore, be considered fairly representative of what may be found in a practical case. The exciter as shown in Fig. 5 derives its field initially from a storage battery. As the speed of the engine generator set increases, the voltage of the exciter rises, and when it reaches a value greater than that of the battery the automatic reverse current relay closes, the exciter begins charging the battery and becomes self-exciting.

Another modification of this connection is shown in

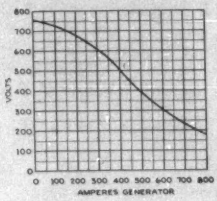


Fig. 6—Volt—Ampere Characteristic of Combined Engine Generator Set

Fig. 7 where the differential series field is applied to the exciter, and reduces the voltage of the exciter which in turn reduces the excitation of the main generator. The advantage of this method of connection is that the space required for the same effect, if applied to the exciter, is less than that required if applied to the main generator, and it therefore reduces the size, weight, and cost of the whole generator exciter equipment. A large majority of the internal combustion electrically driven rail cars and locomotives which are in service in the United States are equipped with one or the other of the two methods of connection, shown in Fig. 6 or Fig. 7.

We have mentioned above the use of an "exciter" for furnishing the necessary excitation to the main generator. The term "auxiliary generator" would perhaps

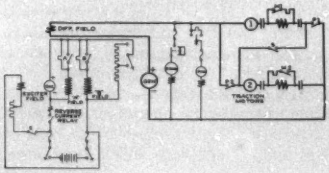


Fig. 7—Connections for Differential Control with Voltage Regulation Applied to Exciter

be a more general and comprehensive term as this carries other circuits besides the generator excitation. It is a little difficult to draw a sharp distinction between the two terms. In this paper when the main function of the machine is to furnish excitation we have used the term "exciter," and when additional circuits are carried from it, we have mentioned it as an "auxiliary generator." Possibly a more consistent convention would be to call it an "exciter" if driven from the same shaft

as the main engine, and an "auxiliary generator', when driven from a separate auxiliary engine, but as a description of the problems and circuits involved does not depend on the method of driving, we have not attempted to draw the distinction along this line.

*d. Battery Charging Field.* Fig. 7 introduces a variation which has not been mentioned up to this point but which is widely used; that is, in the use of a generator field winding in two sections, one of which,

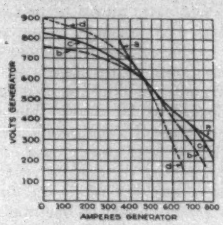


FIG. 8—VOLT-AMPERE CHARACTERISTIC

a—Engine curve 400-hp. engine
b—Generator characteristic constant speed
c—Generator characteristic considering engine regulation
d—Generator characteristic with "dual control"

the *A* field, is excited directly and continuously from the exciter and the other, the *B* field, is in series with the battery and is only excited when the exciter voltage is high enough for battery charging. This arrangement of the field has several functions.

(1) It improves the efficiency of battery charging. Considering as we are, a variable speed engine there must be a certain range in speed during which the battery is charged. An equipment which would charge the battery only at its maximum speed would not furnish sufficient battery charging for ordinary purposes and if the battery is to be charged through a range of speed and voltage a cushioning resistance must be inserted between the charging generator and the battery. The use of the *B* field as this cushioning resistance makes use for excitation of the power which would otherwise be wasted in a rheostat.

(2) It produces better battery charging characteristics than would be produced by a mere cushioning resistance. Since the *B* field adds to the voltage of the main generator, it follows that a given maximum voltage of that generator will be obtained with a lower excitation voltage than if the battery charging current flowed through a dead resistance. The fluctuations of battery charging current are, therefore, less when delivered through a *B* field than through a dead resistance of the same value.

(3) The *B* field has a still more important function in its effect on the generator characteristic. For rapid acceleration of the train it is necessary that the full engine output should be obtained as rapidly as possible. At full engine speed the generator excitation and torque should be such that the generator loads the engine to its full capacity. At the same time at speeds below full speed there should be a margin between the possible torque of the engine and that required by the generator in order to allow the engine to come rapidly up to speed. The use of the *B* field has the characteristic that the maximum excitation of the generator, *i. e.*, the sum of the *A* and *B* field, is not reached until the engine has come up to a speed sufficiently high to permit the exciter to charge the battery, at which time the *B* field adds its quota to the excitation of the generator and brings up the torque of the generator to balance the engine torque at full speed, load, and output.

*e. Single Motor vs. Multiple Motor Load.* One feature that is not always recognized is that different characteristics of the generator are advisable for a single motor load as compared with a multiple motor load. For a multiple motor equipment a wide range of correspondence between the engine and generator characteristics is not necessary as modifications in the connection of the motors can keep the generator working at or near the point where it fully loads the engine. Fig. 8 shows the engine and generator characteristics of a 400-hp. engine (Curve *a*) and generator (Curve *b*) at a normal speed of 900 rev. per min. Curve *c* shows the effect of engine speed variation on the shape of the generator curve. The Curves *a* and *c* practically coincide through the range from 600 volts, 450 amperes down to 350 volts, 700 amperes. An equipment of two GE-297 motors would be conveniently used with such an engine generator set. Fig. 9 shows the speed-

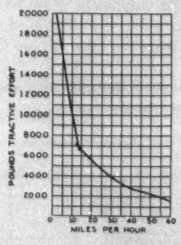


FIG. 9—SPEED-TRACTIVE EFFORT CURVE

Equipment:
1—400-hp. engine
1—Generator, differential control
2—GE-297 motors

tractive effort characteristics of such an equipment. The maximum tractive effort of 20,000 lb. is exerted at 700 amperes per motor in the series position. The change in the controller from series to parallel occurs at 15 mi. per hr., which corresponds to a current of 330 amperes. The generator load (referring to Fig. 8) is therefore changed at this point from 330 amperes and 700 volts to 660 amperes and 400 volts. The change from parallel connection to shunted field connection

occurs at 200 amperes and changes the generator load from 400 amperes and 650 volts to 480 amperes and 550 volts. The effect of this is that through most of the range of the control the generator and engine are running at very nearly their full load. Fig. 10 shows more evidently how nearly the full horsepower of the engine is used throughout the range.

*f. Full Utilization of Engine Power.* Where, on the other hand, only one motor is driven from one engine generator set a wider range of contact is advisable between engine and generator curve, since a variation in the tractive effort can no longer be obtained by varying the combinations of motor circuits, but can only be obtained by variations in the current delivered by the generator. Also, where on account of limited engine power or exacting service conditions, it is desired to use the engine equipment more nearly to its full capacity than shown on Fig. 10, the complications and cost of an equipment for that purpose may have to be considered.

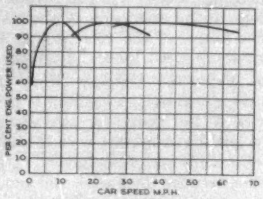


Fig. 10—Available Power

Equipment:
1—400-hp. engine
1—Generator, differential control
2—GE-297 motors

A simple method of thus obtaining a wider use of the engine power is by use of "dual control." Fig. 11 shows

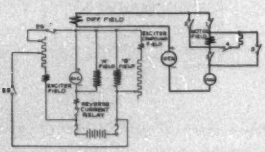


Fig 11—Connections for Dual Control. See Curve *c* Fig. 8

shows the same connections already discussed, but with the addition of a switch *E S* which alters the resistance in series with the exciter field. When switch *E S* is closed and *E B* is open, the exciter becomes self-exciting; its characteristic and therefore that of the main generator becomes steeper and more sensitive to variations in engine speed or differential field current. The characteristic will therefore take a higher and steeper form as shown in Curve *D* of Fig. 8. This switch *E S* may either be a manually operated switch as a part of the controller, or may be a contactor operated by a relay at a predetermined current value. If such an arrangement were used in the case which has been used as an illustration in Figs. 9 and 10, a convenient value for operating this relay would be approximately 450 amperes. With this addition the characteristics of the generator would lie along the line *d* from no load to 450 amperes and along the line *b* for current values above that point.

Where a still wider utilization of the engine power is desired, some automatic means of progressively varying the generator field must be employed. Referring again to Fig. 4, which shows the simplest form of connection, the excitation of the generator must be controlled by some automatic means in order to keep the engine fully loaded at all times, thus automatically reproducing the action of a competent and careful engineer. The relay or other device used for this purpose can be arranged to vary the field current to maintain a constant value of any one of several functions. For example, such a device might be operated in connection with a wattmeter or a speed indicator to maintain in one case a constant value of kilowatt output, or, in the other case, a constant speed; or with some other device, to maintain a constant value of some other function. As a matter of practise, the generator is made

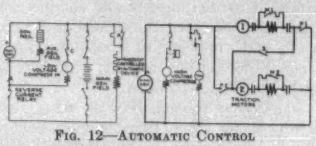


Fig. 12—Automatic Control

separately excited rather than self-excited as shown in Fig. 4. This maintains the field strength for each setting of the rheostat more accurately and definitely than could be obtained by self-excitation. Fig. 12 shows the connections for such a control in which the excitation of the main generator is taken from the auxiliary generator through a rheostat whose resistance is automatically controlled.

One application of such a device as has been described above is an arrangement in which the resistance in series with the generator field is controlled by a relay of which one element corresponds to the current in the generator field and the other to the current in the generator armature. The neutral position of this relay corresponds to some product of the field current and armature current in the main generator. Any variation in load on the generator causes the relay to move so as to adjust the generator field to a value such that the product of the field current and armature current is brought back to the original predetermined value or torque. This evidently demands a certain torque out of the engine independent of the engine condition. For other than full engine speed the torque relay must be adjusted to correspond to the torque of the engine at those speeds.

Another plan for wide utilization of the engine power is based on maintaining a constant engine speed. In this the resistance in series with the generator field is controlled by a relay which in turn is controlled by the engine governor. This relay, therefore, adjusts the strength of the generator field and voltage to such a value that it will hold a given speed of the engine for any value of the armature current. Independently

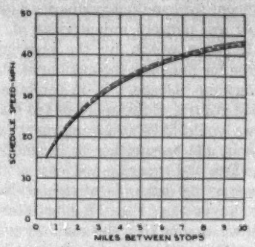


Fig. 13—Schedule Speed 115-Ton Train

400-Hp. gas-electric equipment
——— Differential generator constant speed
– – – Differential generator with engine regulation
— — Automatic control maximum utilization of engine power

of the engine condition this control, therefore, will always bring the engine back to the normal speed and if the engine, for example, will not deliver its full horsepower the generator output will be cut town to correspond. For other than full engine speed the relay must be changed to correspond to the new engine speed simultaneously with the new setting of the engine speed governor.

Whether any plan for full utilization is to be recommended depends upon economic considerations. It is obvious that with the best utilization the voltage is limited on the one hand and the armature current on the other by generator design. The curves of Fig. 13 have been worked up to show the schedules which are obtainable with a 115-ton train and a 400-hp. engine generator set. The lower curve indicates the schedule obtainable with differential control, the engine running at a constant speed, and the upper curve shows the schedule obtainable with full utilization of the engine power through the maximum ranges of voltage and current. As has been mentioned previously, even with differential control the engine regulation or the use of the *B* field will cause a certain amount of shifting of the differential characteristic up toward the full utilization curve and the actual result will be that the differential control will give schedules indicated by the dotted line running about midway between the theoretical differential control and the theoretical full utilization control. Whether the addition of the devices necessary to obtain any form of automatic field control as compared with those required for the simple inherent characteristics of the so-called differential control is or is not justified, can only be decided by economic considerations such as price, cost of maintenance, and the results of practical operation.

*g. Auxiliaries at Idling.* Nothing has been said as to the operation of auxiliary circuits such as compressors, ventilating fans, etc. Most of the illustrations up to this point have shown these circuits as connected to the main generator circuit. This naturally involves variable voltage on the auxiliary circuits with variable speeds and output. A large number of equipments, both on cars and locomotives, have been installed with this arrangement and are in satisfactory practical operation. When it comes to a question of traffic more exacting or complicated in its demands it may be found that some more elaborate arrangement is necessary. This requirement would naturally be presented first on locomotives used for switching service. Here the engine is idling during a large fraction of the time that the locomotive is in service. During the time involved in waiting at switches and making up trains although the engine may be idling, full air pressure is required for brakes and the battery must be kept charged. For motor car service this requirement is not so insistent as the engine is running at full speed during the greater proportion of the time that the car is in service; but even here certain schedules may demonstrate the advantages of compressor operation and battery charging at idling speeds. Where a long grade offers the possibility of coasting without power, it should be possible to take advantage of the characteristics of electrical operation and allow the engine to run at idling speed; and occasionally other classes of service are encountered where long periods of operation at reduced power offer an advantage in air compressor operation or battery charging at idling speed of the engine. Several plans have been evolved to meet this condition.

Fig. 14 shows an arrangement of equipment which has

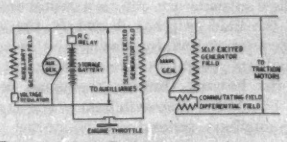


Fig. 14—Differential Control with Constant Voltage on Auxiliaries

been widely used on locomotives. In this scheme of connection the auxiliary generator is equipped with a voltage regulator which holds its voltage constant through the operating range of the engine speed. The storage battery, generator field, and all auxiliaries are wound for the voltage carried on the auxiliary generator. It will be noted that there is now no necessity for a charging resistance in series with the battery and the possibility of using the *B* field which has been previously described is eliminated. In order to com-

pensate for this the generator is given a certain amount of self exciting field which has the same effect as the $B$ field in that it brings up the voltage and torque of the generator as it comes up to full speed and loads the engine at this point, although leaving a reduced voltage and reduced torque at lower speeds.

The plan last described is one that is particularly applicable to equipments in which an oil engine is the prime mover. The idling speed of an oil engine is approximately 50 per cent of its normal speed and it is

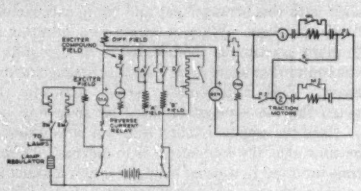


FIG. 15—VARIABLE VOLTAGE ON AUXILIARIES, BUT OPERATION AT IDLING SPEEDS

perfectly feasible to design an auxiliary generator of sufficient capacity to hold its full voltage down to half speed. A gasoline engine, however, frequently has an idling speed of 20 per cent of its full speed and an auxiliary generator with capacity for holding full voltage down to 20 per cent of its full speed would involve a serious increase in weight and dimensions. Fig. 15 shows a scheme of connections which has been applied to motor car equipments. It avoids the excessive size of auxiliary generator and partially meets the requirement of furnishing air and battery charging. In this case the compressor is carried on the auxiliary generator. At normal speeds this auxiliary generator is excited through a switch $E\ N$ to normal voltage. At idling speeds the motor circuits are opened, the generator field circuits are cut to a minimum by the opening of the field switches $A$ and $B$, the auxiliary generator is over-excited by closing the switch $E\ N$, and the auxiliary generator develops sufficient voltage to charge the battery through the small resistance introduced by closing the switch $D$. The compound field of the auxiliary generator is connected in series with the compressor so that when the compressor starts it still further builds up or at least maintains this voltage. As a general thing, in order to keep the size of the auxiliary generator as small as possible, no attempt is made to maintain full voltage on this generator at idling and the compressor does not develop its full rating under these conditions.

A number of other combinations has been suggested. One is operating the auxiliaries from the low voltage auxiliary generator during full speed and shifting the connections to the main generator in order to take advantage of whatever voltage it may develop during idling. Other combinations of circuits have been proposed with the general intention of utilizing what voltage is available at reduced speeds. None of these combinations being of wide practical application, we have not discussed or illustrated the details of the connections. Still other combinations of circuits to obtain similar results will suggest themselves to others interested in the subject.

The plans discussed above readily indicate that the ideal arrangement for handling auxiliaries would be one in which they are entirely independent of the main generator. In other words, by the installation of a separate engine for handling the auxiliaries at constant speed and constant voltage. If, in combination with this, automatic control of the speed of the main engine is installed, we would have an arrangement that would be applicable in all cases, either to locomotive or car equipments where the capacity and cost of the equipment or the exacting demands of the service make it economically advisable. Fig. 12 illustrates this arrangement, if we assume that the auxiliary generator is operated by a separate engine at constant speed and furnishes power for a compressor, the main generator field and battery charging. In order to reduce the size of auxiliary equipment, a high-voltage compressor is carried on the main generator and when the engine is at full speed, full air capacity is obtained from the two compressors in parallel.

*h. Combination Generator-Battery Power Plant.* A form of electric transmission which presents some striking advantages and which seems to have a wide application is the use of a storage battery in parallel with the main generator. Fig. 16 shows a diagram of connections for such an equipment and it will be noted that the arrangement of the equipment is radically altered by the introduction of the battery.

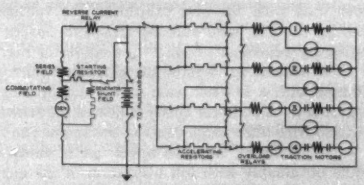


FIG. 16—CONNECTIONS FOR COMBINATION GENERATOR-BATTERY POWER PLANT

No exciter is required as the excitation and all auxiliary operation is taken from the battery.

The generator operates at a constant speed and approximately constant voltage as required for battery charging.

The battery carries all the peak loads, leaving the generator and engine to carry a fairly uniform load. The generator load is added to the battery output in periods of high demand and is expended in charging the battery when the load falls off. This uniform load

and high load factor is apparent in its effect on the fuel efficiency and engine maintenance.

Since the battery maintains an approximately constant voltage, the control is of the constant potential type similar to that on equipments using trolley or other constant potential source of power. In general, the equipment and its control is so similar to trolley control and operation that it would not be mentioned in this paper except that it illustrates one of the combinations which are used in transforming the power of an internal combustion engine into power for traction purposes.

### D. Engine Characteristics as Affecting Electric Equipment

Up to this point the discussion has confined itself to control of the power transmitted at full output of the engine. It is necessary to operate and control such an equipment also at reduced output either during acceleration or during operation of trains at reduced speeds. The features of the electric control for such reduced power are conditioned largely on the engine characteristics and control. It is necessary to distinguish therefore between engines for constant speed and engines for variable speed, and between engines of different capacity.

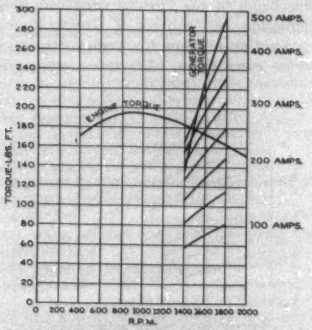


Fig. 17—Speed-Torque Characteristics 55-hp. Engine and Self-Excited Generator

With an engine designed for constant speed, the control of the train speed is necessarily by control of the generator voltage. This type of engine running at a constant speed with voltage control has not been widely used in this country although it is used in Europe.

The equipment used in this country generally obtains reduced output and control of the train speed by varying the engine speed. While this is true in a general sense the problem presented varies with the type of engine. It is frequently stated as a fact that the torque of an internal combustion engine is approximately constant. Whether the electric equipment is to be adjusted to take advantage of this torque depends on the design of the engine.

*a. Small Engines.* For small engines, such as are used on busses, for example, the full torque of the engine is generally available at all engine speeds. The bus generator is therefore designed to deliver a torque equal to the full torque of the engine within normal operating limits which may be 75 per cent to 100 per cent of full speed. Fig. 17 shows the torque curve of a typical bus engine and the torque curves of the corresponding generator with normal excitation at various speeds. It will be seen that the full torque on the generator at full speed may far exceed that of the engine. The generator can therefore absorb the full

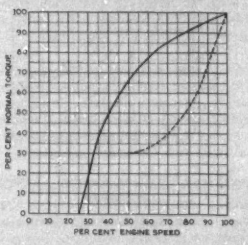


Fig. 18—Variation in Engine Torque Characteristics

torque of the engine at full speed. By over-excitation of the generator this torque can be raised so as to cut the torque at still lower speeds and this is a method very generally used on such equipments.

As a general thing the following represents the sequence of acceleration and operation of such an equipment.

The bus is accelerated at full engine speed and full load which is obtained by a partially excited field. After the full running speed has been obtained, the generator is excited to its full excitation, the increased torque on the generator pulls down the engine speed, and a balance is obtained with the engine at perhaps 75 per cent of its full speed driving the generator at full voltage with full field. When more power than this is desired the generator field is weakened, allowing the engine to come up to full speed and full horsepower. Stated in other words it may be said that with an engine of this sort it is possible to operate the torque of the generator balanced directly against the maximum torque of the engine at that speed. This scheme of operation can only be used with an engine of such design that the generator torque can be allowed to absorb all the torque of the engine.

One comment should be made on the curves of Fig. 17. The torque curve of the engine there shown, although typical of engines as they are designed today, is not

what is most desirable for electric transmission. The peak value of this torque curve occurs at less than 50 per cent of full speed. A more satisfactory engine would be one that carried its maximum torque at a higher fraction of full speed; in fact, for electric transmission it would be preferable to have a constant torque of the engine within the range of operation, and one which did not fall off with increasing speeds.

*b. Large Engines.* With engines as they are designed today we find that when we reach a certain capacity the engine designers raise objection from the standpoint of excessive pressure on engine bearings, excessive temperatures of exhaust gases, danger of

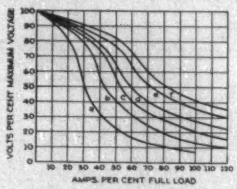


Fig. 19—Generator Characteristics. Throttle Control of Engine

Curves a, b, c etc. represent various throttle openings

pre-ignition and other features to an electric equipment which will absorb the full torque possible from the engine at reduced speeds. If such a requirement is to be met the field and torque of the generator must be modified to correspond to the desirable engine torque. This will generally be done by operating a section of the generator field rheostat in connection with the engine control handle so as to change the generator field simultaneously with the engine speed. What that reduction amounts to and the characteristics of the equipment at various speeds depends entirely on the engine design. As an illustration the curves of Fig. 18 show various conditions of torque which have been encountered in practise as affecting the design of electric equipment.

*c. Engine Control.* In connection with the combination of engine and generator the generator characteristics are affected by the question of whether the engine speed is controlled by the throttle or by adjustment of the governor. In the one case the fuel supply is limited to hold down the maximum horsepower output but at light loads the engine runs up to its full speed. In the other case, the speed is maintained at any step of the control independently of the load. The consequent difference in the shapes of the generator characteristics on various steps is best seen in the curves of Figs. 19 and 20. Both of the equipments in question are of approximately the same power and designed for approximately the same service and graduation of control steps. Fig. 19 illustrates the characteristics produced by throttle control of the engine and Fig. 20 those produced by governor control of the engine.

## E. Conclusion

We have said nothing in regard to multiple power plants consisting of more than one engine generator set. The variations in connections which would be introduced by such a multiplication of power plants would seem to be self-evident. For any of the typical schemes of connection which have been discussed, the addition of another engine generator set would simply mean the addition of the necessary cross connections to operate the two plants in parallel, unless as is sometimes the case the several plants are operated independently of each other, each engine generator set furnishing power to its own motors. The additional illustrations covering such combinations have been omitted as they would unnecessarily complicate the discussion.

It may seem to one unfamiliar with this topic that the various questions raised in this paper and the various solutions indicated are illustrative of the complexity of electrical transmission and control. On the contrary we have shown some of the problems which present themselves for solution, and the questions which we have discussed are only another illustration of the adaptability of electric drive to meet varying conditions.

The discussion of the various problems presented in the transmission and control of electric power for internal combustion engines for transportation is not assumed to be exhaustive. We have attempted to de-

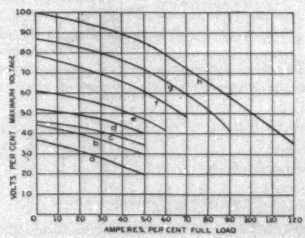


Fig. 20—Generator Characteristics. Governor Control of Engine

Curves a, b, c, etc. represent various governor settings and engine speeds

scribe some of the principal problems presenting themselves to an operating and designing engineer working on the subject, as well as some of the solutions of these problems. Other problems will present themselves under new conditions and other connections and other solutions will suggest themselves to other engineers. We believe, however, that we have given a very fair summary of the situation as it is presented in American railway practise.

## Discussion

**H. Rosenthal:** In comparing the characteristic of an oil-electric locomotive with a mechanical transmission having four different gear ratios, Mr. Dodd says—

> "For each of these gear ratios there is only one point where the engine is developing its normal rated horsepower. Therefore, in the whole of the mechanical transmission characteristics there are only four points where the full normal horsepower is utilized."

While this statement is essentially correct, it does not indicate the infrequency in operation with which the full engine horsepower could be utilized.

With the four different gear ratio transmission, there are four car speeds (each corresponding to the same engine speed) where the engine could develop maximum horsepower. With the car operating at any one of these speeds, the amount of power utilized by the car will depend not on the amount of power which the engine can deliver at that speed but on the tractive resistance of the vehicle, and for any particular car and condition of the road bed at that speed there will be only one grade at which the full engine horsepower can be utilized.

Thus at only four car speeds can the engine develop the maximum horsepower, and on only a single grade at each of these four speeds can the vehicle absorb this maximum power.

**T. H. Murphy:** Mr. Dodd's paper is of considerable interest to electrical engineers who are concerned with the design and application of equipment for railroad automotive rolling stock. In conclusion, he points out the fact that electrical transmission is very flexible and may be adapted to meet any of the conditions required without excessive complication.

Engineers disagree only as to the extent to which the electrical equipment shall perform the desired functions. In the development stages, when engines were the real unknown factors, the simplest electrical transmissions were used with little thought to the best automatic loading and operation of auxiliaries. Hand and automatic differential control were used in various forms on the early cars. Now that engines have proven reliable in service, more importance is attached to the transmission and much thought has been given to eliminate or improve the undesirable loading features of the early schemes and to furnish satisfactory operation of the necessary auxiliary equipment.

The essentials of a modern control are:

1. Economical transmission of power.
2. Automatic full-speed compressor operation at all times.
3. Ample supply of power for battery charging.
4. Full loading of the engine over a wide range of vehicle speed.

Attempts are made to combine all of these features in the present day transmission systems.

Mr. Dodd's paper gives in detail the developments with differential equipment to obtain the essentials of a modern control but I do not believe that he stresses sufficiently other control systems. The no load voltage of Curve *B* is only 650 and that for Curve *C* 750. The comparison may be for different size machines. Further *C* crosses the engine curve and obviously produces an overload. The more efficient use of the engine by manual regulation would be indicated if Curve *C* were drawn to just touch the engine curve, as was done for Fig. 6, and the same no load voltage for the two machines used.

In describing the combined action of the engine and electrical equipment, Mr. Dodd states that concavity is produced by slowing down the engine. This is not shown by any curves. An opposite effect is shown, and that is a speeding up of the engine. If this is permissible with differential control, then higher loading speeds should be permitted with other forms of control. The result will be an increase in the performance difference between differential control and ideal loading.

Curves in Figs. 3, 6, and 8, indicate fixed characteristics built into the electrical equipment. Advance thought in electrical control has discarded the idea of constant characteristics, as it is well known that available engine power changes rapidly with engine temperature, atmospheric conditions, altitude and engine conditions. The system of control to be adopted should, therefore, provide automatic, flexible loading of the engine. When constant characteristics are built into the equipment, the maximum loading must be fixed below the normal minimum engine capabilities in order to prevent continuous overloading and low engine speed.

As pointed out by Mr. Dodd, a torque control has been developed that maintains a constant engine speed. This control is mechanically operated by the engine governor in one case and in the other by a voltage regulator that maintains constant engine speed. In either case the engine is uniformly loaded under all conditions.

With these schemes, devices are necessary in the generator field for regulation, but these are offset by the better loading obtained and the use of smaller generators. It can be seen from Fig. 8 that ideal loading could be obtained with a smaller generator than the one for which the curve is drawn.

Operation of auxiliary equipment is a very important item on gas-electric equipments. The use of the scheme shown by Fig. 14, requires a large auxiliary generator and a large main generator, thereby increasing the cost, weight and space of the electrical equipment. It has been found that it is a relatively simple and easy matter to operate the compressor and charge the battery from the main generator at idling speeds. No special apparatus is necessary in the auxiliary generator field to compensate for wide speed variation. From a theoretical standpoint, a separate engine undoubtedly presents desirable possibilities for operating auxiliaries, but from a practical standpoint, it has yet to be proven whether the additional maintenance required for this small engine will permit of its use.

Mr. Dodd has brought out the fact that the *B* field functions in connection with the battery charging and engine loading. It should be pointed out that the value of battery charging current is a function of the state of battery charge, and that, therefore, the strength of the *B* field must be a function of the battery condition. This means that engine loading must be somewhat dependent on battery condition. But this does not appear logical or justifiable. Furthermore, in studying the indicated differential control systems, it should be remembered that the auxiliary generator voltage varies almost as widely as the generator voltage. This means an unsatisfactory source of battery charging power, and the battery is apt to suffer. Charging regulators and lamps have been used in order to hold the battery charging current to a somewhat constant value. These devices have been merely a means of saving the battery from an inadequate charging source, and at best, the charging current must vary widely, be difficult of adjustment, besides being apparently difficult to maintain a fully charged battery without serious overcharge.

# Auxiliaries for High-Voltage D-C. Multiple Unit Cars

BY C. J. AXTELL[1]
Associate, A. I. E. E.

***Synopsis.***—*The selection and application of auxiliary electrical devices on a high-voltage multiple unit car is of almost as much importance as the application of the main traction apparatus and requires careful consideration.*

*This paper contains a description of the engineering features as worked out for electrified suburban lines operating on 1500-volt and 3000-volt systems.*

*The control circuits have become very generally standardized at 32-volts, which is also well adapted for interior illumination and headlights. A motor driven generator supplies 3- to 5-kw. power per unit for control lights and battery charging. Such devices as heaters and motor-generator sets, requiring a considerable amount of electrical power, are necessarily constructed to operate at trolley potential. On the 1500-volt system, the compressor can be operated directly from the line potential while on the 3000-volt systems, a double commutator motor driving the generator supplies a 1500-volt source of power for the compressor.*

* * * * *

ON any electric car used in a service where multiple unit operation is required, there is a number of electric devices other than those required to actually control the propulsion of the car. Among the more important are the air compressors, heaters, lights, headlights, electric control of air brakes, automatic couplers, whistles or horns, signals, etc. Some of these devices require several kilowatts of power; others but a few watts.

For the control of reasonably large amounts of power,

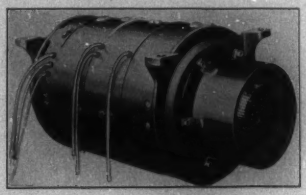

FIG. 1—3000-VOLT DYNAMOTOR GENERATOR

equipment can be economically made to handle power from either 1500-volt or 3000-volt sources. There are, however, many of the smaller devices where such a high potential would necessitate the use of insulating materials entirely out of proportion to the size and importance of the device. Consequently the use of a low-voltage current supply has been very generally adopted for these secondary circuits. Another reason, by no means an unimportant one, is the necessity for having a low-voltage source of power for the headlights, where high-speed operation in suburban zones is required. One of the requirements of a good headlight is that the filament be concentrated as nearly as possible to the focus of a parabolic mirror. This requires a short, thick filament operating at a low voltage. Since it projects an intense light down the track and also produces sufficient diffusion at the side to illuminate the right of way, a 32-volt lamp gives almost ideal headlighting. Fortunately the 32-volt source of power is also ideal for the control and auxiliary circuits. Furthermore, since cars for this class of service must have an auxiliary battery for lighting in case of the failure of power from the distributing system, a 32-volt secondary potential can be most advantageously used.

The only auxiliary device taking any appreciable amount of power, (except the heaters, which can be operated directly from the trolley source of potential), is the air compressor. On any system up to and including that with a 1500-volt trolley, the compressor

FIG. 2—ARMATURE OF 3000-VOLT DYNAMIC GENERATOR

will operate directly from the line potential. At the higher potentials, such as 3000 volts, the use of a dynamotor generator set fulfills the requirements. The dynamotor of this set has a dual function; the first, to furnish a source of power of one-half the line voltage for the operation of the air compressor, the second, to drive a small generator to supply current for the control, lights, headlight and other auxiliary circuits and also to maintain the auxiliary battery in a charged state. Since the dynamotor speed will vary with the line potential, it is necessary to provide a voltage regulator for the generator. The generator potential to be held will be governed by the lamps used and the number of cells and type of battery. With such a set, the battery can be floated continuously across the generator and kept in a fully charged condition.

1. Transportation Engg. Dept., General Electric Company, Erie, Pa.

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30-109

A description of the auxiliaries of two of the modern electrified steam railroad systems using high-voltage direct current, and operating multiple unit cars, may be of interest.

The Illinois Central Railroad suburban electrification in Chicago has a system potential of 1500 volts. This service is operated with 150 units, each consisting of a motor car and a trail car semi-permanently coupled. The length of the two-car unit is 145 ft. 5 in.; the weight, approximately 114 ton.

The Delaware, Lackawanna and Western Railroad

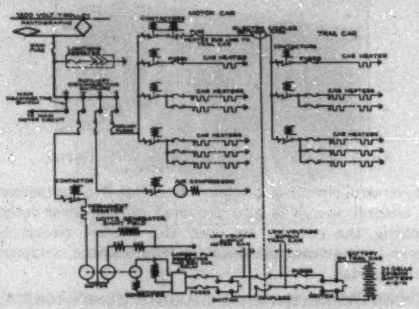


Fig. 3—Typical Connection Diagram of High-Voltage Circuits for 1500-Volt Multiple Unit Cars

suburban line, at Hoboken, N. J., is being electrified for operation at 3000 volts. There will be 141 units, each consisting of a motor car and trailer. The size of the cars is practically the same as those used by the Illinois Central Railroad.

The auxiliary devices and the source of power for supplying them are as follows:

| Apparatus | Source of power |
|---|---|
| Electric heaters | Directly from trolley |
| Motor-generator (1500 volts) | " " " |
| Dynamotor generator (3000 volts) | " " " |
| Air compressor (1500-volt system) | " " " |
| (3000-volt system) | From mid-point of dynamotor |
| Lights, headlights, control current for motor controller, pantograph, heaters, compressor, doors, whistle or horn, signal, etc. | From generator or battery |

## Heaters

Electric heaters are now manufactured for operating directly from 1500-volt or 3000-volt sources of power and are arranged for underseat mounting. The heaters are of the same general outward appearance as have long been used on 600-volt systems. The heater element, however, is of greatly improved type. It is constructed as a helical coil imbedded in highly refractory insulating material in a steel tube. Thus the actual resistance wire is the completely protected. The regulations of the National Board of Fire Underwriters require that the temperature of the heater casing be limited to a relatively low value, which results in the operation of the heater elements at a much lower rating than is used in other classes of service. A high factor of safety exists therefore between the unit rating as applied to the heater and the actual point at which the heater element would fail.

On the multiple unit suburban cars of the Delaware, Lackawanna and Western electrification, the heaters operating from the 3000-volt trolley are placed under the seats. The main heaters consist of two 14-kw. circuits per car. Each circuit has forty 75-volt 350-watt elements in series. The heaters are distributed so that one unit in each circuit is mounted in a heater casing under each seat. On these 3000-volt heaters, there are two insulations in series between the resistor wire and the sheet steel casing. The wire imbedded in its steel sheath is tested at a potential of 3500 volts a-c. for one minute. The sheath of the unit is insulated from the steel casing with porcelain insulators. The complete heater receives a high-potential test of 10,000 volts, alternating current, for one minute from resistance element to casing.

The heater units are so mounted in the steel casing that all terminals and live parts are completely protected and the ventilating louvers arranged to prevent any possibility of inserting an umbrella rod, wire, or any conductor into the case, so that it could make a

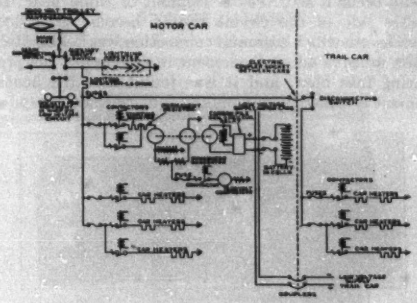


Fig. 4—Typical Connection Diagram of High-Voltage Circuits for 3000-Volt Multiple Unit Cars

contact with the heater sheath or any live part. The heater casings are individually grounded to a No. 6 A. w. g. ground cable, running the length of the car on each side and connected at both ends to the car underframe. These individual heater circuits are protected by 8-ampere fuses of the expulsion type.

The heat in the car is thermostatically controlled to maintain a constant temperature; 3000-volt magnetically operated contactors open and close the circuits for the heaters. These contactors are mounted in a

box underneath the car together with contactors for other auxiliary circuits. This type of contactor is used to permit switching on the heat, to warm up the cars previous to putting them in service, without having to maintain air pressure for operating electropneumatic contactors.

In each operating vestibule are three heaters of two, three, and five elements each. These heater

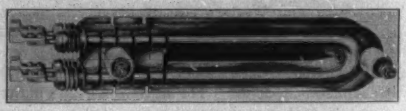

Fig. 5—3000-Volt Car Heater Units

elements are rated 340 watts each, thus providing a total heater capacity of 3400 watts for the vestibule. The cab heater is controlled independent of the car heaters. A push-button switch is provided in the cab to switch the heaters on and off. This switch is also arranged so that it will be opened and shut off power to the heaters if the compartment door is closed, as is the case on all but the operating cab. Trail car heater equipment is a duplicate of the motor car, power being taken to the trail car through a 3000-volt auxiliary bus line located on the roof of the car.

During the development of these electric heaters, tests were made to determine what disturbance, if any, would occur if some heater element or cable near the trolley side of the circuit should become grounded. On a test in which a ground connection was deliberately made to leave only one element in the circuit, the protecting fuse blew, and it was found that the heater element had also open-circuited, but was not grounded

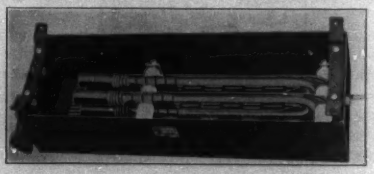

Fig. 6—3000-Volt Car Heater

to its enclosing sheath. No noise or flash was perceptible in the heater case. Tests were also made with a greater number of heater elements in the circuit, under which condition, the fuse protected the circuit completely and the heater elements were not damaged. If the heater element fails, it simply opens up the circuit as does a fuse, but without grounding to the sheath or causing any disturbance. To determine whether or not, after this abuse, the resistor unit was open-circuited, it was necessary to test the unit. The above 3000-volt heaters were manufactured after the same general design as those which had been in service on the 1500-volt electrification of the Illinois Central Railroad, the principal differences being in the increased insulation used on the higher voltage heaters.

The control of the 1500-volt and the 3000-volt heaters is practically the same; the 1500-volt current supply for the heater on the trail car on the Illinois Central Railroad cars is carried through a special 1500-volt contact in the automatic electric car coupler. Provision is made, if the cars should pull apart, to open

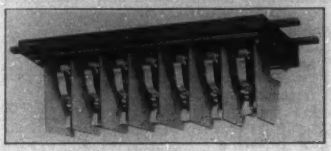

Fig. 7—1500-Volt Auxiliary Contactor Group

the control circuit of the two heater bus-line contactors. A control switch is also provided on the lever interlocking the coupler to open the control circuit of these contactors previous to the electric couplers being parted.

## Motor-Generator and Dynamotor Generator Sets

To supply the various devices with low-voltage source of power, a motor operating from the line potential driving a generator of sufficient capacity for the low-voltage auxiliary circuits is used. On the 1500-volt

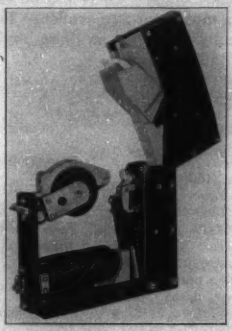

Fig. 8—3000-Volt Auxiliary Contactor

electrification of the Illinois Central, a motor-generator set of 3.5-kw. capacity was used. The set consists of a motor and a generator in a single frame. The motor is a compound-wound machine with sufficient series field to give good starting characteristics when connected directly to the line, and to produce a stable machine operating on a trolley of fluctuating potential. A permanent resistance of approximately six ohms is

used to cut down the first rush of current when starting, and permit the use of a smaller fuse to protect the motor, although it also acts to cut down any current surges which might result from rapid fluctuations of the trolley potential.

The motor is a double-commutator machine, each armature winding operating on 750 volts. The set is of two-bearing design with one ball bearing and one roller bearing, the latter to allow for the slight longitudinal movement necessary. A fan mounted between the generator and motor armature provides for venti-

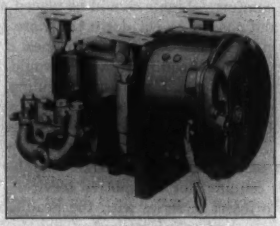

Fig. 9—1500-Volt Air Compressor

lation. The generator is a compound-wound machine, having a rating of 3.5 kw. at 37 volts. For one unit, consisting of motor car and trailer it supplies all of the low-voltage power. The generator on the Illinois Central cars operates at a potential held constant by a carbon pile voltage regulator. The design of the set permits the generator to hold a constant voltage output on any trolley potential from a minimum of 1200 volts to a maximum of 1650 volts. The weight of the motor-generator set is 1300 lb.

On the multiple unit cars of the Delaware, Lackawanna & Western 3000-volt electrification, a dynamotor generator set is used. In general mechanical construction, this is similar to the motor-generator set described. The motor in this set, however, has a dual function, in that it supplies as a dynamotor a potential of one-half trolley voltage for the operation of the 1500-volt air compressor. The output of the dynamotor is 7 kw. at 1500 volts. The control generator will deliver 4.5 kw. at 40 volts at any trolley potential from 2200 volts to 3500 volts. With the larger set and operating on 3000 volts line, an additional resistance of 48 ohms is connected in series for starting. The starting is entirely automatic, being so arranged that when the machine is connected to the line, both the permanent resistance (13.5 ohms) and the starting resistance (48 ohms) are in circuit. As the dynamotor approaches full speed, the generator voltage is built up; this energizes a magnetic contactor, which cuts out the starting resistance. On an interruption of line potential, when the motor slows down to approximately 40 per cent of the normal speed, the voltage of the generator will be sufficiently low to open this contactor and re-insert the starting resistance in the circuit. It was also found advisable to interlock the compressor starting contactor so that the compressor load would not be thrown on the dynamotor until it was practically up to speed. This dynamotor generator runs at a normal speed of 1250 rev. per min., and weighs approximately 2650 lb.

The dynamotor has four brush holders per commutator. The machine is of self-ventilated type, having a fan on the generator end which draws the air through the machine from the dynamotor end. A mechanical air cleaner, consisting of a fan so arranged as to throw out by centrifugal action any dirt that is in the cooling air, is mounted on the dynamotor end of the set.

The machine is supported on the car underframe through special rubber mountings so constructed that the resilience is obtained by having the rubber in tension instead of compression. Provision is made so that in the case of failure of the rubber, the support is taken up by the steel bolt.

### Air Compressor

This is a standard type of single-stage motor-driven compressor, with a piston displacement of 36 cu. ft. per min., when operating at full load on the 1500-volt potential. A series motor running at 1060 rev. per min. drives the compressor, through a single reduction herring-bone gear, at a speed of 188 rev. per min. The two cylinders have diameters of 5½ in., and a stroke of 7 in. The full-load current approximates 4.4 amperes.

### Storage Batteries

These may be of either the lead or nickel alkaline type. The capacity of the battery to be used will be

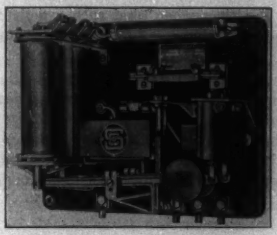

Fig. 10—Generator Voltage Regulator (Top View)

established by the number of hours of lighting desired to be available in case of failure of the power supply. Normally, the battery will be floated across the constant voltage of the generator and will be used to supply power only when the car is in the inspection shop or when some of the small auxiliary circuits, such as the heater contactors, may be supplied from the battery to avoid the necessity of operating the motor-generator set. The conditions of operating the battery are

therefore radically different from those existing when the battery is used with an axle lighting generator, in which case the battery must carry all of the lighting load when the train is standing or running less than approximately 15 mi. per hr.

The Illinois Central Railroad cars carry 24 cells of Edison battery of 300-ampere-hour capacity mounted on the trail car. A lead battery of 16 cells of 300 ampere hour capacity will be used on the Delaware, Lackawanna & Western cars. These are mounted on the motor car.

### Generator Voltage Regulator

The carbon pile type of regulator so long used by the steam railroads on axle lighting sets has worked out extremely well as a regulator for the multiple unit cars. As the generator runs continuously and the speed variation is relatively small compared with the axle lighting generator, the duty imposed on the regulator is much less than when used with axle lighting sets. This type of regulator will hold the generator voltage constant within plus or minus one volt.

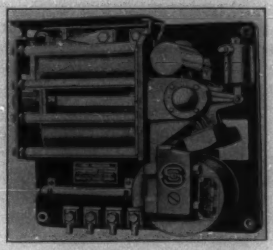

Fig. 11—Lamp Regulator

The reverse current relay has a combination of coils which connects the battery in the charging position when the generator potential exceeds the battery potential by one-half volt. With 25 cells of nickel alkaline battery, it will be necessary to run the generator potential between 37 and 40 volts, depending upon how much the battery is discharged in service, and also depending upon the temperature conditions. With 16 cells of lead battery the generator voltage will be set at some value between 34 and 36 volts.

### Car Lighting, Headlighting, and Lighting Regulator

The car lighting and the headlights used can very well follow the practise which has become standardized on the particular railroad. It is advisable, however, to insure a high enough intensity of interior illumination to enable the passengers, usually commuters, to read with ease and comfort. Lights should be placed as high as possible and shaded to cut down the glare to a minimum. On electrified zones of steam lines, it has been customary to use headlights which would meet the Interstate Commerce Commission's ruling for locomotives. This requires that a man can be seen 800 ft. in front of the car on a dark night and necessitates the use of a lamp of 100 to 250 watts at 32 volts. The headlight also should have marker numbers on the side as is required for locomotive service. Provision is made to insert in series with the headlight lamp a small resistance when it is desired to dim the headlight, a switch short-circuiting this resistance being placed in convenient location for the motorman to reach.

With the nickel alkaline battery a lamp regulator is required to cut down the normal voltage at which the generator operates, to 32 volts at the lamps. With the 16 cells of lead battery, a lamp regulator will also probably be required as about 34 to 36 volts potential is required to charge the battery. With 15 cells of lead battery 32.5 to 34 volts will be the approximate potential required to charge the battery. In the latter case, if the lights were supplied directly from the battery as during a power interruption, the lamps will operate at slightly under their rated voltage. If automatic train signals are used, consideration must be given to the maximum variation of voltage recommended by the signal manufacturers which may necessitate the use of a 16-cell battery and a lamp regulator.

## Discussion

For discussion of this paper see page 1294.

# Auxiliary Circuits for High-Voltage D-C. Motor Car Equipments

BY OTHMAR K. MARTI[1] and WALTER GIGER[2]
Member, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—The increasing demand for frequent and rapid transportation on both suburban and other railways has brought to the fore the multiple unit motor car. The steps taken in the development of the auxiliary equipment for the multiple unit motor coach are quite interesting, and have been made the subject of this paper. The first part of the paper is devoted to cars equipped with apparatus for converting the high-voltage d-c. overhead line current to the voltages required for operating standard auxiliary equipment. The second part is devoted to auxiliary equipment suitable for operation on the higher d-c. voltages now being used in more and more electrification projects. Although this paper refers mostly to development work carried out in Europe, it is nevertheless believed to be of interest to American engineers as the basic principles underlying this development are also applicable to American multiple unit cars.*

* * * * *

## Introduction

With the continued growth of cities and the further expansion of railroad facilities, it will be necessary in the near future for many railroads to consider carefully the electrification of their terminal areas, and this for several reasons, too well known to require repetition in a paper of this scope.

It has been found that for such service the best traction equipment is (multiple unit) motor cars. Moreover, main line railroads are also considering this type of equipment for supplementing locomotive train service. There is no question but that this means of transportation has proved itself to be very economical and efficient. For instance, in order to illustrate the situation, reference may be made to the New York, Chicago, and Philadelphia terminal areas, where hundreds of motor cars are in operation; the first two cases fed by 1500 and 600 volts, direct current, and the last by alternating current.

It is well known that the greatest number of multiple unit cars have thus far been used on subway, elevated, and other city railway systems. Without exception, these systems are operated by 600 to 800 volts, direct current. These equipments, however, will not be considered in this paper, and reference will be made only to motor car equipments for 1500 volts, direct current, and higher.

A further impetus has been given to the use of high-voltage direct curent for railways by the recent development of steel-enclosed mercury arc rectifiers, which are becoming more and more widely recognized, especially because of their high conversion efficiency, small first cost, and lower maintenance requirements. There are several rectifier installations for voltages of 3000 (some of which are tabulated below), while rectifiers are in operation at voltages as high as 13,000.

In recent years several suburban electrifications using motor cars almost exclusively have been carried out with direct current at voltages of 1500 and higher. Many electrifications of suburban lines have been undertaken using direct current at voltages as high as 3000, and one line in particular was electrified and has been in continuous operation for about ten years with 4000 volts, direct current.

In these facts is found our justification for giving a brief outline of the development of the auxiliary apparatus which play such an important part in connection with high-voltage motor cars or multiple unit motor cars.

Experience has shown that it is possible to build electrical equipment for passenger motor cars for 1500, 3000, and even 4000 volts (as mentioned above) with perfect safety to the passengers as well as to the operating personnel.

There is one point on which we wish to touch here, and that is the relation between the multiple unit operation of a car and its operating voltage. There is no direct relation whatever between these two things. This is especially true for control systems where the switches or contactors for the power and speed regulation of the cars are mechanically operated by a cam shaft or by some other mechanical means. A well developed and tested electropneumatic or straight electric multiple unit control system may be used to drive a cam shaft operating either a 600-volt or a 3000-volt switch group. Such switch groups are often manually operated, as will be seen later. The overhead voltage of a system, however, does make a difference as to the way energy is produced for the operation of the control system. Here we naturally have different solutions for 600-volt, 1500-volt, and 3000-volt systems.

For the speed regulation of the vehicles either unit switches, operated electrically or electropneumatically, or cam-shaft driven switch groups are utilized. We favor the latter because an absolute mechanical interlock is maintained between the various switches, thus considerably reducing the possibility of failures. Again, a cam-shaft switch group can be operated by various

1. Chief Engineer, American Brown Boveri Co., Inc., Camden, N. J.

2. Railway Department, American Brown Boveri Co., Inc., Camden, N. J.

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30-95

drive systems, such as pneumatic drives controlled by magnet valves, electric motor drives, or by manual operation with mechanical transmission from the engineer's compartment to the power controller. This last system is used very extensively in European countries,—especially in Italy where a considerable number of smaller railway systems have recently been electrified with high-voltage d-c. systems, using in most cases mechanically and manually driven controllers.

Some of the recent d-c. main line electrifications using motor cars for 1500 volts or higher voltages on the overhead line are the following:

| Railroad | One-hour rating at wheels Hp. | Voltage |
|---|---|---|
| In the U. S. A. | | |
| Illinois Central R. R. | 965 | 1500 |
| Chicago, South Shore & South Bend R. R. | .... | 1500 |
| Piedmont & Northern R. R. | .... | 1500 |
| Delaware, Lackawanna & Western R. R. (under construction) | 885 | 3000 |
| In Canada | | |
| Canadian National Rys. | 575 | 2400 |
| In Australia | | |
| Suburban Electrifications in Melbourne and Sydney | 720 and 560 | 1500 |
| In India | | |
| Great Indian Peninsula Ry. (Bombay) | 1100 | 1500 |
| Bombay, Baroda & Central India R. R. | .... | 1500 |
| In Java | | |
| Java State Rys. | 450 | 1500 |
| In Japan | | |
| Japanese Government Rys. | 536 | 1500 |
| In Holland | | |
| Netherland State R. R. | 800 | 1500 |
| In France | | |
| Midi Ry. | 700 | 1500 |
| Paris-Orleans Ry. | 1000 | 1500 |
| In North Africa | | |
| Moroccan Rys. | 700 | 3000 |
| In Spain | | |
| Spanish Northern Ry. | 920 | 1500 |
| In Switzerland | | |
| Nyon-St. Cergue-Morez R. R. | 385 | 2200 |
| Chur-Arosa R. R. | 385 | 2200 |
| In Italy | | |
| Pinerolo-Perosa-Argentina R. R. | 330 | 2200 |
| Biella-Oropa R. R. | 380 | 2400 |
| Biella-Valle Mossa R. R. | 340 | 2400 |
| Pescara-Penne R. R. (under construction) | 380 | 2600 |
| Spoleto-Norcia R. R. | 400 | 2600 |
| Roma-Ostia R. R. | 362 | 2600 |
| Fermano-Porto-St. Giorgio-Fermo Amandolo R. R. (under construction) | 400 | 2600 |
| Sangritana R. R. | 400 | 2600 |
| Arresio-Sinalunga R. R. (under construction) | 580 | 3000 |
| Vicenza-Chiampo R. R. (under construction) | 580 | 3000 |
| Dolomiten R. R. (under construction) | 380 | 3000 |
| Norte-Milano R. R. | 730 | 3000 |
| Torino-Cirie-Valle di Lanzo R. R. | 388 | 4000 (4700) |
| In Austria | | |
| Peggau-Uebelbach R. R. | .... | 2200 |

It is noticeable that especially in Italy the railroads are more and more employing high-voltage direct current. During a recent trip to Europe one of the authors received the information that the line voltage on the Torino-Lanzo Railroad for some time had been steadily raised and is now being maintained at about 4700 volts at the substation. This was done in order to increase the speed of the trains somewhat. Apparently the traction motors, as well as the line and substation equipment, are able to work continuously at this voltage. This particularly high-voltage traction system has been in operation for about ten years, and from the beginning no serious troubles have been encountered.

Most of the above-mentioned railroad systems that are operated at voltages higher than 1500 do not make use of multiple-unit operation of cars, but are equipped with manually operated cam-shaft controllers. It is only in recent years that multiple-unit operation has been employed on motor cars at voltages higher than 1500. The very first 3000-volt d-c. multiple-unit motor car operation was put in service during the year 1929 on the lines of the Norte-Milano Railroad in Italy. It is probably not well known that almost all high-voltage d-c. railroad electrifications in Europe, especially those for 2000 volts and higher, were carried out by the Brown Boveri companies.

Many of the lines enumerated above are not of large size so far as trackage and number of cars are concerned; especially when compared with North American railroads. Nevertheless, the basic studies had to be made; the development was undertaken, and in all cases the electrifications have proved to be a success.

This paper will be divided into two parts; the first dealing with the power supply for the auxiliary circuits using high-voltage to low-voltage conversion equipment, a system which is exemplified by two typical lines—the first ever built for this type of equipment; the second part will describe in detail the development of auxiliary equipment for voltages equal to those of the overhead distribution systems.

## I. Auxiliary Circuits Supplied by High-Voltage to Low-Voltage Conversion Apparatus

There are several circuits requiring electric energy in a motor car in addition to the main motor circuit. Provision must therefore be made to supply the various auxiliary circuits with the proper voltage.

The following are the auxiliaries dealt with in most cases:

*a.* Control system. Power for the operation of relays, magnet valves, contactors, reversers, etc.

*b.* Pneumatic system. Compressed air is used on almost all electric vehicles for the operation of various apparatus, for the air-brakes, whistles, sanders, etc. Frequently the brakes are vacuum operated.

*c.* Lighting of vehicles.

*d.* Heating of vehicles.

*e.* Other auxiliary power circuits, such as for blower motors for traction motor blowers, if they are necessary, etc.

*f.* Automatic train control, if used.

There are several ways in which the above power demands can be taken care of. The best way to show what developments have been made in the art since the first high-voltage motor cars were placed in regular operation back in 1914 is to analyze some of the early

electrifications and compare them with those being made today.

The insulation problem naturally is of the utmost importance in high-voltage d-c. machines, particularly when it comes to machines of small output. Very careful work during the manufacturing processes, and careful inspection once the equipments are in service, are necessary. When the first high-voltage motor cars were built, neither the manufacturers nor the operators thought it possible to operate satisfactorily, direct from the overhead line, as is being done today, almost all the auxiliaries. These early cars therefore were equipped with large motor-generator sets, suspended underneath the floor of the cars. These motor-generators had to be of capacity ample to furnish power to the air compressors, the heaters, the lights, and for the control system in general.

Typical examples of such equipment are the cars operating on the lines of the Nyon-St. Cergue-Morez, and the Chur-Arosa railroads, in Switzerland. The first of these two lines has been in operation since 1914; the second since 1916. Both are working with 2200 volts, direct current. The Chur-Arosa line connects the end-station, Chur, of the Swiss Federal Railways with the well-known sport and recreation resort Arosa. Most of the trackage of this system is on heavy grades. (Over a length of 11 mi. the average grade is 6 per cent; exactly 50 per cent of the entire line consists of curves, and 28 per cent of the entire line consists of curves of 32 deg., *i. e.*, radius of 179 ft.) To take care of its passenger traffic this railroad uses motor cars only. Each car is equipped with four motors having a combined one-hour rating of 400 hp. Speed regulation of the car for motoring as well as during electric braking is obtained by means of a manually operated cam type controller. This applies to all cars of the Chur-Arosa Railroad., as well as to those of the Nyon-St. Cergue-Morez line. The latter are also rated at about 400 hp. All motor cars of both systems are equipped with motor-generator sets of 40-kw. continuous rating. This motor-generator furnishes power for all auxiliaries. The generator of this converting set furnishes power at 300 volts, which is used for the following purposes:

*a.* Motor of vacuum pump for air-brake system (approx. 4 kw.). The brakes in the motor car and the trailers are regulated by means of this vacuum brake system.

*b.* Motor of air compressor (approx. 3 kw.). This air is needed for the pneumatic operation of the pantograph current collectors, the main switch (line switch), the reverser of the traction motor circuit, and the pneumatic rail brakes. In the system of rail brakes used on these cars a brake-shoe is forced against the head of the rail by means of compressed air. Such rail brakes are very extensively used on railroad systems where speeds are comparatively low but where heavy grades are encountered. Four rail brake-shoes are used per car. The brake-shoes are fitted with carborundum blocks which are employed to obtain a high coefficient of friction. The cylinders operating these brakes are so dimensioned that the full braking force is exerted with a pressure of about 14 lb. per sq. in. A special reservoir is provided for the rail brake equipment; it is supplied with air at a higher pressure and therefore allows of working the rail brake for a longer period of time in case the contact line voltage should fail. Rail brakes give excellent service, particularly under bad traction conditions such as in thick fog, or when fallen leaves or ice cover the rails. Under those conditions, the rail brakes are applied lightly and serve to clean the rails and thus improve adhesion.

It may be of interest to note that these cars are equipped with four entirely independent brake systems; namely, hand brakes, electric resistance brakes (using the traction motors as generators, the energy generated being absorbed by resistances), vacuum brakes, working on the wheels of the trucks, each of which is equipped with four brake-shoes, and pneumatic carborundum rail brakes, as described above.

In normal operation and on easy grades the electric resistance brake is used to control the car speed, and the vacuum brake is applied for bringing the car to a standstill. If trailers are used, and especially on heavy grades, the trailing cars are retarded by means of the vacuum brakes, while the motor car is braked only electrically. In emergency cases, both air brakes (rail brake and vacuum brake) are applied, and the electric resistance brake may be used on the motor car also.

*c.* Lighting and heating of motor car and trailers (approx. 33 kw.). The heating elements are direct-connected to the 300-volt d-c. auxiliary power system, by means of snap switches. Twenty-two heaters are installed in each motor car, consuming a total of about 18 kw. About 11.5 kw. are available for the trailing cars and about 2.5 kw. for lighting purposes. Three 100-volt lamps are always connected in series, and 10 such circuits, giving a total of 30 lamps per car, are installed. The power required for these lamps amounts to about 1.5 kw.; approximately 0.5 kw. is therefore available for lights in trailing cars.

The motor-generator set of the cars under consideration consists of a motor with single commutator, wound for direct-connection to the 2200-volt overhead line. The generator, as mentioned before, furnishes 300-volt direct current. Fig. 1 shows a motor-generator set as used on the above-mentioned cars.

Motor-generator sets of later design are equipped with an additional small exciter which is especially provided to keep the generator voltage constant with varying loads and with varying primary voltages. Such a motor-generator set for an output of 1.5 kw. is shown in Fig. 2. Similar converting sets for outputs ranging from 1.5 to 40 kw. and secondary voltages from 40 to 500 volts, have been built in large numbers for primary voltages up to 3000. Fig. 3 shows a section

through such a converter set, but having no auxiliary generator.

Fig. 4 shows one of the Chur-Arosa motor cars. The operation of the line switch, the pantographs, and the switch for the motor-generator are controlled by a single valve located in the driver's desk. This valve has three positions: in the first, the pantographs are raised by compressed air; the second closes the switch for the motor-generator set; and in the third position, air is applied to the closing cylinder of the line switch. All three operations are accomplished by air controlled directly from the driver's desk, and without any electric wires whatsoever. So far as experienced, mechanical operation of the main controller, and pneumatic operation of the apparatus mentioned above, results in the minimum amount of maintenance costs of any system of control. This system, however, is not suitable for multiple unit motor car operation, but has shown excellent results on equipments of the type just described.

Fig. 5 is a diagram of the electric and pneumatic equipment of a motor car. Fig. 6 shows a dummy master controller for a control system as described above.

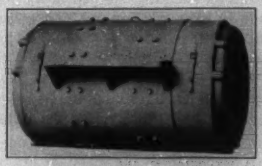


Fig. 1—Motor Generator, 2200/300 Volt, 40 Kw.

Fig. 2—Motor Generator with Auxiliary Exciter, 3000/48 Volts, 1.5 Kw.

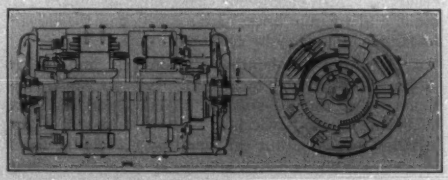


Fig. 3—Section through 40-Kw. Motor Generator, 2200/300 Volts

Fig. 4—Motor Car of the Chur-Arosa R. R., Switzerland, 385 Hp., 2200 Volts

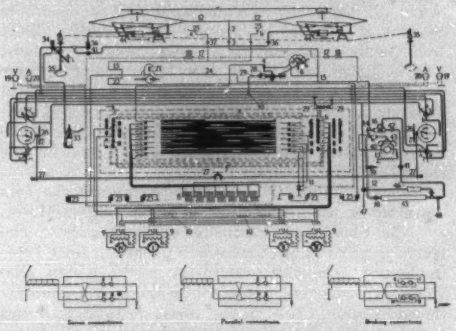


Fig. 5—Diagram of the Electric and Pneumatic Equipments of a Motor Coach

1. Pantograph current collector
2. Choke coil
3. Roof insulator
4. Overload release
5. Contact line
6. Main switch
7. Main controller
   a. Main drum
   b. Reversing drum
   c. Motor cut-out drum
8. Starting and braking resistances
9. Traction motors
   a. Field winding
   b. Interpole winding
   c. Rotor
10. Protective resistance
11. Ammeter shunt
12. Disconnecting switch
13. Compressor motor
14. Compressor governor switch
15. Fuse for compressor motor and heating current for trailers
16. Compressor governor
17. Fuse for voltmeter
18. Series resistance for voltmeter
19. Voltmeters
20. Ammeters
21. Heating switch
22. Fuse for heating circuit
23. Heaters
24. Main fuse for heating circuit
25. Rod coupling
    a. Rod
    b. Contact sockets
26. Dummy controller
    a. Valve for current collector and compressor governor
    b. Operating valve for the reverser
    c. Control handwheel
27. Mechanical drive of main controller
28. Pneumatic drive of main switch
29. Cut-out cocks for pneumatic drive of reverser
30. Change-over valve
31. Pneumatic drive of reverser
32. Three-way cock
33. Hand pump
34. Interlock
35. Retaining device
36. Roof insulator for compressed air
37. Roof insulator for heating current
38. Non-return valve
39. Safety valve
40. Oil separator
41. Air release cocks
42. Dust filter
43. Air compressor
44. Throttle valve
45. Main air reservoir
46. Auxiliary air reservoir
47. Air pipe to whistles and sanders
48. Air pipe to brakes

## II. Development of Auxiliary Equipment Operating at the System Voltage

It was soon realized that it was not economical to equip all motor cars with large motor-generator sets as on these first high-voltage electrifications; larger compressors also had to be used, particularly when the outputs of the cars kept increasing, and in many cases

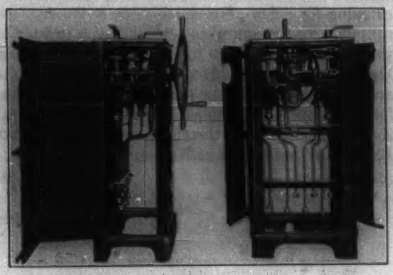


Fig. 6—Dummy Controller with Built-In Valves
Side and rear views, open

higher outputs were necessary due to the fact that more trailing cars which required greater power for heating and lighting were pulled by the motor cars. In other words, in cases where before 40 kw. were sufficient for the auxiliaries, it was now necessary to provide from 50 and 60 kw.

*a. Compressor Motor.* High-voltage auxiliary motors were then developed and first employed in connection with the air compressors. Such a motor

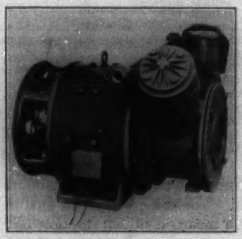


Fig. 7—Motor Compressor for 1500 Volts, Direct Current

compressor for 1500-volt d-c. operation is shown in Fig. 7. The compressor is direct-connected to the motor without any gear reduction. The motor shown is designed to furnish about 10.8 hp. The compressor delivers about 42 cu. ft. per min. at a pressure of 112 lb. per sq. in. Hundreds of such compressors are in operation on various railroad systems. Today compressor motors are being run directly on the 3000-volt trolley lines. Most of the motor cars are equipped with one compressor only, which means that the entire line voltage has to be cared for by one motor.

As a consequence, the motor-generator sets could be considerably reduced in size. The sets used today average from approximately 1.5 to 2.5 kw.; the rating naturally depends upon the requirements, which differ for the various equipments.

*b. Heating Circuit.* Parallel with the development of high-voltage auxiliary motors the development of heaters for high-voltage d-c. circuits was undertaken, with the result that for a great number of years, car heaters have been direct-connected to circuits of 3000 volts and higher with no difficulty in service nor danger to the passengers; in fact, experience shows that 3000 volts are no more dangerous than 1500 volts. As early as 1920 there was an undertaking which at that time was considered very risky, and which was not duplicated for many years. This was the connection of car heaters direct to a 4000-volt d-c. system. The Torino-Lanzo-Ceres R. R.

Fig. 8—Turn-Button Switch for Heating Circuit

Co. in Italy, which operates its system at that voltage, had the courage to undertake what was then believed impossible. It proved to be a complete success, and up to this time not a single accident caused by the heating system has been reported, although the line has been in service for 10 years, and in spite of the fact that during the last two years the line voltage has gradually been raised to about 4700 volts, as mentioned previously.

We are thus not far from the d-c. systems of 5000 volts which were once predicted.

Heating circuits in high-voltage d-c. equipment are utilizing control switches of new design. Such switches are normally located under the car floor or in special compartments provided inside the car body. Special switches that can be located inside the car, accessible to the passengers and the train crew, have also been developed. They are of a very compact design and for a smaller interrupting capacity. These are ordinarily used for the disconnection of branch circuits, and are hand operated. Such a switch for 2600 volts, direct current, and about 5 kw. interrupting capacity, suitable for mounting inside the passenger compartment, is

shown in Fig. 8. This switch, besides being of very small size, is quite neatly designed, and so far as appearance is concerned, can easily be located inside of a passenger car.

The heating of several cars in a train from a motor car naturally requires special couplings between the cars. Various couplings to solve this problem have been

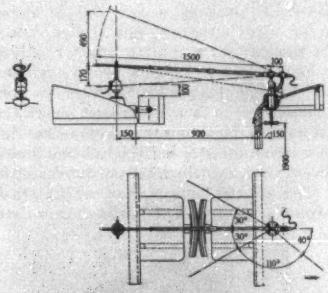



Fig. 9—Rod Coupling for Heating Circuit

designed. In many countries connectors located on the roof at the ends of the cars have been used. Such a coupling is shown in Fig. 9. The comparatively small currents taken by car heating systems at high voltages can readily be handled by couplings of such a design. About 15 to 20 amperes can be carried by a roof coupling of this type, the cost of which is quite low. If the cars separate, the movable part disengages easily, and the contact rod of the car, which in the coupled position reaches over to the other car and engages in a catch,

Fig. 10—Train-Heating Coupling for 400 Amperes 3000 Volts, D-C. or A-C.

automatically turns back to its uncoupled position by making a turn of 90 deg. In this position it does not project over the end walls of the car, and cannot be reached by any passengers or the crew. The turning of the coupling rod to engage with the next car is accomplished by means of an insulated handle fastened either outside the car end wall or operated from inside the end vestibule of the car. It might be of interest to know that this type of coupling is often used also for the connection of lighting circuits between cars. For large current ratings, the above-mentioned coupling naturally is not suitable, and heavier couplings had to be developed. Such couplings are in most cases hand operated. Their general appearance is reminiscent of the control-current couplings extensively used on multiple-unit car equipments.

It is, however, quite a different task to build a coupling for a few amperes only, as is the case with couplings for the control current, than it is to build one that is able to carry 300 to 400 amperes continuously. Heating couplings of high current-carrying capacities are usually built for one pole only. A coupling designed for 400 amperes continuous current, at 3000 volts, is shown in Fig. 10. It is therefore possible to carry about 1200 kw. at that voltage with a coupling of this type.

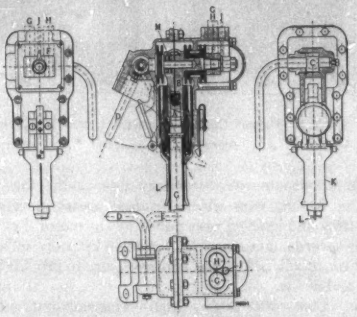


Fig. 11—Coupling Box and Pin for Train-Heating Circuit

A. Contact pin
B. Clamp in two parts
C. Eccentric
D. Eccentric lever in open position (contact loose).
E. Eccentric lever in closed position (contact clamped)
F. Cable terminals
G. Cable connecting the coupling box and pin
H. Cable connecting the two coupling boxes
J. Cable going to the heaters
K. Handle of plug
L. Ground wire
M. Spring
N. Insulating tip

It is desirable not to disconnect the coupling while the power is on. For this purpose an auxiliary contact is provided, by means of which the holding circuit of the heating system main switch, normally located in the motor car, is opened, and the circuit interrupted before the coupling contacts separate. This is done in such a way that the plug of the coupling must be pulled out about one-half inch, whereby the holding circuit mentioned above is interrupted. The plug must now be turned slightly before it can be pulled out, and the main contacts will disengage only after the plug has been moved about one more inch. The time necessary to make these three movements is sufficient to open the main switch before a trainman can uncouple, and any

danger of producing an arc when uncoupling is therefore precluded. Several thousand such couplings are in service at voltages of 1000 to 1500 without having any interlocking contacts at all. A section through such a coupling is shown in Fig. 11. This coupling has no interlocking contact; a coupling with an interlocking contact is shown in Fig. 12.

The heating units themselves are not much different from those for lower voltages, except that their insulation is considerably increased. In most cases, the heating element is embedded in an insulating material (micanite, or something similar); this unit is then fully enclosed in a metal shell, and several of these elements are, in turn, placed within a metal frame of the conventional design by means of a secondary insulation material. The outer housing is usually designed in such a way that it is impossible for any unauthorized person to come in contact with any of the units inside the box. That such a safety measure is

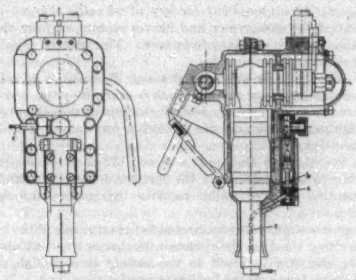


Fig. 12—Coupling for Train Heating with Safety Interlocking Device

a. Interlocking contact on the plug
b. Interlocking contact on the coupling box
c. Auxiliary cable

within the range of possibility has been amply demonstrated by the great number of such heating systems as are in operation in high-voltage d-c. motor cars.

From the above it may be seen that the tendency to connect as many of the auxiliaries as possible direct to the high-voltage circuit and do away with all converting apparatus prevails.

*c. Control-Current and Lighting Circuits.* There are, however, two other circuits which require a power supply and which up to now have not been—and probably never will be—connected directly to the high-voltage system of the motor car. These are the circuits commonly known as the control-current and the lighting circuit.

For a considerable period of time the control current for 600-volt d-c. systems has been taken from the main power circuit, series resistances being inserted into the circuit to permit the use of standard relays, magnet valves, and other apparatus which are necessary for the control of the car, but which are not built for such high voltages. This system is very inefficient, however, and its main disadvantage is that the line voltage must be carried into the master controller, which is very undesirable. In newer equipments, the control circuit and the lights are supplied directly from motor-generator sets with control voltages as high as 300. Still more modern equipment is usually furnished with the control circuit fed from a storage battery in combination with a motor-generator provided for charging the battery, or combined with a battery and a train-lighting axle generator. The voltages employed vary greatly, and equipments are in operation at voltages of 12, 14, 18, 24, 32, 36, and even 48. If motor-generators are used, machines with an output of about 1000 to 1500 watts are sufficient to take care of the lighting and control-current requirements. If the lighting current of several trailers is to be supplied from a motor car, outputs as high as 4000 watts may be required, depending upon the number and wattage of the lamps installed in the cars.

Considerable difficulties were experienced with the high-voltage motor of such motor-generator sets, which, on the whole, gave more trouble than the motors and apparatus of the main power circuits. It was therefore also decided to eliminate this converting machine, and the logical thing to do was to connect the lights and the control circuit to a low-voltage axle generator, as mentioned above.

*Evolution of Auxiliary Equipment.* Some cars of the Torino-Lanzo R. R. which were placed in operation in the year 1920, were already equipped with such axle generators, to which the lights and the control-current circuit were connected. In this particular case the compressor motor was also driven by this axle generator. The average voltage of this system, which is used in conjunction with a storage battery, is 48 volts. The axle generator is designed for a continuous output of 3.5 kw. at variable speeds ranging from 305 to 1400 rev. per min. The capacity of the storage battery is 145 ampere-hours. The motor of the compressor is built for an intermittent rating of 2 kw. A second, mechanically driven, compressor was also furnished for these cars. This compressor was connected up with one of the truck axles. The system of having two compressors, one for operation also from the battery in case the train is not moving and the other direct-connected to an axle, has decided advantages. On this line, grades up to 3.5 per cent are encountered, but due to the above described system of two compressors it is possible to descend all grades on the line, even when the power fails. As these motor cars are also equipped with the resistance braking system, it is possible to lower the pantographs on the mountain sections when descending the heavy grades, and still have full control over the entire train.

With the solving of the main power and control-current problems, as on the Torino-Lanzo and later

electrifications, solutions have been worked out which have resulted in the present day high-voltage d-c. equipments.

The most modern 3000-volt d-c. traction system, where multiple unit motor cars were utilized for the first time, was put in operation by the Norte-Milano R. R. Co., in Italy, during the spring of 1929. The entire d-c. power supply of this railway system is furnished by mercury arc rectifiers (6000-kw.). The motor cars as well as the trailers of this line are of modern steel-car design. The motor cars are equipped with four axle-suspended motors, each with a one-hour rating of approximately 190 hp. The motors are of the self-ventilated type. The compressor motor is direct-connected to the overhead line, the necessary apparatus, such as compressor governors and contactors, being connected into this circuit at the proper places. The heaters of the motor cars and trailers are also fed from the overhead line and are controlled by means of suitable controllers. Control current, as well as power for the lights, is furnished by the axle generator at an average voltage of about 36. The trailing cars are also equipped with train-lightning generators. The current for heating the trailers, however, is furnished from the motor car, and couplings similar to those shown in Fig. 9 are utilized for the interconnection of the cars.

Protection of the high-voltage auxiliary circuits against excessive currents is accomplished by fuses, these fuses usually being located underneath the floor of the car in boxes especially provided for the purpose, or in high-voltage compartments inside the car.

From the above it can be seen that great contributions toward the development of high-voltage d-c. motor car equipments have been made during recent years. From all indications which we have on this matter and also from the experience gained with equipments now in service, we feel sure that the use of high-voltage d-c. motor cars for passenger transportation in the future presents itself as a technically and economically sound solution of many transportation problems.

## Discussion

### AUXILIARIES FOR HIGH-VOLTAGE D-C. MULTIPLE UNIT CARS

(C. J. Axtell)

### AUXILIARY CIRCUITS FOR HIGH-VOLTAGE D-C. MOTOR CAR EQUIPMENTS

(Marti and Giger)

**M. Parodi:** The system of electric traction of the French Railroads has been standardized on the basis of direct current at 1500 volts in France, and at 3000 volts on the lines in North Africa.

The general characteristics of the French Railroads involve the use of considerable auxiliary apparatus.

#### Storage Batteries

The batteries in use are all of the alkaline type. Originally ferro-nickel cells were used. There is a tendency to use cadmium nickel cells, which have the same sturdy characteristics as ferro-nickel and likewise require but little maintenance. This type carries long continued loads as well as the iron-nickel cell, and is not affected by low temperatures. It is operated where stability of electric characteristics and a high degree of retaining the charge under all conditions are of importance, as is the case in connection with supply of locomotive control circuits. It lends itself much better than the iron-nickel cell to trickle charge operation there being no risk of breakage of the internal connections.

On the Paris-Orleans System 72 ampere-hour batteries are always used. Motor cars do not have storage batteries. The locomotives (except one test type) are equipped with a battery of 24 cells connected in series, sometimes on the circuit with two motors used for driving the traction motor blowers, sometimes with two compressor motors, and occasionally with all four motors. This battery supplies only the control and the auxiliary control circuits. The test type of locomotive mentioned above is equipped with a battery of 54 cells, charged from a 1500-72-volt motor-generator set which supplies the control and lighting circuits.

On the Midi System a large number of locomotives are equipped with 85 ampere-hour batteries of 48 cells, charged from the current of the two traction motor blower motors. This battery supplies the control and lighting circuits. The same arrangement applies to another type of locomotive, except that the battery is charged by the compressor motor circuit, or directly from the trolley line, through charging resistance. Another type carries a 132 ampere-hour battery of 64 cells, charged by the current of the compressor and blower motors, or from the contact line through charging resistance. This battery supplies the control and lighting circuits.

On the Paris-Lyons-Mediterranean Railroad a 48-cell 240-ampere-hour battery is used, which is charged by the blower and compressor motor current, and which supplies the control circuit, the lighting circuit and the excitation for the exciters used in regeneration.

On the Algerian Railroads a 48-cell 132-ampere-hour battery is used which is charged by the current of the blower and compressor motors, and which supplies the control and lighting circuits.

An over-voltage relay connected to the terminals of the battery opens either the high speed circuit breaker or the contactor controlling the supply circuit to the battery in case high voltage results from breaking the battery ground connections.

#### High Tension Auxiliary Apparatus

The motor cars on the Paris-Orleans System are equipped with a motor-generator set of about 3 kw., 1500-72 volts, with a voltage regulator (without battery), for feeding the control circuits and for the lighting of a part of the train—two ends of each motor car.

The locomotives, except two test types, do not have motor-generator sets, the control circuit and auxiliary circuits being fed from a battery. On one type of test locomotive there is a motor-generator set of 3-kw., 1500-72 volts, (with a regulator), charging a battery for supplying the control circuit and the locomotive lighting current; on another type of test locomotive there are two motor-generator sets about 30-kw., 1500-110 volts, with a regulator (without battery) for supplying the control circuits, the locomotive lighting circuits and two motor blower sets which supply air for the traction motors; one is a service set and the other reserve.

A high tension motor-generator set consists essentially of:

1. A 1500-volt motor completely compensated, the armature of which carries two distinct windings each terminating in a commutator (one placed on one end of the armature, with the other on the opposite end). These two armatures are operated in series for 1500-volts.

2. A d-c. shunt generator with auxiliary commutating poles wound for 72 volts. The voltage at the terminals of the set is maintained practically constant by means of a special regulating device essentially comprising of a small shunt motor,

the armature of which is in series with the shunt winding of the generator and the field of which is shunted at the terminals of the generator with a high resistance. The scheme is indicated in Fig. 1. The speed of the small motor is limited by a small fan at the end of the shaft. The voltage at the terminals of the small motor varies according to whether it is excited or not; energizing or de-energizing its excitation is affected by armature $A$ or relay $E$. The relay and its vibrating armature constitute a simplified Tyrrill Regulator. The relay $E$ is provided with two windings; the first, tapped to the terminals of the 72-volt generator, is supplied by a voltage closely proportional to the voltage of this generator; the second, wound in the opposite direction and connected in series with the field winding of the small motor, facilitates the movement of armature $A$ and stabilizes the voltage by reducing the difference between the voltages corresponding to the opening and closing of $A$.

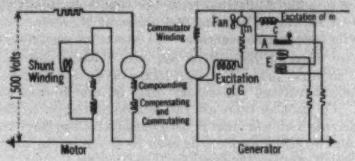



Fig. 1—Special Regulating Arrangement of a Motor-Generator Set

These low-capacity, high-voltage, motor-generator sets installed on the Paris-Orleans System have not given good service, for 68 out of 80 equipments have been damaged.

On the motor cars of the Midi Railroad and in Morocco the supply for auxiliary circuits is accomplished by rotary transformers.

A machine has been designed for this purpose to transform direct current of a given voltage to direct current of another voltage. This is composed of an armature carrying two independent windings, each one being connected to its own commutator. One of the windings is a motor; the other a generator. The magnetic circuit is common to the two windings. The electric field circuit carries two windings, one wound in series with the motor windings and the other as a secondary on the generator winding. This type of machine is generally constructed without auxiliary poles, the resultant ampere-turns on the armature at constant load being virtually nil.

If such a machine is used on a direct current locomotive for the production of the low voltage direct current necessary for supply of the auxiliary circuits, there would be poor commutation whenever there is a variation either in the load on the generator or in the voltage of the power supply to the motors. The series and shunt windings present a strong coefficient of mutual induction, and when, for instance, the supply voltage rises, the flux produced jointly by the two field windings follows this change with difficulty. A sudden increase in the current flowing in the motor winding results, which immediately produces an overload on the brushes, and also poor commutation. For this reason Mr. Royer and I were led to develop a scheme to insure good commutation at both collectors not only under normal conditions but under variable conditions produced by changes in the supply voltage or in the load.

Commutation may be improved by providing auxiliary commutating poles, the field circuits of which have two windings, one wound in series with the motor armature and the other in series with the generator armature, producing bucking ampere turns, the former winding being slightly predominant over the other, under normal conditions.

Excellent results are obtained without commutating poles by providing a reactance in the machine circuits as indicated in Fig. 2.

$S$ —Reactance
$M$ —Motor armature winding
$G$ —Generator winding
$Im$—Inductor winding in series with $M$
$Ig$ —Inductor winding in series with $G$

The current of the motor armature $M$ flows through the reactance $S$. For example, when there is a rise of voltage the voltage at the terminals of $S$ becomes very high. Since the voltage at the terminals of $I\,g$ is equal to the sum of the voltages at the terminals of $S$ and of $G$ (circuit $S$—$I\,g$—$G$), an increase in the voltage in $S$ results in an increase in the voltage in $I\,g$ and in the opposite direction; that is, in a direction opposite and equal to that which $I\,m$ produces by induction on $I\,g$. This is thus counterbalanced, and the inertia which the whole assembly $I\,g$-$I\,m$ would produce in order to establish flux, disappears. The main flux thus quickly follows the variation in the series ampere turns.

This type of machine has been adopted for general use in the motor car equipment of the Midi Company to transform current at 1500 volts to 72 volts for supply of control and lighting circuits, as well as on the Morocco Railroad Company, where the transformation is from 3000 volts to 120 volts. The power developed on the low tension side may amount to about 12 kw.

Locomotives equipped for electric regenerative braking as used on the Midi System or on those of Northern Africa, are equipped for supplying the low voltage auxiliary apparatus with units consisting of a high tension motor connected to two low voltage generators, one for constant voltage, the other for variable voltage.

The high tension motor is connected to the trolley supply line through permanent resistance as a protection against variations in line voltage, and through two circuit breakers in series, which open on overload following overspeed in the set. This motor has compound excitation with a compensating winding, and a separate excitation, furnished by the constant voltage generator.

The motor circuit includes safety devices for disconnecting it from the line in the event of failure of supply power or overload of the motor.

The constant current generator is of a shunt type, regulated by resistance. It supplies the auxiliary equipment with low voltage power.

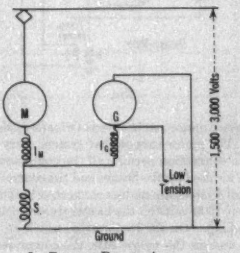



Fig. 2—Parodi-Royer Arrangement

The variable voltage generator plays the part of exciter, for regeneration, its armatures in that case being connected to the fields of the traction motors, functioning as generators. Its excitation is accomplished in part by a winding fed from the constant current generator, the current of which is controlled by means of resistance which regulates the apparatus through electro-magnetic contactors; and in part by an "anti-compound" winding fed from the trolley supply circuit.

When a motor has two field windings, one series and one shunt or independent, the coefficient of mutual induction of these two windings prevents the resultant flux from following the variations in the supply voltage. There may result poor commutation and

sparking, if the supply voltage is high, as is the case in the locomotives of the French Railroad systems.

We can partially remedy this difficulty by tapping the shunt winding at the terminals of the commutator and by a reactance in series with the latter; it is then acted upon by the sum of the voltages in these two parts; that of the reactance being very important at the instant of variation in the supply voltage. In this case a potential is developed in the shunt winding, in the opposite direction to that which is induced in the series winding, and the effect of mutual induction is counterbalanced.

The arrangement invented by Mr. Royer amplifies the compensatory voltage produced in the shunt winding by placing the primary $P$ of a transformer (Fig. 3) in series with the motor armature $M$ and its secondary $S$ in series with the shunt field $B$. In the accompanying figures where $A$ represents the series field winding, $E$ an exciter and $G$ a generator winding, we have in Fig. 1 the arrangement with a second shunt winding, in Fig. 2 with a second separate excitation winding, while Fig. 3 shows the arrangement with a motor-generator.

This device is in operation on the Paris-Lyons-Mediterranean System locomotives.

### Compressors

Two compressor sets are often installed on the locomotives, one being in continuous service while the other is in reserve. Starting is accomplished automatically by a pressure regulator.

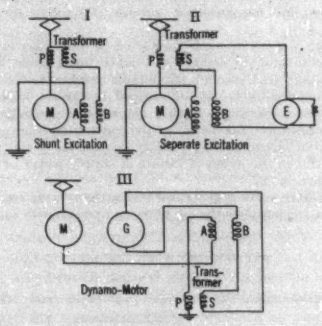



Fig. 3

All compressor motors on the Paris-Orleans System, operate at 1500 volts. The motor cars of that system carry but one compressor, but a connection permits all the compressors to share in the supply of air used by the brakes and the control facilities.

On the Midi System the motors connected to the two compressors operate at 1500 volts on the locomotives which are equipped for static braking. On the locomotives which are equipped for regeneration and on the motor cars, the compressors operate on low voltage power.

On the Paris-Lyons-Mediterranean System the two compressor motors operate at 1500 volts; and in Morocco and Algiers they are fed at low voltage.

There is a tendency to increase the compressor capacity up to 2400 litres per minute (85 cu. ft. per minute) and even to carry three compressors. The use of rotary instead of reciprocating compressors can be foreseen.

The charging pressure is 7, 8 or 10 kg. per sq. cm. (100, 114 or 142 lb. per sq. inch) depending on the type of compressor.

### Ventilation of the Motors

On the Paris-Orleans System the ventilation of traction motors on locomotives is accomplished by two blowers (one for each pair of traction motors), each of these blowers being driven by an independent motor operating at 1500 volts; there are thus two independent sets. On one test type there are two sets each consisting of a motor driving two blowers (one for each traction motor). On another test type there are also two groups, each consisting of a motor driving three blowers (one for each traction motor). There is no forced ventilation on the motor cars of that system the motors being self ventilated.

The ventilation of the traction motors on a number of locomotives on the Midi System is accomplished by two sets, each consisting of a motor connected from the 1500-volt circuit through permanent resistance, driving two blowers; there are thus four blowers for four traction motors—one blower for each motor.

Another type of locomotive has two blowers (for the four traction motors) driven by the 1500-volt motor which drives the constant voltage generator; that is, one blower for two motors. On another there are two sets consisting of a 1500-volt motor driving a blower; that is, two blowers for the three traction motors and on still another type each 1500-volt motor drives one blower which supplies the ducts for three motors.

Certain locomotives of the Paris-Lyons-Mediterranean System have two sets of two blowers for the six traction motors. These blowers are driven by 1500-volt motors. On another type of locomotive there are two sets, with one blower each for the six traction motors; that is, one blower for three motors. These blowers are driven by 1500-volt motors.

On the Morocco systems, on certain locomotives there are two blowers for two motors. These blowers are driven by the 3000-volt motor which drives the constant voltage and the variable voltage generators. On other types there are two sets consisting of one motor fed at low voltage by the constant voltage generator which drives two blowers; thus four blowers for four traction motors—one blower for each motor.

There are three blowers for the traction motors, drawing from a central reservoir on the systems of Algeria; that is, three blowers for six motors. These blowers are driven by the 3000-volt motor which drives the constant-current and the constant voltage generators.

On the table next attached are shown figures on the capacity of the auxiliary groups, the blower sets and the compressor sets used on the various types of equipment.

### Ventilation of the Cab

There is no provision for ventilating the cab on the French systems. But on the Moroccan and Algerian systems the ventilation of the cab is accomplished by a special blower driven by a low-voltage motor supplied by the low-voltage constant potential generator of the high-voltage motor-generator set.

### Heating the Cab

On the Paris-Orleans System this is accomplished by two 800-watt electric radiators mounted in series on the 1500-volt circuit.

On the Midi System there were installed at first 200-watt heaters operating at 120 volts. More recently 200-watt heaters have been installed in series on the 1500-volt circuits. On certain locomotives 750-watt radiators have been installed in series on 1500 volts.

The Paris-Lyons-Mediterranean System heating is accomplished by three 500-volt radiators in series on 1500 volts, utilizing a total of 2500 watts.

On the Algerian Railroads two 200-watt heaters have been installed fed at 150 volts from the constant potential generator of the high voltage motor-generator set.

The same arrangement is used on the Moroccan System.

### Electric Heating of Trains

The tendency is to heat the passenger coaches by electric power taken from the contact wire. Some installations have already been made by the Paris-Orleans Company, which is progressively equipping the coaches which are hauled by elec-

tric locomotives. They are using radiators connected directly to 1500-volts. This necessitates a high voltage bus the length of the train. In order to avoid hazard the couplers are equipped with an interlocking device which does not allow them to be opened when there is voltage.

### Lighting the Cabs

The lighting circuit comprises:

1. In the interior of the locomotives a certain number of ceiling lamps, a lamp lighting the speed indicators, a lamp for the controller and sockets for inspection lamps.

2. On the outside, the regulation lights on each end of the locomotive.

On the Paris-Orleans Railroad locomotives, (with the exception of a few test types) the outside lights and the interior lamps, except the lamps for the controller and the instruments, are connected in series and in series with resistance on the 1500-volt circuit; the instrument lamps are fed from the 32-volt battery. In the test locomotives the lamps are supplied from the battery or from the low voltage generator of the high tension motor-generator set. On motor cars the lighting is also supplied from the low-voltage generator.

On the other systems, the lamps are arranged in parallel on low-voltage circuits, the voltage of which depends upon that of the battery.

To avoid burning out the lamps by excess voltage caused from undue variation in charging and discharging the battery, when the voltage of each element is greater than 1.05 to 1.8 volts a relay connects the lamp circuit to a reduced number of cells while the battery is being charged. On the other hand, when the battery is being discharged the lamps are supplied by the entire number of cells. This protection has proven very effective.

### General Arrangement in the Locomotives

The tendency on locomotives of the French Systems is to avoid as far as possible the installation of cables and to replace them with bare bars. When the installation of insulated wire is necessary, instead of placing the cables in rigid conduit they are installed in flexible conduit, not only inside the cab but under the cab. As to the location of apparatus inside the cab, a central compartment is provided in which all the auxiliary rotary apparatus are installed. This compartment is wide enough to admit a man in spite of the crowding of the apparatus. On either side are cells in which all the appliances (contactors, resistances, etc.) are installed. This arrangement allows easy access for maintenance and the apparatus can be easily removed.

MIDI SYSTEM

| Type of locomotive | BB | BB | BB | 2C2 | Loco. coach | Motor coach |
|---|---|---|---|---|---|---|
| H. P. Continuous | 1000 | 1000 | 1600 | 1500 | 650 | 500 |
| Hour | 1400 | 1400 | 1760 | 2200 | 800 | 700 |
| **Blower sets** | | | | | | |
| Number | 2 | 2 | 2 | 2 | | |
| Motor rating h. p. | 10 | * | 13 | 10 | * | * |
| Voltage | 1500 | | 1500 | 1500 | | |
| Capacity cu. ft./sec | 28. (2) | 59. (2) | 47. | 85. | | |
| **Compressor sets** | | | | | | |
| Number | 1 | 1 | 2 | 2 | 2 | 1 |
| Motor rating h. p. | 18. | 18. | 15. | 18. | 10. | 9. |
| Voltage | 120. | 120. | 1500 | 120. | 1500 | 120. |
| Capacity cu. ft./min | 42.5 | 42.5 | 42.5 | 42.5 | 21. | 21. |
| Charging pressure | 100. | 114. | 100. | 100. | 100. | |
| **Auxiliary sets (M-G) Number** | 1 | 1 | | | | |
| Motor rating h. p. Hour | 80. | 80. | | | | |
| Continuous | 50. | 50. | | | | |
| Motor voltage | 1500 | 1500 | | | | |
| Constant potential gen. rating kw. | | | | | | |
| Hour | 22. | 22. | | | | |
| Continuous | 12. | 12. | | | | |
| Constant potential gen. voltage | 120. | 120. | | | | |
| Variable potential gen. rating kw. Hour | 22. | | | | | |
| Variable potential gen. voltage | 75. | | | | | |
| **Rotary transformers** | | | | | | |
| Primary voltage | | | | | | 1500 |
| Secondary voltage | | | | | | 120. |
| Rating (hour) kw | | | | | | 10. |

(*Blowers on auxiliary set shaft.)

PARIS-ORLEANS SYSTEM

| Type of locomotive | BB | BB | BB | BB | 2D2 | 2D2 | 2CC2 | Motor car |
|---|---|---|---|---|---|---|---|---|
| H. P. Continuous | 1320 | 1540 | 1320 | 1240 | 3380 | 3200 | 2040 | 640 |
| Hour | 1640 | 1720 | 1680 | 1420 | 4200 | 3600 | 3000 | 860 |
| **Blower sets** | | | | | | | | |
| Number | 2 | 2 | 2 | 2 | 2 | 2 | 2 | |
| Motor rating h. p. | 5.5 | 9.0 | 18 | 13. | 16 | 16 | 17.3 | |
| Voltage | 1350 | 1350 | 1350 | 1350 | 1350 | 1350 | 1350 | |
| Capacity cu. ft./sec | 47. | 82 | 65. | 94. | 147. | 71. (2) | 65. | |
| **Compressor sets** | | | | | | | | |
| Number | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| Motor rating h. p. | 12 | 9.5 | 12 | 12 | 10.8 | 10. | 17.5 | 12 |
| Voltage | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| Capacity cu. ft./min | 44. | 51. | 44. | 44. | 60. | 60. | 75. | 44. |
| Charging pressure | | 100. | 100. | 100. | 113.8 | 113.8 | 142.2 | 100. |
| **Auxiliary sets (M-G) No.** | | | | | | | | |
| Motor rating h. p. Hour | | | | | 40. | 5. | | |
| Motor voltage | | | | | 1500 | 1500 | | |
| Const. pot. gen. rating kw. Hour | | | | | 30. | 3. | | |
| Const. pot. gen. voltage | | | | | 110 | 72. | | |

| | P. L. M. system | Morocco system | | | Algerian system |
|---|---|---|---|---|---|
| Type of locomotive | 1CC1 | BB | BB | Motor car | CC |
| H. P. Continuous | 1500 | 1000 | 1300 | 500 | 2040 |
| Hour | 2100 | 1400 | 1620 | 700 | 2400 |
| **Blower sets** | | | | | |
| Number | 2 | 2 | 2 | | 3 |
| Motor rating h. p. | * | * | 13.5 | | * |
| Voltage | | | 120 | | |
| Capacity cu. ft./sec. (each) | 104. | 64.7 | 47. | | 94. |
| **Compressor sets** | | | | | |
| Number | 2 | 2 | 2 | 1 | 2 |
| Motor rating h. p. | 15. | 18 | 18 | 9. | 15. |
| Voltage | 1500 | 120. | 120. | 120. | 120. |
| Capacity cu. ft./min. | 21. | 21. | 21. | 21. | 21. |
| Charging pressure | 100. | 100. | 100. | 100. | 128. |
| **Auxiliary sets (M-G) No.** | 2 | 1 | 1 | | 1 |
| Motor rating h. p. Continuous | 50 | 90. | 90. | | 140. |
| Motor voltage | 1500 | 3000 | 3000 | | 3000 |
| Constant potential gen. rating kw. hr. Continuous | | 16. | 39. | | 22. |
| Constant potential gen. voltage | | 120. | 120. | | 120. |
| Variable potential gen. rating kw. hr. Continuous | 15 | 23.5 | 23.5 | | 38. |
| Variable potential gen. voltage | 48 | 130. | 130. | | |
| **Rotary transformers** | | | | | |
| Primary voltage | | | | 3000 | |
| Secondary voltage | | | | 120. | |
| Rating (hour) kw | | | | 10. | |

(*Blowers on auxiliary set shaft.)

# Railbonding Practise and Experience
## on Electrified Steam Railroads

BY H. F. BROWN*

Member, A. I. E. E.

***Synopsis.***—*This paper deals primarily with the development, description, and characteristics of various types of rail bonds used at track joints for traction return and incidentally signal track circuits. It outlines their performance and reasons for their selection on representative electrified steam railroads, which include:*

*Baltimore & Ohio*
*Boston & Maine*
*Chicago, Milwaukee, St. Paul & Pacific*
*Delaware, Lackawanna & Western*
*Illinois Central*
*New York Central*
*New York, New Haven & Hartford*
*Norfolk & Western*
*Pennsylvania*
*Reading*
*Virginian*

*No attempt is made to discuss the track circuit characteristics and requirements for either signaling or propulsion return. Cross-bonding, impedance bonding, and structure grounds are also outside the scope of this paper.*

*The track construction and maintenance, weight of rail, type of joints, condition of roadbed, ballast, traffic density and frequency, wheel loadings, amount of current to be carried, track signal circuit requirements, etc., all have a direct bearing on the design and proper application of the rail bond, which is thus a problem involving mechanical as well as electrical features.*

*From the data submitted, an attempt is made to indicate the trend of bond design.*

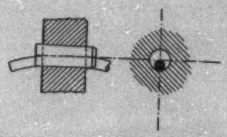
### I. Development of Various Types of Rail Bonds

THE problem of making a continuous circuit of comparatively low resistance out of a large number of joined conductors such as track rails, has been one which has confronted electrical engineers since the earliest application of electricity to railroading, not only for traction power return, but for signaling. It was evident from the very earliest attempts to utilize the rails as part of any electric circuit that some means would have to be devised to shunt out the high, or at the best, very variable, resistance which the rail joints created. As far back as 1872, wire connectors, or bonds, around the rail joints were devised for track circuits in connection with signaling. Since that date, the problem has had the attention and study of two different groups working along different lines, the street railways and the electrified steam railroads seeking an economic method for providing a low resistance path for currents of large magnitude, whereas the requirements for signaling alone were for relatively small currents.

#### Channel Pin Type Bond

The earliest type of rail bond was the so-called channel pin type, developed in 1872 by Dr. William Robinson for track circuits in connection with railway signaling. This type has continued in use down to the present time for such circuits, practically without modification. As used for signal bonding, this takes the form of a tapered pin having a channel or groove of the size of the bond wire. A hole is drilled in each rail, usually in the web, large enough to admit the small end of the channel pin. The wire, usually about No. 8 steel, is inserted through the rail, and the channel pin is then driven in, tightly wedging the wire into close contact with the rail (see Fig. 1). This device has been widely used because of its simplicity and relatively low cost. Two separate bonds per joint are generally used to insure reliability.

Later, when electric traction requirements called for heavier wires, the same method, with larger channel pins, was used with some success. With larger wires,



a

g

Fig. 1—Channel Pin Signal Bond

a. Detail of channel pin
b. Double bond of No. 8 wire around joint

however, there is more chance of the pin not completely filling the hole, thus allowing the entrance of moisture, with consequent impairment of contact. The larger bonds were also relatively expensive, since they were made of copper and of course had to span the splice bar. They were also exposed to injury and liable to theft.

Split sleeves or bushings have been devised for these larger wires, as a modification of the channel pin idea, but all such methods are open to the objection of the

*Assistant Electrical Engineer, N. Y., N. H. & H. R. R., New Haven, Conn.

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30-90

possibility of moisture entering and causing corrosion between the rail and the pin or sleeve, with resultant increase in the contact resistance. Bonds of this type (see Fig. 2) were always of single solid wire, which was subject to rapid crystallization and ultimate fracture at the entrance to the rail where vibration and movement of the joint proved very severe.

### Soldered and Brazed Bonds

The need for greater flexibility with larger capacity conductors, together with the need for a better and more permanent method of contact with the rails, brought about the soldered bond. This type of bond consists of one or more laminated or stranded conductors forged or soldered into a terminal, which in turn

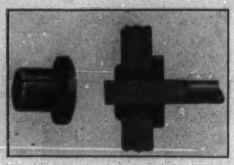


Fig. 2—Solid Wire Bond with Split Sleeve

is soldered or brazed to the rail head, web, or flange, (see Fig. 3) at a point previously cleaned, usually by means of a portable emery wheel. When applied next to the ends of the rails, such bonds are relatively short and inexpensive. Where the splice bar is spanned, they are

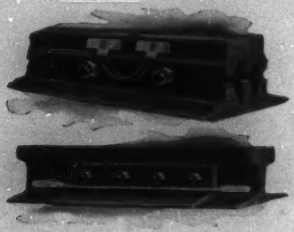


Fig. 3—Soldered Bonds

Top: Soldered terminal bond on ball of tee rail
Bottom: Soldered terminal bond on web of tee rail

obviously more expensive. The labor cost of cleaning and tinning the rail and applying the bond is relatively high for this type of bond.

Brazed bonds are similar in design to the various types of soldered bonds in so far as the terminals are concerned. The refinements which have been made during the past few years to the conductor design and its attachment to the terminals in connection with arc weld and flame weld bonds have also been incorporated in the more recent designs of brazed bonds. The application to the rail differs from soldering, in that a more intense heat is required. The brazing metal melts at a temperature which does not differ greatly from the melting temperature of the bond terminal, thus actually fusing with it and producing a much stronger union with the rail than is obtained with a soldered joint. This is a very superior method of attaching bonds to rails, from the electrical as well as the mechanical point of view. A typical installation is shown in Fig. 4.

The brazed type of bond has a distinct advantage over other types of heat applied bonds, in that it is applied at a definite temperature which is not dependent upon the skill of the operator. It has the disadvantage, in addition to the same preliminary preparation of the rail surface as with soldered bonds, of requiring special equipment which must be attached to the rail during the process of applying the bond, thus offering an obstruction to traffic, and usually requires electric power of special characteristics, not always available on some electrified systems, for the necessary heat.

### Stud Terminal Bonds

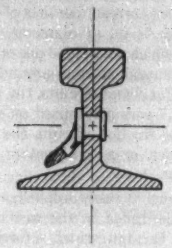
*A. Compressed Terminal.* Bonds of this type consist of one or more laminated or stranded conductors

Fig. 4—Double Brazed Bonds (L. I. R. R.)

forged or welded into a solid terminal at each end, having a cylindrical stud, ¾ in. to 1 in. in diameter, and slightly longer than the thickness of the rail web or flange (see *A*, Fig. 5). The stud is introduced into a slightly larger hole drilled into the rail web or flange, and then compressed by heavy pressure applied to both ends of the stud, to completely fill the hole, with a head or shoulder on each end to seal the joint. If the holes have been freshly drilled or reamed, and contain no grease or moisture, a very low resistance contact can be made between the rail and the bond, which has a fair degree of permanence. On the other hand, if improperly or carelessly applied, they are subject to all the disadvantages of channel pin bonds. The necessary compressing equipment is rather cumbersome and requires considerable time to apply to the bond and to compress the terminal. An obstruction is offered to traffic while the apparatus is in place on the rail, which is a serious disadvantage. Short, inexpensive bonds of this type were designed to be applied at the ends of the rails, removing the splice bars for their application (see *A*, Fig. 6). Longer, more expensive bonds were designed to span around the outside of the splice bar (see

*B*, Fig. 5). Either design resulted in a fairly expensive bond, in place, considering material and labor costs.

A modification of the compressed terminal type bond which was formerly used to some extent, but which has



a

b

Fig. 5—Compressed Stud Terminal Bond

a. Detail of terminal
b. 4/0 stranded
Exposed type used on the New Haven 1900-1911

now practically gone out of use, was the "twin stud terminal" type, designed to be applied to the head of the rail (see Fig. 7). In this type the terminal studs were smaller in diameter (about ½ in.) than the usual compressed terminal, two on each terminal, and of definite length. Two holes were drilled to the proper depth and spacing in the side of the rail head, and then an undercut ring or thread was made in each hole. The terminal studs were then forcibly hammered and

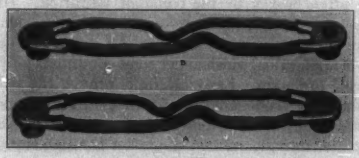


Fig. 6—Duplex Concealed Type Stud Terminal Bonds

a. Compressed stud terminal
b. Pin expanded stud terminal

expanded into these holes. The labor cost of installing such bonds was relatively high.

Combinations of stud type bonds with terminals also soldered to the rail have been extensively used, especially in street railway work. Their chief advantage was the high mechanical strength of the stud terminal with the low permanent resistance of the soldered connection. This was offset to a large extent by the greater cost of installation.

*B. Pin Expanded Stud Terminal Bonds.* This is a refinement of the compressed stud terminal design, in that the stud terminal has an axial hole to take a short

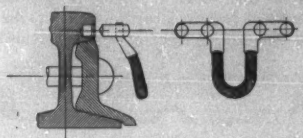


Fig. 7—Twin Stud Terminal Bond

steel plug tapered on one end, having a diameter larger than the hole. The rail is drilled or reamed, as in the case of the compressed terminal bond, and after the bond terminal is in place a hard steel tapered drift pin is driven through the hole in the terminal, expanding it

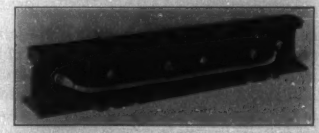


Fig. 8—Pin Expanded Stud Terminal Bond, Exposed Type

to completely fill the hole in the rail. The hole in the terminal is then filled by driving in the short steel plug, which is of slightly larger diameter than the drift pin (see Fig. 8).

This type of bond has proved very satisfactory in extensive use, chiefly because of the flexibility of design

Fig. 9—Pin Expanded Stud Terminal Bond, Concealed Type. (N. Y. C.)

and ease of application. It has been used in all lengths and capacities, from small signal bonds up to the largest sizes of traction bonds, applied to either the flange or web, concealed beneath the splice bars as in Figs. 9 and 6B, or extending around the outside as in Fig. 8. The chief disadvantages of this type are the uncertainty of contact, especially if the holes in the rail have not been previously freed from rust, moisture, or grease, and the relatively high cost of the bond itself and the cost of drilling or reaming the holes in the rails.

A modification of the pin expanded stud terminal bond which is extensively used consists of a stranded conductor having the forged-on terminal on one end only. The other end of the strand is tinned, and is soldered into a separate pin stud terminal, (see Fig. 10) after having been placed in position beneath the splice bar, after which both terminals are applied to the rails in the usual manner. A crimp or bend is provided in the

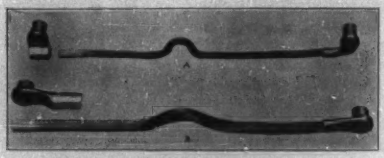
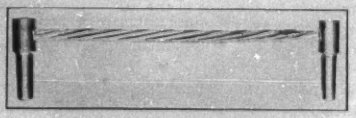


FIG. 10—PIN EXPANDED STUD TERMINAL BOND, WITH SEPARATE SOLDERED TERMINAL

a. Similar to bond used on N. & W.
b. Similar to bond used on Virginian

strand, between the first and second bolt of the joint, to allow for rail expansion, and to prevent removal of bond without taking out the first bolt, which is removed for the installation of the bond. This type of bond has given a high degree of satisfaction on one or two electrified railroads because of its ease of installation (since no splice bars need be removed), its concealed and protected location beneath the splice bar, and its high



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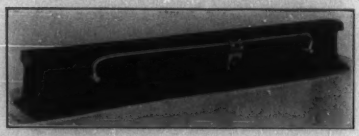


b

FIG. 11

a. Taper pin terminal signal bond
b. Taper pin terminal bond in place on rail joint (double conductor type used experimentally on P. R. R.)

salvage value because of its possibility of re-application. A disadvantage is the additional cost of the soldering operation, although this is easily done since the wire and terminal are already tinned. It is obvious that separate terminals of this type can be used on each end to make up such bonds in the field of any length desired from stranded copper wire.

## TAPER PIN TERMINAL BONDS

A type of bond developed primarily for signal circuits, but which has been used to some extent on multi-track railroads electrified with high-voltage alternating current (where there are consequently comparatively low values of rail return current) consists of a tapered steel pin approximately ⅜ in. in diameter, having an enlarged head, into which are welded one or more stranded conductors, long enough to span around the splice bar (see Fig. 11A). For signal circuits, the conductors are usually of ⅜ in. 7-wire galvanized or copper covered steel strand. For traction circuits the double strand wires are of copper, or a combination of copper and steel wires (see Fig. 11B).

This type of bond is easily applied, requiring but a small (⅜ in.) hole drilled in the web of the rail just outside the splice bar, into which is forcibly driven the taper pin terminal.

The length and exposed location of these bonds give them the disadvantage of liability to injury from dragging equipment or otherwise, or to theft if of copper; and if they once become loose they are not easily kept tight without renewal of bond.

FIG. 12—TYPICAL ARC WELD BOND—U-TYPE

## HEAT APPLIED BONDS

Mention has already been made of the various types of bonds applied to the rails by means of solder. Such bonds had very good contact resistance characteristics, but the soldered joint was mechanically weak, and was very often broken by the constant vibration. Hard soldering, or brazing, produces somewhat better strength characteristics, but requires a higher temperature of application, which under some conditions may be difficult to obtain. Early attempts proved the entire feasibility of arc-welding the bonds to the rails, using either the carbon arc or a metallic electrode, and taking the power from the contact conductor through suitable controlling apparatus. With the subsequent development and improvement of portable electric welding equipment, there have been many types of bonds designed for application in this manner. The latest designs (see Fig. 12) are very short, for application at the ends of the rails, and are consequently of relatively low cost. The cost of application, with properly qualified labor, is also relatively low, making this type of bond a very desirable one from an economic standpoint. It has a fairly high service performance record, although subject to the usual hazards due to its location

on the rail. Where electric power of suitable characteristics is available for such purpose, this type of bonding seems to justify serious consideration.

### Flame Weld Bonds

With the rapidly increasing use of the oxy-acetylene torch for cutting and welding processes, both in shop and in field, within the past few years, and with the increasing use of this tool by track maintainers to build up worn rail ends at the joints, frogs, and switch points, it was only natural that this method should be used for applying bonds similar to those designed for arc welding; and accordingly new designs have been made especially for this process, both for signal and for traction bonds. There was naturally some question on the part of those responsible for track design and maintenance regarding the effect of such intense local heating on the structure and performance of the rail. After exhaustive study the Rail Committee of the American Railway Engineering Association reported in 1926 that there could be no objection to the use of welded bonds "if applied to the head of the rail, and within the limits of the splice bar." Since that date there has been an increasing use of this type of bond for all purposes. Fig. 13 shows various forms of this type of bond. It has the advantage of low material cost and low installation cost. Being short and applied next to the end of the rail, it affords greater protection against broken rails than does a long bond placed around the splice bar. It is entirely exposed, which makes it easily inspected, although its exposed position makes it liable to damage from derailments and malicious interference, and to theft. There is, however, small value in the amount which can be stolen, because of its short length. On account of its short length, heating caused by heavy currents is rapidly dissipated by convection through the larger mass of terminal and rail metal, which allows use of other and less valuable metal than copper, to give, in some cases, a longer life under severe vibration, and to reduce the risk of theft.

It has been found that a coating of heavy grease has a tendency to prolong the life of these bonds under vibration, as well as to render them less attractive to theft and malicious damage.

### Other Types and Methods of Bonding

Numerous other types and designs of rail bonds have been proposed, involving splice bar design and material, set screws, springs, etc., most of which have not been commercially successful for obvious reasons. Abroad, bonds of various types between one rail and the splice bar and from the splice bar to the other rail have been used to some extent. It is, however, obvious that this not only doubles the number of bonds and contact resistance points, but for the same number of contacts per joint has but a small fraction of the reliability for signal circuits that double or multiple bonding has. This method has, however, the advantage of getting the bond away from the point of greatest rail movement. No information is available as to the increased life of bonds applied in this manner.

### Substitutes for Bonding

A discussion of the various methods of rail bonding would not be complete without at least a brief mention of various methods which have been tried to do away with their use.

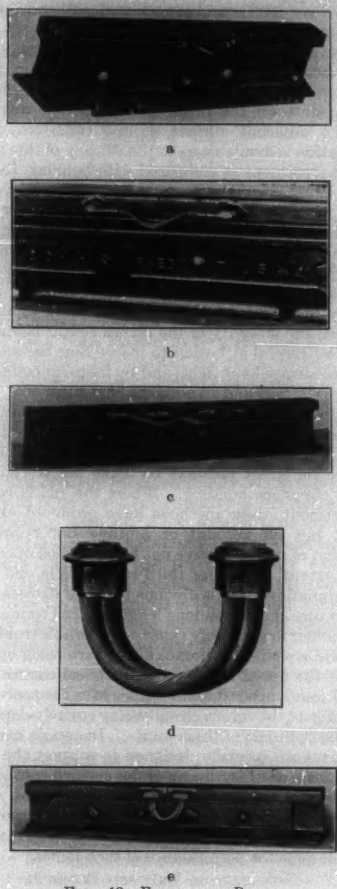



Fig. 13—Flame weld Bonds

a. Stranded copper flame weld signal bond (one terminal not welded to rail)
b. Stranded steel flame weld signal bond
c. Double 250,000 cm. stranded copper flame weld bond
d. U-shape double flame weld bond—detail
e. U-shape flame weld bond on rail joint

One of the earliest attempts which was used with some success was to clean the inside of the angle bar and rail, and apply a small button shaped spring containing a soft amalgam which maintained the necessary contact between the two parts. Two such contacts were required per joint, one between each rail and the splice bar, being held in place by the splice bolts.

Some experiments have been made more recently both abroad and in this country with the process whereby a corrosion-resisting metal is sprayed in a molten state on the inside surface of the angle bar, and the adjacent surface of the rail. No definite information is available as to the efficacy of this method of joint treatment as compared with bonding, its prime object being originally to retard corrosion in the joint itself, which is considered a major cause for joints becoming loose. The present cost of this method of surface treatment makes it prohibitive in this country as compared with other methods of bonding.

On at least one section of steam railroad in this country operating electrically, no bonding whatever is installed, the integrity of the return circuit being maintained by careful attention to insure that the angle bar bolts are always kept tight, and by frequent connections between the rails and an aerial ground wire.

Welding the rails to the splice bars by various methods, and welding the ends of the rails to each other by the "Thermit" process, have been successfully used by the electric street railways to make better rail joints and to eliminate bonding. Where the rail is confined by pavement, these methods have produced excellent results, but on account of limiting opportunity for expansion of rail they have not been used on open track to any extent, except for third rail joints in one or two test installations. It is obvious that the stresses due to temperature changes in long lengths of rail connected in such manner might easily cause considerable trouble.

Several electrified railroads abroad are being operated without the use of any kind of electrical connection at the rail joints other than the splice bars themselves, the continuity of the return circuit being entirely dependent upon the tightness of these joints. In certain cases, the splice bars are specially designed to support the rail at points, instead of by linear or by surface contact, and these points are supposed to be kept bright and in condition for good electrical contact by the motion of the joint under the loads. No specific information is available as to the performance of such joints.

### Concealed *vs.* Exposed Bonding

All bonds are necessarily located at the one place in the track which requires the maximum maintenance attention, namely, the rail joint. Consequently, exposed bonds are always more or less in the way when any work is done on the joint and are subject to damage from wrenches and other track tools. When applied to the rail head, they may be injured by derailments or dragging equipment. They are also exposed to malicious damage and to theft.

Against these disadvantages, the ease of application without disturbing existing joint conditions, and the ease of inspection, are important advantages.

Concealed bonds, (see Figs. 6, 9, 19) while free from the above mentioned hazards of damage and theft, may be carelessly installed and pinched when the splice bar is re-applied, (unless they are inserted behind the bar and later soldered) and if not damaged when the bolts are first tightened, may under such conditions fail shortly after from the movement of the joint. Such conditions are not apparent until a signal failure or test of the joint indicates the faulty condition, and the splice bar must be removed to discover and remedy the trouble. Joint testing, rather than mere visual inspection, is necessary to determine the condition of the bond.

When properly applied, however, the concealed bond on well maintained track has given a very excellent performance record.

### Single *vs.* Double Bonding

As stated above, nearly all types of signal bonds are usually installed in pairs to assure the integrity of the track circuit. When traction current densities require bonding to the approximate equivalent capacity of the rail, single copper conductors might be too large for convenient application, so that usually two or more bonds having total conductivity requirements are applied to each joint, giving a multiple path for the propulsion current and likewise affording to signal circuits, if they exist, the required degree of reliability.

Fig. 14—Double Flame Weld Bond used on the New Haven Since 1928

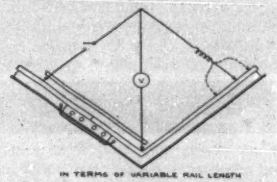
With the high-voltage systems of electric traction, the necessity for large bonds, or for more than one bond per joint, is not so great, especially if track signal circuits are not involved (as on some branch lines) unless the service is unusually heavy. Single bonding has given very satisfactory performance under such conditions. Where signal circuits are involved, the reliability is increased by using double bonds, which may be then of smaller cross section, and in some cases, no larger than a bond designed primarily for signal circuits. (Figs. 1, 4, 13c, and 14 show typical methods of double bonding.)

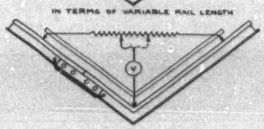
### Bond Testing Methods

Many commercial methods have been devised for testing the electrical resistance of rail bonds in place, and thus determining their efficacy as part of the return circuit.

The method generally used is to measure, by the Wheatstone bridge method, the drop in voltage across the joint as compared with a fixed length (usually three feet) of the rail with a variable resistance; or with a fixed resistance and a variable length of rail; and there are several instruments on the market, portable in form, for making tests of this kind (see Figs. 15A and B). It is obvious that there must be a direct current flowing in the rail, to enable a test to be made.

On d-c. railways there is usually enough current flowing in the rail to give proper indication on the instrument, although where traffic is infrequent such current may not exist. For such conditions a small dry battery is often used with the testing apparatus, or a definite amount of current may be drawn from the contact conductor, through suitable resistance, to furnish the required rail current.

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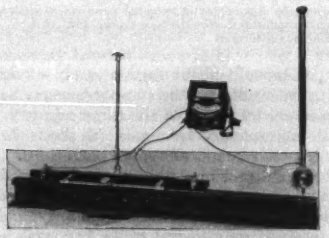

b

Fig. 15

a. Bridge methods of bond testing
b. Portable bond testing instrument—bridge method, giving joint resistance in equivalent length of rail

Some electric roads have fitted up special cars with more elaborate equipment, which not only indicates but also records, and marks with paint, faulty bonds in the track over which the car is operated.

On the "New Haven," which is operated by alternating current, a portable testing set, shown diagrammatically in Fig. 16, is used. This consists of a storage battery B which delivers a definite amount of current (50 amperes), adjusted by means of a variable resistance *R*, and measured on a millivoltmeter in conjunction with the shunt *S*, when the three-pole double-throw knife switch *S W* is in the correct position. With the knife switch in the other position, the millivoltmeter *M V* reads directly the drop across the bonded joint.

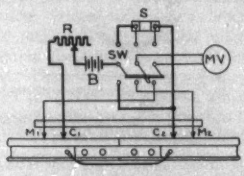


Fig. 16—Portable Bond Testing Set using Potential Drop Method

An upper limit reading on the millivoltmeter is established for a bond known to be good, and all joints which test higher are marked for replacement. The Boston & Maine also uses a similar testing set.

No commercial method of testing yet devised will give other than an approximate indication of actual resistance conditions between the bond and the rail, since such testing is invariably done with the splice bar in place and in many cases, especially where there is no necessity to bond to the full capacity of the rail, a tight joint unbonded with the splice bars in good condition will test lower than will a properly applied bond without splice bars. The real test for satisfactory electrical contact is from the bond conductor near its terminal, to the rail to which the terminal is attached, but such tests obviously cannot be made on all types of bonds, especially where they are entirely concealed.

## II. Experience with Rail Bonding on Electrified Steam Railroads

*New York, New Haven & Hartford Railroad.* The history of traction rail bond application on the New Haven, going back as it does to the earliest days of electric operation of railroads, may be cited somewhat in detail as indicative of the development of the art in general. In the earliest installations beginning in 1895, where the overhead contact or the third rail was employed at 600 volts direct current, the flanges of both the third rail and the traction rails were drilled directly under the joints and a short heavy laminated copper bond was used with split stud terminals expanded into these holes by means of small metal wedges, (see Fig. 17). Later, in 1900, when several additional branch lines were equipped for electric operation at 600 volts direct current, with overhead contact conductor, the track rails (mostly 75 to 90 lb. weight) were bonded with two compressed terminal bonds consisting of 4/0 stranded copper wires around each joint attached to the

web of the rail. No attempt was made at that time to conceal or protect these bonds. The service on these electrified branch lines consisted of electric passenger trains composed of from one to six 40-ton cars, on half hourly schedule, with one or two steam freight trains, daily. The tracks had ordinary earth ballast and consisted of rails weighing from 75 to 90 lb., with standard 4-bolt splice bars. This type of bond proved

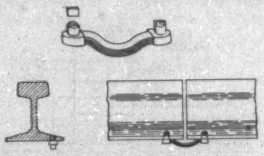

Fig. 17—Early Bond on the New Haven (1895)

very satisfactory both electrically and mechanically, although where joints became loose some breakage of the wires near the terminal occurred after two or three years of operation; and in the urban districts there was some loss due to theft.

Based on this experience, it was but natural, when the electrification of the main line between New York and Stamford was undertaken in 1906, with 11,000 volts 25 cycle alternating current, that a bond of this type should be adopted for the rail return. One 4/0 compressed terminal stranded copper bond was accordingly installed around each rail joint (see Fig. 5). No record was kept of the performance of these earliest bonds on the first electrified section of the main line. The track was well ballasted with broken stone. The rails were 100 lb., but not new, and the joints were with 4-bolt angle bars. The traffic consisted of frequent high-speed passenger trains and heavy freight service, with axle loadings up to 60,000 lb. It is known that some failures were experienced due to broken strands near the bond

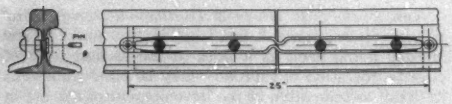


Fig. 18—No. 0 Duplex Pin Expanded Stud Terminal Bond used on the New Haven

terminals, and some loss due to theft occurred in the more densely populated districts.

Several years' experience on this section of the main line demonstrated that with such a multi-track construction. frequently cross-bonded, the rail currents with the high-voltage system used were not of large magnitude, and therefore smaller bonds could be used. The pin expanded terminal bond had already come into extensive use so that in 1911, when the 6-track Harlem River Branch was electrified, a No. 0 duplex pin expanded terminal bond (see Fig. 18) was used on the main track rails, applied beneath the splice bar for protection against mechanical injury and theft. The duplex type bond was selected as affording a double conductor for maintaining signal circuits in event one conductor should become broken. In the several very large freight yards on this branch line one rail only was bonded in each track and for this purpose a No. 2 copper-covered steel wire was used, located under the splice bar where the space permitted, otherwise around it, attached to the rail by means of channel pins.

In 1913 when the main line to New Haven was electrically equipped, the same type of No. 0 duplex bond with pin expanded terminals was used on the main tracks. This type of bond was continued as standard for several years, during which period the failures experienced were carefully studied. One of the principal causes of failure was found to be the faulty application of the splice bar after the bond had been applied, causing the bond strands to become pinched, and after a short time, broken. About 1923 an extensive rail renewal in

a

b

Fig. 19

a. Concealed pin expanded stud terminal bond No. 0 stranded copper, single conductor used on the New Haven, 1923-1928
b. Bond in place in rail joint

this section brought about further study of this problem, with the result that the standards were changed to a single conductor bond, of the same capacity (No. 0) also with pin expanded terminals, (as shown in Fig. 19 A and B) concealed under the splice bar.

On the single track branch line between Stamford and New Canaan which is 7 miles long and fed from one end, a 4/0 single conductor bond with pin expanded terminals, exposed outside the splice bar, was adopted, since the conductivity requirements were somewhat greater than on the main line. The latest major installation of pin expanded terminal bonds was made in 1925, when the Danbury Branch was electrified. A 2/0 single conductor pin expanded terminal bond was installed beneath the splice bars on this section, which is single track, fed from balancer transformers at each end and an intermediate point. Single bonds at each joint of both rails were deemed adequate on both these branch lines which have in general no track signal circuits.

On the busy yard tracks, the original single No. 2 solid copper-covered steel bond soon proved inadequate mechanically and was replaced about 1914 with a single No. 3 stranded copper conductor pin expanded terminal bond. Some of these bonds are still in service, although as a type, they soon gave evidence of being inadequate mechanically. For the last 8 or 10 years the practise has been to bond one rail of each yard track and side-track with one No. 0 single copper conductor, exposed pin expanded terminal bond, which has given satisfactory performance for this type of track and service conditions. (See Fig. 20.)

Failures of the pin expanded terminal type of bonds

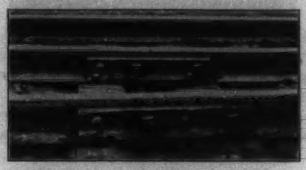

Fig. 20—Exposed Pin-Expanded Stud Terminal Bond used on Yard Tracks on the New Haven

on main tracks have been due chiefly to mechanical fatigue, from vibration, which causes the bond to fail near its terminal; or due to pinching (in the case of concealed bonds) which has caused a similar failure near the center of the bond. These failures have been estimated to be at the rate of 0.25 per cent per year.

During the period 1920-1926 the flame-weld bond had been developed and had gained extensive use, so that in 1926 when the New York Connecting Railroad was electrified, as an extension of the New Haven's electrified territory, it was felt that this type of bond would be justified for economic reasons. Each joint was accordingly bonded with one 13 in. No. 0 stranded copper bond having forged copper terminals, flame-welded to the outside of the head of the rail. These bonds failed almost completely within one year after their application, due to strand wires breaking near the terminal from vibration. This particular track was about nine years old and had 125 lb. rail with standard 4-bolt angle bar joints and broken stone ballast. The natural period of vibration of the particular length and size of bond used was held to be responsible for the large number of failures, and further experiments were made using a smaller shorter bond, and installing two per joint, since signal track circuits were also involved. These gave very much better results, and finally resulted in the adoption, as a standard, of a No. 2 stranded copper bond, 7½ in. long, with pressed steel terminals, using two bonds per joint, (see Fig. 14).

This type of bond has been used since 1928 on all new rail laid in the electrified territory and as the program calls for practically complete substitution of 130-lb. rail for the present 107-lb. rail within the next year or so, it will not be long before this type of bond has replaced the pin expanded type for main track use.

Failures of this type of bond are readily found by the track inspectors and taken care of first with a temporary bond clamped to the rail flange around the joints, and later replaced in kind. The failures experienced have been mainly the breaking away of the terminal from the rail, due to faulty weld or application too near the top of the rail, or the breaking of the strands at the terminal due to vibration. Occasionally strands break inside the terminal and remain in place. Such failures may be found by testing the bond mechanically with a slight prying force. These bonds are given a coating of a special grease after they are applied, which not only tends to damp the vibration, but prevents corrosion of the terminals and wear of the strands and also renders them unattractive to malicious interference.

All bonds are tested twice annually by means of a portable testing set already described. (See Fig. 17.)

On the New Haven, the track supervisors are respon-

a

b

Fig. 21

a. Double flame weld bond used on the Baltimore & Ohio, Staten Island lines

b. Installing flame weld bonds on the B. & O., Staten Island lines

sible for the bonding, reporting to the division engineer. The maintenance organization consists of one bonding foreman, three assistant foremen, and 24 bonders. There are approximately 382 miles of bonded main track, and 195 miles of bonded track in yards and sidings in the a-c. electrified zone.

*Baltimore & Ohio Railroad.* Pin-expanded stud terminal bonds have been used, one per joint, until very recently on the 650 volt d-c. Belt Line electrification in Baltimore, and have given very satisfactory service. On account of the frequent rail renewals due to heavy volume of traffic, the life of the bonds was relatively

short. On the latest rail renewals in the longest tunnel (1.25 miles) two flame-weld bonds were applied to the head of the new rail at each joint and their performance to date has been very satisfactory. The pin terminal type has indicated an increase in resistance as the period of service has lengthened, due to corrosion of the rail contact surface, sufficiently to cause unbalancing of track signal circuits, and necessitating numerous renewals for this reason.

The Staten Island lines of the B. & O., also operated at 650 volts direct current, when electrified in 1926 were equipped with new 100-lb. rail, and flame-weld bonds were used, two applied to the outside of the head of the rail at each joint (see Fig. 21-A and B). No injurious effect on the rail has been indicated caused by welding, and no bonds have been lost to date (except on one or two sharp curves due to extreme wear of the inside rail), indicating a very satisfactory performance. The principal data on both these installations are given in Table I.

TABLE I

| | Belt Line electrification | | Staten Island electrification |
|---|---|---|---|
| Weight of rail | 130 lb. R. E. | | 100 lb. A. R. A. |
| Type of joint | 100% Hd. contact, reinforced | | 100% Hd. contact |
| No. trains per day (One direction) | | | |
| Passenger | 17 | | 233 |
| Freight | 20 | | 4 |
| Axle loads max | 60,500 lb. | | 32,440 lb. |
| Type of bond | Pin exp. terminal, | flame weld | Steel terminal, flame weld |
| No. bonds per joint | 1 | 2 | 2 |
| Size of bond | 400,000 cir. mils | 250,000 cir. mils | 250,000 cir. mils |
| Length of bond | 42 in. | 13½ in. | 13½ in. |
| No. of strands | 91 | 91 | 91 |
| Cost of bonds | $2.12 | $0.58 each | $0.58 each |
| Cost of bond application per joint | $4.32 | | $3.45 |
| Percentage of renewals per year other than for new rail | 4% | —— | —— |

*Boston & Maine Railroad.* Initial installation in 1911, for the 11,000-volt a-c. electrification of the Hoosac Tunnel, was with 4/0 stranded copper, compressed terminal, exposed bonds, one per joint of both rails, applied to web of rails outside the angle bar.

During the early years of operation, renewals were made using 4/0 pin expanded terminal concealed duplex bonds, applied to the web of the rail under the splice bar. In 1925 the short U-type of flame-weld bond was adopted, of 4/0 capacity, 7 in. long, similar to bond shown in Fig. 24, applied to the outside head of the rail, and this type has been continued since as standard. Fig. 22 shows installation equipment and crew.

During the past twelve years bonds have been tested at intervals by passing a direct current from a portable storage battery or generator through each joint and reading drop across joint with a millivoltmeter. The condemning limit for the bond is set at 7 millivolts with a current value of 60 amperes.

No definite record of failures has been kept, but performance seems to indicate a life of approximately 7 years for the pin terminal bonds under existing conditions. Failures of flame-weld bonds have been due chiefly to improper welding, and occasional shearing off

Fig. 22—Flame Weld Bonding Equipment used on the Boston & Maine

of the bond. The track is 100-lb. rail with 100 per cent angle bar joints.

*Chicago, Milwaukee, St. Paul & Pacific Railroad.* The initial installation of bonds in 1914 and 1915 for

Fig. 23—U-Shaped Flame Weld Bond on the Delaware, Lackawanna & Western

this 3000-volt d-c. electrification was with 250,000-cir. mil single conductor pin expanded terminal bonds, one or two per joint of both rails, depending upon propulsion current requirements. Where the joint construction

Fig. 24—U-Shaped Flame Weld Bond on the B. & M., C. M. St. P. & P., and Illinois Central

and conditions permitted removal of splice bar, concealed bonds were used. If space under the angle bar permitted, but conditions did not allow of removing the bar, concealed bonds were used with one detached terminal, soldered on the bond strand after bond was in

place. Where joint construction did not permit the use of concealed bonds, exposed bonds were used around the splice bar, on the inside of the rail, as this location appeared to result in less damage to the bonds in cases of derailment. The length of these bonds varied from 20 in. in the case of concealed bonds, to 37 in. and 42 in. in the case where two bonds of the exposed type were used at each joint.

On account of the high value of the bonds, they were, when removed from the rail for any reason, brought into the store-room, re-formed, and the terminals re-shaped, and returned to stock.

In 1921 the use of flame-weld bonds was started, since which time they have been used on all new rail, and for much of the maintenance work since 1924. One U-shape double conductor bond, 7 in. in length, of 4/0 capacity, and having pressed steel terminals, is used, welded to the outside of the head of the rail (see Fig. 24). This type of bond was adopted because of its lower cost, more reliable and permanent contact with the rail, and greater ease of inspection as compared with the original pin terminal bonds. The estimated relative economy of the two types is as follows:

| | | | | |
|---|---|---|---|---|
| Pin terminal type | 37 in. | Material $1.50 | Labor $0.45 | Total $1.95 |
| Flame welded type | | Material 0.70 | Labor 0.38 | Total 1.08 |

showing a saving of $0.87 per joint, which is increased in territory where double bonding was formerly used, since one welded bond only is used in these locations. Experience to date indicates a very satisfactory performance of this type of bond. Many of the old pin terminal type originally installed are also still giving satisfactory service.

*Delaware, Lackawanna & Western Railroad.* For this 3000-volt d-c. electrification, construction of which is nearing completion, the engineers have selected after careful tests under actual track conditions, a 4/0 U-shaped double stranded conductor bond, 8½ in. long, with steel terminals (see Fig. 23), which will be welded to the outside of the head of the rail at the joint, using one bond per joint where both rails are used for the propulsion current return, or two per joint where single rail return is used. This type of bond was selected because of lower first cost and lower resistance as compared with longer pin terminal type bonds.

*Illinois Central Railroad—Chicago Terminal Electrification.* Flame-welded bonds are used on the Chicago Terminal electrification which has 133 miles of main track and 17 miles of yard track operated at 1500 volts direct current. Both rails are used for track signal circuits and for traction current return and joints are single bonded except through interlocking plants, where one rail only is used for traction return with joints double bonded, the other rail being single bonded with the same type bond for signal track circuit.

The rail used is standard ARA-A section 9020, joined with standard I. C. 24-in. oil treated angle bars, having four 1-in. bolts and with tie under each end of angle bars. The traffic is very dense, consisting chiefly of suburban passenger service. The speed of all I. C. trains averages 26.4 miles per hour and the average train-miles per day is 7306, with 27,366 car-miles per day. The cars average 63.4 tons each with load and have 4 axles. In addition to the I. C. trains, the Chicago, South Shore & South Bend operate their electric suburban service over part of the terminal tracks, averaging 1169 train-miles or 2934 car-miles daily. The average car weight of this service is 57.1 tons, carried on 4 axles.

A single 4/0 -127 strand bond about 8 in. long, with solid copper sleeve terminals, was originally installed. The terminals were welded to the outside head of the rail, approximately 7 in. between terminals, thus leaving enough slack in the bond for a slight bend or depression to allow for expansion and vibration. Bonds were coated with heavy crude oil at the time of installation. After a three year period of operation, it was felt that a change was desirable because of malicious interference, a large number being damaged in certain areas by trespassers turning the bonds up over the rail and allowing trains to cut them off. It was therefore

Fig. 25—Single Flame Weld Bond used on the Reading

decided to discontinue the use of this bond and to make all replacements with a standard U-shaped bond.

The U-shaped bond now used consists of two No. 0, 61 strand copper conductors 8 in. long, fitted with thin copper sleeves at each end, clamped into a pressed steel terminal which is flame welded to the outside of the head of the rail (see Fig. 24). Some of these bonds have now been in service for three years and are proving in general very satisfactory, although there are certain features which have given some trouble. The core of the stranded conductors seems to be under a greater tension than the outer strands, since the terminals are clamped on before the strands are bent into the U-shape, and the center strands invariably break first under fatigue due to vibration. Vibration also causes the strands to wear away where the two conductors cross each other, and it has been necessary to renew some bonds on this account. Coating the bonds with a heavy oil seems to overcome this feature, and in addition, tends to damp the higher frequency vibrations, thus prolonging the life of the bonds in general. This treatment also retards corrosion and oxidation of the bond and its terminals.

About 49,000 bonds were installed originally. Of these, approximately 19.39 per cent have been replaced by U-bonds due to all causes. During the three and one-half year period of operation, 19,286 U-bonds have been used, and of this number a total of 9.88 per cent have been replaced. The following tabulation indicates the approximate proportion of bonds replaced, and the chief causes for their replacement:

| | Original Bonds | U-Bonds |
|---|---|---|
| Rail changes | 11.85% | 8.03% |
| Fatigue failures from vibration | 3.01 | 0.43 |
| Malicious interference | 2.32 | .. |
| Defective welding | 1.36 | 0.40 |
| Dragging equipment | 0.85 | 1.02 |
| Total replacements | 19.39% | 9.88% |

About 90 per cent of the bonds removed for rail changes can be reclaimed and used again. It is expected that fatigue failures may increase as the service life lengthens. Malicious interference losses were chiefly due to trespassers turning up the original bonds on to the top of the rail. The U-bond has eliminated this item. Defective welding includes original application and re-application if removed for building up joints by the welding process, the latter operation being the chief cause for failures of this type.

The traction bonding maintenance is in direct charge of an Assistant Engineer reporting to the Supervisor of Electrical Maintenance. Under him are three welders and three welder's helpers. The bonded area is divided into three districts with one welder and one helper responsible for each district. A fourth welder is employed as an instructor and to assist otherwise.

*New York Central Railroad.* The New York Central has for many years standardized on a pin expanded stud terminal duplex bond, entirely concealed beneath the splice bars, for the 660-volt d-c. electrification of the New York Terminal, which includes 328 miles of bonded track. Bonds of 400,000 cir. mils or 500,000 cir. mils capacity are used, two per joint on both rails. This bond is shown in Fig. 9. The terminal studs are 1 in. in diameter, spaced 16.8 in. apart. The rail used is 105 pound Dudley section, connected at the joints by six-bolt angle-bars, with a tie immediately under the ends of the rails. The service is unusually severe, 505 passenger trains and 45 freight trains operating over the electrified territory daily. Axle loadings are as high as 50,400 lb. on the heaviest locomotives, the average being about 38,000 lb.

Each joint is tested at regular intervals, the whole bonded area being covered about twice in three years.

*Norfolk & Western Railway.* On the section of the Norfolk & Western, which is electrified with 11,000 volts alternating current, a No. 0 concealed, stranded, pin-expanded stud terminal bond similar to Fig. 10A has been used since inauguration of electric operation.

Originally, the bonds had one pin-expanded terminal forged on, and the other end was soldered into a separate expanded pin terminal after being fished under the splice bar. This practise of having one terminal forged on has since been discontinued, to avoid having two different terminals, and because the forged-on terminal cannot be re-applied if the bond wires are damaged. Two separable terminals are now used, one soldered to each end of the bond strand, which simplifies maintenance stock and permits making bonds to any length required. These soldered terminals have not given any more trouble than the forged-on terminals which they replaced. No definite records have been kept of the bond maintenance cost, few bond failures occurring before they are removed on account of changing rail.

The terminals, after removal, are re-shaped and used again where possible, using an oversize pin.

The track is laid with 130-lb. rail with continuous joints. The traffic consists chiefly of very heavy tonnage trains with high axle loads at low speeds. Rail life is so short that broken bonds are practically unknown.

The type of bond used has been very satisfactory because of its ease of application without special heavy tools difficult to transport, since bonders are sent out considerable distances from headquarters to install bonds as rails are changed; also on account of the ability to salvage the terminals and to re-apply them.

*Pennsylvania Railroad.* Experience with electric traction rail bonds has been obtained by the Pennsylvania Railroad System in four zones, namely, the West Jersey & Seashore Railroad, the Long Island Railroad, the New York Terminal electrification, and the Philadelphia suburban electrification.

The West Jersey & Seashore Railroad line between Camden, Millville, and Atlantic City, New Jersey, makes use of a 650-volt d-c. third rail system. Multiple unit trains with maximum axle loadings of 31,000 lb. are operated at maximum speeds of 70 mi. per hour. Local steam freight service is also operated over the electrified lines. These lines can be roughly classed in the medium traffic zone, with cinder and stone ballast, and rail weights of 100 lb. and 130 lb. P. S. section.

The original traction bond used was a compressed terminal concealed bond of 400,000 cir. mils cross-section. These bonds showed a tendency to fail under the joint bars of the joint due to a pinching action between the bars and the flange of the rail. Due to the difficulty of detecting these failures and to the difficulty of making a replacement, this type was abandoned and an exposed compressed terminal bond 35 in. long of 400,000-cir. mils cross-section substituted. This bond was satisfactory from the point of view of ease of maintenance and length of life. Because of the relatively large amount of copper in the bond some difficulty has been experienced due to theft. The cost of this bond installed is high as compared to more recent types of bonds, and investigations are being carried out to determine a cheaper bond suitable for the service conditions imposed.

Since the initial electrification in 1906 with the d-c.

650-volt third rail system, traction rail bonds have been installed on the Long Island Railroad under a variety of service conditions, ranging from dense main line multiple unit and freight and passenger steam traffic to light branch line service with maximum speeds up to 70 mi. per hour. Rail weights have varied from 70 lb. A. S. C. E. to 130 lb. P. S. section, and axle loadings from 15,500 lb. to 33,200 lb. for multiple unit cars and from 8000 lb. for empty freight cars to 75,000 lb. for electric locomotives. Roadbed conditions have generally been good with cinder ballast predominating.

A soldered type of rail bond was adopted for the initial electrification in 1906. These were short bonds soldered either to the ends of the joint bars and to the head of the rail, or to the under side of the web at the rail ends. These developed failures at once under rail vibration, the soldered terminal breaking away from the rail.

A concealed compressed terminal bond was then used. This was a double cable bond so formed that it would fit around the joint bolts under the joint bars. These developed broken strand failures under the joint bars, due to vibration and to a pinching action between the bars and the web of the rail.

A long semi-concealed single cable compressed terminal bond was then developed. Because of its length, the copper cross-section had to be increased in order not to increase the joint resistance. While the service life was favorable in length, the cost of the bond was disproportionately high and maintenance was relatively difficult. Typical failures were similar to those of the double cable bond.

Development of a brazed terminal bond was then begun (1912). This was first a U-shaped ribbon bond. Difficulty was encountered in applying this due to a new design of joint bar with a projecting shoulder under the head of the rail. This was especially difficult where two bonds per joint were required. Broken ribbons also developed under joint vibration. Several adaptions of this U-ribbon bond were tried without successfully overcoming its objectionable features.

The present type of rail bond was then developed. This is a 250,000-cir. mil single cable bond 13 in. long with a terminal brazed to the head of the rail (see Fig. 4). There is only a slight loop in the bond, sufficient to provide for rail movement. This type has worked out quite successfully under the traffic and roadbed conditions generally prevailing on the Long Island Railroad. In general the life of the bond equals that of the rail, except at those points where a considerable amount of joint vibration exists. The majority of failures there are due to broken strands in the bond.

The New York Terminal electrification also uses the d-c. 650-volt third rail system. Traffic conditions are those of dense main line passenger service with axle loadings varying from 15,500 lb. for M. U. cars to 75,000 lb. for locomotives, and with maximum speeds of 70 mi. per hour. Roadbed conditions are exceptionally good, having rock ballast in general, with 130 lb. P.S. section rail.

A 35-in. exposed compressed terminal bond of 400,000 cir. mils cross-section was originally installed and has given very satisfactory service, the life of the bond generally equaling that of the rail. However, because of its relatively high cost as compared with recent types of bonds, its use has been discontinued and the standard Long Island Railroad bond (Fig. 4) is now being used for necessary renewals.

The Philadelphia suburban electrification uses the 11,000-volt single-phase overhead catenary contact system, requiring a traction rail bond of small cross-section as compared to the d-c. traction bonds. Service conditions are those imposed by heavy high-speed trunk line service on 100 lb. and 130 lb. P. S. section rail with rock ballasted roadbed, and with axle loadings varying from 8000 lb. for empty freight cars, and 37,000 lb. maximum for multiple unit cars, to 75,000 lb. for locomotives, and with maximum speeds of 70 mi. per hour.

The original traction rail bond used was a pin-expanded concealed bond with the cable of the bond soldered into the pin terminal which gave satisfactory service life. Typical failures of this bond were by broken strands under the joint bars of the joint. A flame-weld type of bond, No. 1 in cross-section, 7½ in. long, is now being used, the installed cost of which is approximately one-half that of the original type.

Favorable experience over an extended period of time with a taper pin terminal, double cable steel and copper strand exposed signal bond, supported by clips held by the joint bolts, especially with renewals made necessary by track maintenance, has suggested the possibility of still further reducing the installed cost of bonds for this service. Investigation shows that sufficient conductivity can be introduced in this bond in order to make it a suitable traction bond by the addition of nine copper strands to each cable and enlargement of the head of the cable, without changing the dimensions of the pin end of the terminal. The bond is thus interchangeable with existing signal bonds and experimental installations are now being made. (See Fig. 11B.)

It can be deduced, in general, from the Pennsylvania Railroad System experience with various types of bonds under differing service conditions that: (1) an exposed type of bond, so designed as not to interfere with track joint maintenance, is necessary; (2) all types of bonds so far used will fail on track so maintained as to permit a considerable amplitude of joint vibration; (3) the typical failure under such conditions is due to broken strands or ribbons near the bond terminal; (4) the installed cost of large section traction bonds for d-c. systems can be brought to the lowest point by using types that do not require drilling of the rail, as where the bond terminal is attached to the outside head of the rail by a welding or a brazing process.

Experimentation under actual service conditions is

now being carried out to determine those types most suitable, from the points of view of installed cost, life, and ease of replacement, for the various service conditions to be met. Sufficient experience has not yet been obtained to permit of definite conclusions.

*Reading Railroad.* The Reading, which is electrifying some of its suburban traffic routes in the vicinity of Philadelphia, with 11,000 volts alternating current, but which is not yet in operation, has conducted tests with a number of experimental installations of bonds to determine the most satisfactory type for the track and operating conditions met with.

The standard rail used for main line tracks is 130 lb. of the "head-free" type. With this type of rail the depth of the vertical section of the head is only about ¾ in., of which ⅜ in. must be allowed for wear. The full depth of wear must be allowed on outside of railhead as well as inside, since rails are canted and foreign cars with wheels worn by level rails wear the canted head-free rail particularly on the outside edge. There remains only about ⅜ in. of vertical section, which had to be given thorough consideration in preliminary consideration of types of bonds, so that the limitations of the welded bond might be determined. The remainder of the rail head slopes at an angle of 29 deg. from the vertical and there was some question as to whether this would be suitable for welding.

Test installations of welded bonds were made, largely for the purpose of determining any limitations in application of the bond. These included various sizes of bonds from 250,000 cir. mils to No. 2, the latter being a commonly used size of welded signal bond. It was determined definitely that there was no appreciable inconvenience in welding either a large or a small bond to the head-free rail and the sloping side of the rail head could be used readily for this purpose.

The test bonds are also being observed to note any effect of fatigue but the length of time available for such observation has not yet been sufficient to show any conclusive differences.

Conditions of traffic on this rail will include suburban passenger service, main line passenger traffic, and main line freight trains. The heaviest axle loading for both through passenger and freight engine is approximately 65,000 lb. and on some sections of the railroad the speed of passenger trains will regularly be 85 mi. per hour. Density of traffic will be as great as 3-minute headway on certain of the lower speed sections of the line. Freight traffic will include heavy tonnage coal trains traveling at relatively high speed.

The continuous head-free type joint is used with the 130-lb. rail and an unusually high standard of maintenance is obtained throughout all sections of the territory. Joints are therefore depended upon to be free from play, so that weaving of the bond need not be provided for. Observations also indicate that vibration conditions will not be severe even under the heavy conditions of traffic.

Theoretical comparison of short welded bonds and expanded pin terminal bonds extending beyond the limits of the angle bar, and having capacity to give comparable resistance of joint showed that the installed cost of the copper pin expanded terminal type of bond would be greatly in excess of the cost of a short bond welded to the head of rail. The latter, as is well known, also has some advantage in the case of broken rail protection. The pin expanded terminal type was eliminated from further consideration. The electrically welded bond was eliminated because gasoline engine driven generator sets would be required after operation as well as during construction, since trolley voltage will be 11,000 volts alternating current.

A detailed study of maximum current in the rails showed that a short welded bond as small as No. 1 gage would have ample current carrying capacity and that moreover the large amount of contact of the continuous joint bars with the high degree of maintenance would give further factor of safety as to carrying capacity. The problem therefore became one of mechanical requirements rather than electrical. Accordingly, a No. 1 A. W. G. 61 strand copper flame-weld bond, 8 in. long with 1½-in steel terminals has been adopted, one applied to each joint of both rails. (See Fig. 25.)

Observation of the various sizes of welded bonds applied for test indicate that long life can be expected from a small bond such as No. 1 as well as from a larger bond of 4/0 or 250,000 cir. mils capacity. (Study of test results on some of the other railroads verified this view.) Although the installed cost of the larger bonds is not higher in direct proportion to the size of bond, they will cost materially more and it is therefore considered that a small, short welded bond will be adequate as well as most economical. This bond will furthermore lie snugly within the limits of the angle bar and be well protected from damage by track wrenches. The U-type of bond is impracticable due to the shape of the angle bars, and the straight type of bond with a liberal amount of loop has been chosen. Consideration was given to using two bonds per joint, and it was decided that the advantages would be very small in comparison to the increased cost of installation and maintenance.

Branch lines will have 100 lb. R. E. rail but the type of bond chosen for the 130 lb. H. F. rail is equally suitable for the smaller rail section, and also for 130 lb. R. E. rail.

*Virginian Railway.* The Virginian operates probably the heaviest freight trains in the United States. The traffic is very similar to that of the Norfolk & Western, consisting of very heavy tonnage trains with high axle loads at low speeds. The greater part of the main line in the electrified territory is of 130-lb. rail, with 4-bolt, 26-in. continuous rail joints. Sidings and yard tracks are mostly of 100-lb. rail, with either 4-bolt or 6-bolt rail joints. Locomotive axle loads are as high as 79,000 lb. and loaded freight car axle loads are as high as 53,000. The freight traffic consisting chiefly of coal,

is handled eastbound from the mines to tidewater, with as many as 10 to 11 tonnage trains daily including local service. The westbound traffic consists of handling the empty cars back to the mines. The passenger traffic is light, with but three trains each way daily.

The main line, which is double track for 22 mi. and single track the remainder, has both rails double bonded at each joint with two No. 0 37 strand copper conductors of lengths varying from 32½ in. to 54 in., having pin expanded stud terminals ¾ in. in diameter by 13/16 in. long. (See Fig. 10B.) The hole through the terminal is 11/32 in. in diameter and is expanded with a 7/16-in. diameter steel pin. Double bonds are used throughout the electric zone because of the heavy currents involved in moving trains of from 6000 to 9000 tons over the heavy grades which exist on this line; also to afford protection to the joint if one bond should fail. Side tracks have both rails single bonded to the main track every 1000 feet.

Two forms of bonds were used, depending upon the nature of the rail and joint. Where space under the splice bar permitted, two semi-concealed bonds of the same length, with terminals extending beyond the angle bar were used, one on the inside and one on the outside of the rails. This type bond has a crimp or double bend between the first and second bolts to provide for expansion and flexibility; and to avoid the necessity of removing the splice bar it has only one forged-on terminal, the other end being soldered into a separate terminal after being fished underneath the splice bar. Where space under the splice bar was not sufficient, exposed bonds having forged-on terminals on both ends were used around the bar on the inside of the rail, long enough to provide the necessary working clearance, and to permit stapling to the ties. One bond is four inches longer than the other to avoid crossing. The location on the inside of the rail appeared to be more favorable to the bond in case of derailment.

Bonds are inspected and tested at regular intervals by means of a Wheatstone bridge type of instrument applied to each joint. Defective bonds are immediately replaced.

When rails are changed, bonds are knocked out, and reclaimed by careful inspection and re-shaping of terminals. When re-applied such bonds are expanded with an oversize pin ½ in. in diameter. After the second removal, the forged-on terminal is cut off, and replaced by a soldered-on terminal, giving the bond approximately its original length.

Experimental installations of other types of bonds have been made. One of such installations was the taper pin type similar to bonds used in signal service, of No. 0 capacity, applied to the outside of the rail around the joint, and held tight against excessive vibration and displacement by means of a clip under one of the track bolts. This type is satisfactory the first time it is applied, but cannot be satisfactorily applied the second time, as the taper terminal becomes loose in the hole in the rail.

The other experimental installation was of flame weld bonds, which so far have given satisfactory results. Failures of this type have been few, consisting of strands breaking out of the terminals. One case has been noted where such a bond became loose from the rail, probably because of improper welding.

## Summary

It will be seen that there is not only a great variety in the types of bonds now in commercial service, but that different performances may be expected under different conditions of operation or track maintenance from the same type of bond. It cannot be definitely said that any one type of bond requires a higher degree of track joint maintenance than another, although loose joints permitting of free movement of bolts and splice bars are, in general, destructive both to the short heat-applied types and the longer concealed types of bonds. It may be said that in general the greatest cause of mechanical failures in bonds is that due to fatigue, caused by vibration set up from the pounding of the heavy axle loads over the rail joints. It has been proved by laboratory and service tests that long bonds have a longer life than short bonds under the same conditions of such low-frequency vibrations. Hence it might be deduced that long bonds around joints would outlast short bonds applied to the extreme end of the rails. There are, however, under service conditions, vibrations of much higher frequencies, which are difficult to reproduce in laboratory tests. These vibrations can be, and often are, more destructive to the longer types of bonds than to the shorter types, under actual service conditions. The mass of the material involved, its physical properties, natural period of vibration, inertia, etc., all have a bearing on the problem and on the performance of any type under given conditions. All types of bonds seem to give satisfactory mechanical performance and length of service under good track joint maintenance.

Relative to electrical performance, the only cause for failure which is possible is the change in contact resistance, as between the bond terminal and the rail, or between the bond conductor and its terminal. The latter cannot exist without mechanical failure, in any properly manufactured bond; the former can exist without mechanical failure in the mechanically applied bonds only. The heat applied bonds thus seem to possess better characteristics from the electrical point of view.

The problem resolves into a careful study of all conditions which are to be met, and selecting the most economical type, taking into consideration the following requisites:

1. The bond must have a low resistance, in place.
2. Its contact with the rail must be permanent, so that resistance will not vary with time.

3. It must be easily installed by equipment readily available.

4. It must have a low first cost.

5. It must have a low maintenance cost.

Taking all factors into consideration the trend seems to indicate an increasing preference for the heat applied types.

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## Discussion

**H. H. Febrey:** This is the first time an attempt has been made to publish in one article the story of rail bonds on electrified steam railroads. It is rather surprising how much can be said about the art of rail bonding in all of its phases. Those of us who have been associated with the manufacture of bonds realize how much time and expense has been devoted to its problems for many years.

The manufacturers are devoting considerable attention to rail bonding problems in their laboratories. The company with which I am associated is extending laboratory facilities and equipment constantly and some very interesting and valuable facts are being determined from the numerous experiments which are being carried on. This will result in marked benefits to the consumer. It is natural that the development work is approached not only with the idea of improving the rail bond but to developing manufacturing processes which will reduce costs without any impairment of the quality of the bonds.

A glance at the manufacturers' catalogues today reveals an array of bond types which upon reflection seems unnecessary. Present welded type bonds require different designs of bond terminals for each welding method employed in their application. That is to say, we cannot interchange the rail bonds for application by oxy-acetylene flame, steel electrode arc welding, copper electrode arc welding and brazing or soldering. Because of this great variety of rail bonds and the number of sizes in which it is necessary to make them, the manufacturing practise has been very much of a hand proposition. Machinery used in manufacture is hand fed throughout the various manufacturing operations. Obviously this condition promotes high manufacturing costs. We may well say that bonds are "tailor made."

Efforts are being made to simplify bond designs and reduce the number of kinds, making them interchangeable between the different welding methods of application. We have been working for some period to develop machinery for automatically manufacturing rail bonds. Machines of this type are very expensive to develop and costly to manufacture. In order for them to be economical it is necessary to have a volume of work equal to the capacity of the machines. Simplification of bond designs will bring this about and the consumer will benefit to a very large degree if he will cooperate with the manufacturers in their efforts to reduce the number of bond designs to an absolute minimum.

In regard to the methods of applying welded bonds, there seems to be an unnecessary number of processes, all of which result in approximately the same cost per bond installed. Furthermore, the total resistance of the bonds installed is so nearly the same that we could very well eliminate some of the kinds of field welding.

Oxy-acetylene flame welding has many decided advantages for rail bonding, particularly on new work and for maintenance on high voltage systems where portable arc welding sets are not as practical to use. In arc welding we have three methods in use today; steel electrode, copper electrode and carbon electrode.

The simplest of these is steel electrode welding. It has the very decided advantage of being applicable by all types of arc welding equipment because the polarity of the electrode may be either positive or negative. The nature of the welding process is such that the same shapes of terminals which are correct for flame welding are equally suitable for steel electrode welding.

We are accustomed to demand the use of copper in welding the bonds to the rails, because it has lower resistance and is non-corrosive. Consequently we have the copper electrode and the carbon electrode methods of applying bonds with copper. Both of these methods require that the bond terminals be cup shaped or that a separate carbon mold be used with a more simple design of bond. The copper electrode process requires positive polarity of the electrode and demands a very much higher amperage than a steel electrode. The proper current requirements are actually beyond the range of a number of commercial welding sets which were designed primarily for steel electrode welding. The carbon electrode process requires negative polarity and therefore a rotary type of welder. If we could eliminate these welding processes the manufacturers' problems of design would be greatly simplified because the same bonds could be used for flame welding and steel electrode arc welding. The volume of bonds of one design would be increased and make economically possible the use of automatic machinery in production.

The use of steel for the terminals of welded type bonds has become largely standardized because better results are obtained

than with copper terminals. Steel is a rather poor conductor of heat and protects the bond conductor from the welding heat to a degree. In the mechanically attached terminal bonds where the welding is done directly upon the end of the conductor, those with steel terminals have stood up better under fatigue stress than similar bonds having copper terminals. If the poor heat conducting property of steel is carried further by welding a solid steel terminal to a copper conductor in the factory, still better results are obtained. A welded type bond is now being placed upon the market which has solid steel terminals welded on in the factory. The factory welding is accomplished in such a manner that the conductor is not injured by the heat nor injured mechanically. When this bond is applied the welding is done upon the solid steel terminal and the heat is not transmitted to the conductor nearly as much as with the mechanically attached steel terminal. In laboratory tests these solid steel terminal bonds have withstood vibration much longer than any bonds known before.

The solid steel terminal has slightly higher resistance but has the advantage of being applied equally well with the oxy-acetylene flame or steel electrode arc welding. The solid terminal simplifies the field welding and insures full efficiency of the bonds. The danger of the operator failing to weld all of the wires in the conductor is eliminated. This development follows the lines of simplification because the bond is applicable by two welding methods.

It is pertinent to emphasize the high cost of heat applied bonds as we have them today. In many cases too much is added to the price of the bond alone for accessory materials. The labor cannot be changed very much as the time of welding is quite rapid and approximately the same for the various processes in use. As an illustration, the Baltimore & Ohio Railroad reports a flameweld bond costing 58 cents for the bond and $1.73 installed, or $1.15 for labor and accessory materials. In other cases of flameweld bonding on electrification work we find the following relations:

| Bonds | Labor and accessories |
|---|---|
| 42 cents | 62 cents |
| 40 " | 68 " |
| 20 " | 60 " |
| 19 " | 56 " |

This is one of the problems which is being studied and experiments are being conducted in an effort to develop less expensive methods of installation, some of them contemplating a very marked reduction in labor costs.

Mr. Brown has pointed to failures of rail bonds from fatigue. Troubles of this nature have been more pronounced with the short welded bonds applied to the head of the rail than was the case with the more expensive concealed types of bonds or the long bonds installed outside of and around the splice bars. The fatigue failures are somewhat peculiar. Large numbers of bonds of the same type will stand up under the same traffic conditions and a certain percentage will fail very rapidly, sometimes in just a few months. Observation of the track and joint conditions does not seem to reveal why a failure occurred on one joint and not on another where the age of the rail and condition of ties and ballast are about the same. Considerable study has been given to the problem of vibration and almost countless vibration tests have been made by manufacturers on various kinds of machines which accelerate the failures of samples in order to break them within a reasonable length of time. Definite conclusions from these laboratory tests are almost impossible to reach. Consequently, efforts are being made to determine the nature of the vibration to which the bonds are being subjected and endeavor to reproduce similar conditions on the laboratory machine which will give an accelerated test.

Certain devices have been perfected for the study of vibration in all sorts of structures. One of these is known as the Electric Telemeter devised by Mr. O. S. Peters at the time he was with the U. S. Bureau of Standards. With this device an oscillograph record can be made of the vibration in any structure and the results are very enlightening. This device will be used on tracks under various traffic conditions and a study will be made in an effort to determine what takes place at rail joints where rapid failures of bonds occur. It may be of interest to point out that one record was made with the telemeter on one of our Eastern roads on 130-lb. rails with train speed about 70 miles per hour. The frequency of vibration was found to be as high as 1250 cycles per second. This high frequency vibration has a very marked effect upon the bonds and it is very probable that certain sizes and shapes of bonds respond to vibration corresponding with their natural periods and vibrate in harmonics of exceptionally high frequency.

It is hoped that an interesting insight of the vibration problem will be obtained with the telemeter. By applying these field observations to the laboratory vibration equipment we hope to obtain the correct frequency and amplitude of vibration which will enable us to accelerate failures in tests of all sizes and lengths of bonds. Up to the present time it has not been practical to test long bonds satisfactorily in the laboratory. Any frequency which has been selected for the laboratory equipment has been necessarily an arbitrary choice. Under these conditions we cannot be assured that the laboratory results are properly indicative of the manner in which the bonds will perform in service.

Mr. Brown in his paper mentions rather briefly the tapered pin terminal bond, Figure 11A and 11B. Experiments with different bonds of this general construction have given us information which is rather interesting. Until the tapered steel terminal bond was suggested for electric traction the experience with stud terminal bonds was confined entirely to copper terminals, either compressed or pin driven, that is, expanded with steel drifts. These copper terminals were of relatively large diameter, ¾ in. to 1 in. and sometimes 1-1/16 in. It was felt that the larger diameters were necessary for the larger capacity bonds. However, load tests on tapered steel terminal bonds have shown surprising results. In the case of the bond illustrated in Figure 11A and 11B, the total copper cross section is a little less than 1/0 AW gage. With a load of 400 amperes at 25 cycles the temperature rise in the conductor of a 48-in. bond is about 75 deg. cent. The ⅜-in. terminals remain cool.

While it may seem as though a backward step was being taken to consider long pin terminal bonds versus short welded bonds, the welded bonds are more expensive in first cost and more expensive to maintain. Comparing the installed cost of two No. 1 AWG 8½ in. flameweld bonds with one 48-in. double conductor bond mentioned in Mr. Brown's paper installed shows the latter to be but slightly over half the cost of the two flameweld bonds.

In the summary of his paper Mr. Brown points out certain requisites which have the aspect of the millenium in rail bonds. Items 1 and 2 combined with items 4 and 5 would result in perfect rail bonds. When all factors pertaining to railroad operation are taken into consideration should not the most economical bond be selected? We have developed new rail bonds which combine low first cost with low maintenance cost but which require some compromises in the other of Mr. Brown's requisites. In order to keep the maintenance cost down the bonds must stand up in service with minimum failures. Furthermore, it should be emphasized that many maintenance renewals are due to rail changes which occur regardless of the type of bond used.

**G. H. Müller:** The electric rail joint used by the Swiss Federal Railroads comprises a copper cable of 35 mm.² (0.54 sq. in.) cross section and 320 mm. (12.60 in.) long as indicated on the accompanying drawing.

The electric resistance of this type of rail joint is about 600 microhms, that of the electrically welded joint about 350

microhms and that of a joint without bond about 2000 microhms. In other words, since a rail length is usually 15 meters (16.40 yards) the conductivity is increased in the ratio of two to one by bonding the joints.

This considerable increase in conductivity naturally produces an important increase in the normal rail current.

The reduction in voltage induced in the conductors of a cable along the right of way when four rails are electrically bonded amounts to 46.6 per cent.

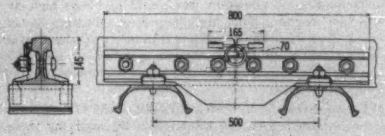


Fig. 1—Swiss Federal Railways, Rail Joint

The ends of the copper cable are terminated in iron or copper blocks electrically welded to the head of the rail. Autogenous welding at the base of the rail has been abandoned because it caused numerous failures.

The results which have been obtained by electrically welded rail bonds have been very satisfactory.

**Ivan Olverholm:** Rail bonds are no longer used in electrified railroads operated by the Swedish State. They were used in the beginning on the Ore railroad in the North of Sweden, but were discarded on account of high maintenance. The experience in Sweden has indicated that operation may be satisfactorily performed without rail bonds.

On some of the smaller direct current railroads in Sweden copper rail bonds are used. However, in no case are these railroads more than 15 kilometers long. The electrical engineers of these railroads would be glad to eliminate rail bonds but they have found it impossible when direct current is used.

The Swedish State Railways employ single phase distribution at 16,000 volts, 15 cycles per second.

**M. Paradi:** The system of electric traction for the French Railroads has been standardized on the basis of direct current at 1500 volts for use in France and at 3000 volts on the lines in North Africa. In the more remote colonies where local conditions are entirely different, a decision has not yet been reached between using direct current at 3000 volts and single phase at 11,000 22,000 volts.

The general characteristics of the French Railroads involve the handling of heavy currents, which necessitates the use of thoroughly reliable rail joints of low electrical resistance.

*First Type.* (Fig. 2) This rail bond consists of two copper cables of 180 sq. mm. (0.28 sq. in.) section and about 0.8 to 1

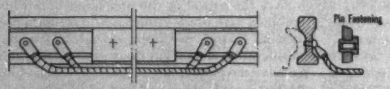


Fig. 2—Terminal Connection by Means of Pins

meter (2.61 to 3.38 ft.) long, depending upon the type of rail. At each end of the cable is welded a copper terminal in the form of a cylindrical plug. The plug and its shoulder are drilled with a cylindrical hole. After the plug has been placed in a hole drilled in the web of the rail, a cylindrical steel pin tapered at one end with a maximum diameter of 18.5 mm. (0.73 in.) and a length equal to the thickness of the web of the rail, is forced into it.

The electrical resistance of the rail bond by itself (that is, with the splice bolts not tightened) is equivalent to that of a standard rail 3½ meters (11.5 ft.) long weighing 46 kg. per meter (92.7 lb. per yard). The electric resistance of the bond as installed (that is, with the splice bar bolts tightened) is equivalent to that of 1.85 meters (6.0 ft.) of standard rail.

The terminal is useless on the average after three re-installations; that is to say, this type of rail bond has a life covering three changes of rail.

The installation of this bond is simple, as it does not require skilled labor or cumbersome tools. It can be installed quickly and does not interfere with operation. On the other hand, the hole drilled in the web of the rail must be absolutely cylindrical, which is not easy.

After a time the steel pin corrodes, producing a reduction of pressure between the rail and the bond terminal. The passage of trains produces variations in compression on the rail; consequently, upon the terminal. The steel of the rail reacts to these variations of compression with more elasticity than does the copper of the terminal, and this may result in loosening. Loosening may be caused by the difference in coefficient of expansion of the two metals—copper and steel—which are in close contact.

These rail bonds are very liable to damage. They are sometimes broken by the track tools or by equipment dragging from trains. Furthermore, as the terminals are fastened at either end of the splice bars, the copper cable has considerable length, and as it lies on the ground, is in danger of being stolen.

This type of rail bond was adopted at first by the Paris-Orleans Railroad and by the State Railroads. In spite of its defects it is still installed on all routes, since tests made with other proposed types have not given better results.

*Second Type.* (Fig. 3) This is composed of a copper cable each end of which is inserted into a split hollow copper cone. A

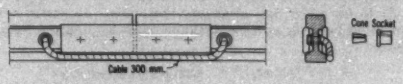


Fig. 3—Railroad Wedge, Cone Connection

hole is drilled on either side of the joint into which is inserted a Pairard compressive socket—a cylindrical socket, which is applied to the outside of the web of the rail. This socket is of copper and is split. The hollow cone is forced into the socket by hammering. Compression of the conductor in the cone is thus produced, as well as compression of the cone in the cylindrical body of the socket and that of the socket in the hole in the rail. In order to increase the compression, the interior and exterior walls of the hollow cone are corrugated.

The precautions necessary in installation are the same as those of the preceding type and the installation is as simple.

From the point of view of the value and permanence of contact, this type presents the same limitations as the preceding type. Since there are more contact surfaces it permits greater opportunities for corrosion. The cone is of copper; the compression of the socket on the rail is thus less than that obtained on the terminal by means of the steel pin. On account of the lighter compression, and also because there are in series six frictional contact resistances, the electrical resistance is greater than that of the preceding type, which presents but four resistances in series, of which two are friction contact resistances and two are welded contacts.

This rail bond, as liable to damage as the preceding type and presenting the same chance for theft, is in addition less desirable from the viewpoint of electric resistance, permanence of contact and durability in service. It is not employed for the original track installation, but has been adopted by the Paris-Orleans Railroad as a means of salvage of cable from rail bonds of the preceding type after the terminal has been destroyed.

*Third Type.* (Fig. 4) This consists of a copper cable 176 sq. mm. (0.27 sq. in.) cross section, each end of which is equipped with a terminal consisting of a simple drilled lug. A hole is drilled in the web of the rail at either end of the splice plate.

In direct attachment of this kind the contact would rapidly become poor on account of corrosion. By inserting an amalgam of tin between the copper of the terminal and the steel of the rail, the contact is greatly improved, for the amalgam penetrates all the interstices and forms a protective covering on the copper and the steel of the parts in contact, thus delaying corrosion. In order to facilitate tightening, steel washers are installed between the web of the rail and the nuts.

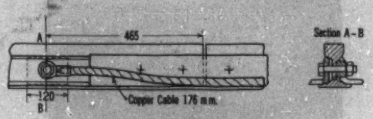


Fig. 4—Bolted Lug Connections With Use of Amalgam (Fayet-Chamonix Line)

The terminals should be of pure copper and not of bronze or brass; otherwise the structure may become spongy under the action of the amalgam. It may be cast, but in that case a good contact should be assured between it and the cable.

The results in service are good. Installation and maintenance requirements do not interfere with traffic. Cumbersome tools and skilled labor are not required. On the other hand, this type presents the same danger of physical damage and the same opportunity for theft as do the preceding types.

This type has been adopted by the Paris-Lyons-Mediterranean Railroad for one of its electrified lines (Fayet-Chamonix).

*Fourth Type.* (Fig. 5) This comprises an ordinary splice bar, to each end of which is electrically welded a group of 34 strips 12 mm. (0.5 in.) wide and ½ mm. (0.02 in.) thick and 12 cm. (4.7 in.) long, arranged horizontally. The other ends of these strips are fastened to a copper terminal drilled in the center. This terminal is fastened to the web of the rail by a bolt; between the terminal and the web of the rail a tin washer is installed to assure a good contact.

The installation and maintenance do not interfere with traffic and the tool equipment is not cumbersome; furthermore, skilled

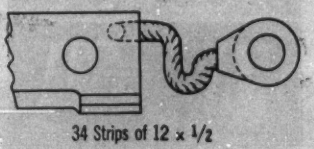


Fig. 5—Electric Connection to the Splice Plate

labor is not required. There is involved the risk of theft as with the preceding types, and a bond may be injured by track workers. The resistance value is on the order of two meters (6.6 ft.) of standard rail.

This type has been adopted by the Paris-Lyons-Mediterranean Railroad for one of its electrified lines (Culoz-Modane).

*Fifth Type.* (Fig. 6) This comprises a cable equipped at each end with a copper or bronze terminal which is welded to the head of the rail. The welding is accomplished by means of an oxy-acetylene flame with bronze welding rod, and while it does not require cumbersome material it does require the employment of skilled labor.

The electrical resistance of the rail bond as installed (with splice bolts tightened) is equivalent to that of 1.5 meters (4.9 ft.) of standard 46 kg/meter (92.7 lb. per yard) rail.

The danger from theft is reduced because the length of cables is only about fifteen cm. (5.9 in.). But this type of bond may be criticized in that it is open to mechanical danger caused by the passage of trains. Furthermore, the high temperature to which it is necessary to bring the rail and the weld may modify the constitution of the rail and impair its mechanical qualities. Finally, it is in the way of removal of the splice bars.

The Paris-Orleans Railroad has had about a hundred in service for about a year on the Paris-Vierzon line, and these have proved satisfactory.

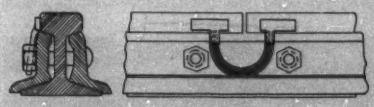

Fig. 6—Welded Connection to Head of Rails

*Sixth Type.* (Fig. 7) The Briois-Bertrand rail bond comprises three strips of copper of the width of the base of the rail, perhaps 132 mm. (5.2 in.), an average length of 530 mm. (20.9 in.), and each strip of a thickness of about 1 mm. (0.04 in.). They are placed under the base of the rail, between the rail and the ties and are pressed against the rail by the tightening of the rail spikes. Between the ties the strips are formed into a bend, which allows expansion due to temperature changes. The copper conductor is made up of several strips in order to give the whole bond more elasticity. If a strip of 3 mm. (0.12 in.) thickness was used, this single strip would break at the bottom of the bend, as has been shown by tests carried on by the Paris-Orleans Railroad Company.

In order to insure that these strips do not slip under the action of motion caused by the passage of trains, each of the two halves fastened between the base of the rail and the tie is drilled with eight holes countersunk at 90 deg., 3 mm. (0.12 in.) in diameter. Into each of three of these holes is riveted a plug 3 mm. (0.12 in.) in diameter. The plugs penetrate the wood of the tie and prevent slipping. Into the five other holes rivets are placed which assure contact among the three strips and prevent the shearing of the plugs.

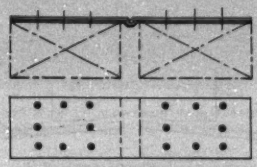

Fig. 7—Connection *B B* (Three Strips)

The tightening of the track spikes is of great importance in the value of the contact. The electric resistance of this type of rail bond, with the splice bolts tight, is equivalent to between one and three meters (3.3 to 9.8 ft.) of standard rail of 46 kg. per meter (92.7 lb. per yard).

The surface of the rail making contact with the copper strip should be as clean as possible and free from dampness. The bottom of the rail should be cleaned with a file.

This type offers great simplicity of installation; it is not necessary to employ special tools or skilled labor. The manufacture is easy and risks of theft are eliminated. But on the other hand,

it necessitates loosening the tie spikes, which may be a serious disadvantage where installation is made on a line on which dense traffic is maintained. The electric resistance depends largely on the degree of tightness of the track spikes.

Before a decision can be reached as to its merits, it will be necessary to know the results which the rail bond is to give in service. The Orleans Railroad Company installed 1000 on the Paris-Vierzon line some months ago.

*Seventh Type.* (Fig. 8) The Coullié rail bond differs essentially from those described above in that it contains no part of copper. It is a short mechanical splice bar with two bolts having a special shape, shown in Figure 8. Once installed the bar is in

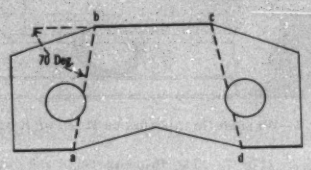


Fig. 8

contact with the head and flange of the rail along its upper and lower edges, indicated by the heavy lines. On account of the shape of the splice plate, complete tightening of the joint would make the rails (freed from all attachments) take the position indicated in Figure 9. On a track equipped in service, this lifting is very slight—1 or 2 mm. (0.039 to 0.079 in.) above horizontal;—the ends of the rails thus elastically deformed tend to assure their normal horizontal positions. The result is a free and permanent contact between the parts shown at *A*, *B*, *C* and *D* (Fig. 9). At each passage of a locomotive or car the angle *X O Y* opens a little and then assumes the initial position. The joint is elastic; the ends of the rails are lowered together the same distance under the effect of the load without producing the slightest space between the plate and the rails. The shocks which are produced when a wheel passes over the joint are no longer experienced. The passage is indicated only by the inevitable noise which results from the gap between the rails.

Finally this rail bond offers an excellent electric conductivity on account of the permanence of its contact with the rails. This is attained without the use of special contact devices which are

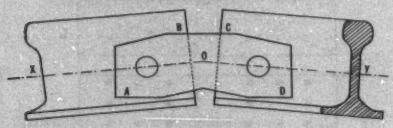


Fig. 9

always costly to install and maintain. On account of its design it produces a very good contact when there is nothing passing on the track, and when equipment is passing, this contact is improved by the pressure on the rail. The electric conductivity is preserved, thanks to the cleaning which is produced at *A*, *B*, *C* and *D* at each passage of a wheel on account of the automatic opening and closing of angle *X O Y* already seen in Fig. 9. When a rail joint is dismantled the surfaces in contact are bright. The resistance of the rail bond when there is no load on the rail is equivalent to 2.5 to 3 meters (8.2 to 9.8 ft.) of standard rail.

The bolts used with the rail bond should be provided with locks so the nuts cannot come off. To accomplish this the Midi Railway Company has successfully utilized the Montupet locknut shown in Fig. 10.

This type of joint possesses numerous points of superiority as compared to others.

Its position is the most simple and consequently the most economical that can exist. There is no necessity of heavy and cumbersome installation equipment, neither does it require the employment of skilled labor.

It does not interfere with traffic.

Fig. 10

It is not exposed to damage by tools of track workers and there is no danger from theft.

The contact preserves its value in a permanent manner, and is not impaired by work on the track or by atmospheric conditions.

Its price is less than that of an ordinary mechanical rail joint, for it is much shorter and requires fewer bolts.

For these reasons, after the results obtained at the end of a year of test the Midi Railroad decided to equip all its road—electrified or not—with the Coullié rail joint. On electrified lines the old rail bonds have been progressively removed. The Coullié rail bonds have been installed on more than 500 km. (310.69 miles) of track and by reason first of the low cost of this joint and the low expense of installation, and second of the possibility of salvage of copper from old rail bonds, it happens that the operation of substitution of the Coullié rail bonds for old ones is an economy rather than an expense. By its superiority, electric as well as mechanical, this rail bond is now the standard for electrified and non-electrified tracks on the Midi Railroad. It is possible that this new rail bond, which produces the best results, will be used in the future on other systems. The Compagnie du Chemins de fer Economiques de la Gironde has already undertaken preliminary tests and the results have been so satisfactory that it has adopted the joint for its lines and several thousands of Coullié joints have already been installed on its system.

Fig. 11—View Taken of the Midi Railroad System

In conclusion it may be said that on a section of line of 20 km. (12.4 miles) equipped with this type of rail bond, the Midi Rail-

way Company has experimented by removing copper connections installed between rails for electric signaling, and their experience has proved that electric signaling functions better on lines equipped with the Coullié rail bond without special connections than upon lines not equipped with Coullié rail bonds and with special connections. This produces a new economy and an appreciable simplification.

The Coullié rail bond is the only type which has given practical results sufficiently well enough to definitely determine its adop-

Fig. 12

tion. The other types of rail bonds comprise either material under test or material which was adopted at the time of electrification, only because the most satisfactory material was not then available.

**I. W. Wechmann:** Bonds in the rail return circuits are used only on the 800-volt d-c. lines in the Berlin suburban service. On the trunk lines, electrified with 15,000-volt, $16^2/_3$ cycle current, bonds have hitherto been found unnecessary either to reduce voltage drop or to mitigate interference with communications circuits.

The continuous connection of the ends of the rails is accomplished in several ways, as follows:

(a) Zinc spraying the surface of the splice bar and its seat on the rail.
(b) Zinc spraying the splice bar and "roll zincing" the seat.
(c) Welded bonds.
(d) Bonds with driven terminals.
(e) Bonds with conical screw terminals.

Fig. 13—Welded Bond Cross-Section. 95 Sq. Mm. (0.14 Sq. In.)

(a) The Meurer process zinc sprayed joint was adopted on all lines which were subject to rail renewals before the Berlin electrification, and also on such lines as were already electrified whenever there was rail renewal. The zinc sprayed joint, which has good conductivity with careful maintenance, originally was to have become the standard for electrified sections. Standardization has, however, been delayed because the conductivity has decreased considerably after a comparatively short time. The majority of the joints show only slight traces of the zinc after two to two and a half years' service and have a conductivity equivalent to 33 ft. or more of rail. (A new joint has the equivalent of about 6 to 10 ft.). Zinc sprayed joints will thus be used only when individual rails are replaced in sections where those joints are in use.

(b) With the rolled zinc joint the angle bar is sprayed with zinc, while the rail seat is given a coating of zinc-tin alloy after a cleaning and roughening of the surface by means of a milling rack. This coating is rolled on to the cleaned surfaces of the rail seat by a roll on a flexible shaft driven by a motor. The rolled zinc joint has been used only in an experimental way on a short section which has been in service for but a brief time. It had initially a satisfactory conductivity which fell sharply, however,

Fig. 14—Welded Bond. (U Bond) Cross-Section 95 Sq. Mm. (0.14 Sq. In.)

Fig. 15—Welded Bond (Embru) Cross-Section 95 Sq. Mm. (0.14 Sq. In.)

Fig. 16—Bond With Driven Terminals Outside the Angle Bar Cross-Section 95 Sq. Mm. (0.14 Sq. In.)

after a short time because the zinc-tin coating worked off the rail.

(c) Welded bonds so far have been used in three forms. Fig. 13 shows the oldest development, which has been given up because the U-shaped copper strand, which was welded into the iron rail head welding terminal, broke at the point of welding.

The bond pictured in Fig. 14 does not have this disadvantage. In this case iron sleeves are pressed in terminals which are welded to the rail head. This type of bond was used only in small numbers because its conductivity was somewhat less than the "Embru" bond shown in Fig. 15. In addition, it has a disadvantage in the fact that it can be installed only once and when replacement is necessary has value only as scrap. A further point against general installation of this type with addition of the pressed iron sleeve is that in a short time the inside rusts and thus

the life of the bond is shortened. Experience has shown that this modification was an error.

The "Embru" bond (Fig. 15) can be used several times if it is carefully handled during replacement. The iron terminal which is welded to the rail head is galvanized internally and in addition is welded at the end with the copper strand. Its conductivity is good, equivalent to three or four feet of rail.

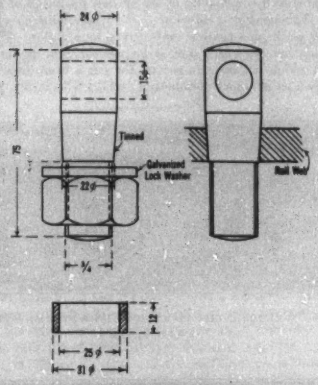


Fig. 17—Railbond

Welded bonds were used, with the few exceptions noted, for all electric traction rails and rails used for a negative return which were not relaid with zinc covered rail ends before the beginning of the electrification.

The greatest objection with the welded bonds is the difficulty of welding replacement bonds. This work can be done only at night and if only a few are to be replaced the costs are high. For this reason no welded bonds will be installed with future rail renewals.

(d) The future standard can be seen in the bond with driven terminals shown in Fig. 16. It can be installed without difficulty in the daytime. Furthermore, it can be used at least twice with the exercise of care. This type only will be used in equipping urban railways, because it seems to be suited to such conditions. It will also be used at switches on the sections which are equipped with welded bonds, because easy replacement of bonds facilitates the renewal of switch parts.

(e) The bond with the conical screw terminal has a conical galvanized iron terminal instead of a driven copper terminal. This type can be changed often and has been used with success as replacement for driven terminal bonds where individual rails or switch parts are replaced as frequently as three months.

The preceding discussion relates exclusively to longitudinal bonds. For cross bonding the type with driven terminals described under (d) is used.

**Guiseppe Tronconi:** These bonds (Fig. 18) are standardized on every system of electrification in use in Italy.

**H. F. Brown:** Mr. Febrey in his discussion presents the manufacturers' point of view and some of their problems, which are always of great interest and value to those who are responsible for the application, operation and maintenance of rail bonds as well as any other product. His remarks relative to the necessity for simplification of bond design and elimination of some of the many processes now used for applying welded bonds, are very timely, for a great deal of study is being given at the present time to these very points by various committees of the American Electric Railway Association and the American Railway Association, with every indication that some of these desiderata will be attained in the near future. Simplification and standardization cannot fail to produce not only a better article, but a cheaper one as well.

The data contributed by Messrs. Müller, Ofverholm, Parodi, Wechmann and Tronconi are of extreme interest and importance, in that a very complete resumé of European practise is given. It

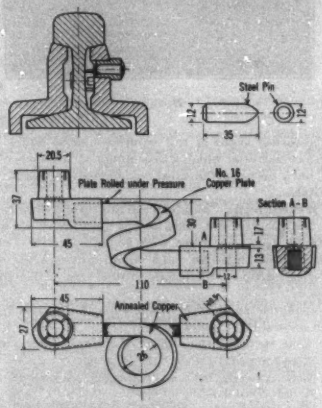


Fig. 18

is interesting to note that in general this is similar to our American practise, with the exception of the use on the French Railways of the Coullié Joint (sometimes called the "chevron joint"). So far as I know, this has not been tried to any extent in this country. It would be of interest to know just how long such a rail joint would last without excessive maintenance under the heavier axle loadings and on the larger rails in general use in America.

# An Electron Tube Telemetering System
## (Part I)

BY A. S. FITZGERALD[1]

Member, A. I. E. E.

***Synopsis.***—*The paper describes a varying frequency telemetering system which employs an electron tube beat frequency oscillator, the frequency of which is controlled by a small condenser mounted upon the movement of the instrument, the reading of which is to be transmitted. The reading is reproduced at the receiving end by a frequency meter having a scale corresponding to that of the transmitting meter. The outstanding feature of this system, when furnishing a single indication, is that, except for the movements of the transmitting and receiving instruments themselves, there are no contacts or moving parts. The system does not require instruments of unusual type, and it is not limited to the transmission, only, of electrical readings, but may readily be applied to any deflection instrument indicating, for instance, pressure, temperature, etc. The accuracy of the system is not affected by changes in the impedance of the channel of transmission. The system is equally suitable for transmission over wire conductors or by means of carrier current or radio.*

*A method of furnishing a number of telemetering indications over a single conducting circuit or carrier-current channel, is also described, which uses automatic telephone type selectors at transmitting and receiving stations. A feature of this system is that no synchronizing channel or synchronous power is required. By a system of impulses, the selectors automatically establish and maintain synchronism.*

*A field installation which has given satisfactory results is described.*

### Introduction

*General.* Recent developments in power system operating methods, especially in the direction of remote and automatic control of apparatus in distant stations, make it increasingly necessary that the load dispatcher be fully informed as to the load conditions at remote parts of his system. This paper describes an attempt to furnish a method of telemetering of more general scope than existing schemes and which it is hoped may prove especially suitable for application on large interconnected systems.

The basic problem is to make available, at the required location, one or more instrument readings relating to the power conditions at some remote point. An elementary step in this direction is to extend secondary connections from a current transformer at one place to an ammeter at another. The limitations of this principle are obvious. What we have to do in order to realize a successful telemetering system, suitable for general application, is not to transmit the power to be indicated and to measure it at some remote location, but to measure the electrical conditions where they occur, to convert this measurement into some electrical effect, transmit this as far as may be necessary, and then to translate this effect back into a visual or a graphic reproduction of the original indication.

This effect, which is to serve as the vehicle which carries the telemetering indication, must be determined with special reference to the channel over which it is to be transmitted. Many of the existing systems of telemetering require a special wire line. Some of these are influenced, in respect of their accuracy, and thus limited in scope, by the resistance, impedance or insulating properties of the connecting circuit. In the present system it has been felt desirable to avoid a vehicle involving any definitely quantitative electrical effect, but rather to employ one which will, as far as possible, be independent of the nature of the channel over which it is transmitted and of the conditions of the channel.

If we will ask ourselves the question as to what electrical effect can best be transmitted over an unlimited distance, over a channel of undetermined and possibly variable impedance, taking into account leakage or attenuation and possible inductive interference, *without loss of identity*, we shall clearly perceive the fundamental requirements of a telemetering system. If we further consider what kind of effect can readily be controlled by an instrument deflection and can as easily be translated back into a scale reading, it will become evident that a frequency system offers the best promise of furnishing the characteristics required.

A frequency can as readily be transmitted by a conducting circuit, by radio, or by carrier current; even by a light or sound channel if necessary. And, provided that transmission be actually accomplished, the frequency received can hardly be other than that which is sent out, even though a high order of extraneous variations in transmission efficiency, or of interference, be present.

We will therefore employ a frequency as the vehicle by means of which the instrument reading is conveyed from one place to another. When the load—or whatever it is that is to be metered—is small, a low frequency will be transmitted. As it increases, a frequency proportionately greater will be sent out. By directly measuring the frequency which is received, the magnitude of the distant instrument reading can be ascertained.

How such a frequency may be generated and controlled, and what order of frequency will be suitable, will now be considered.

1. Engg. Dept., R. C. A. Victor Corp., Camden, N. J. Formerly with the Radio Engg. Dept., General Electric Co., Schenectady, N. Y.

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30-82

## Principle of Operation

Most of the existing systems of telemetering require more or less cumbersome additional apparatus for the purpose of translating the instrument reading into the electrical effect which is to be transmitted. In general, some such device as a motor-operated follower movement which will reproduce the position of the instrument pointer is usually necessary. It will be an advantage if such methods can be avoided. A means of converting an instrument reading directly into a corresponding frequency without the necessity for additional mechanical moving parts will be distinctly preferable.

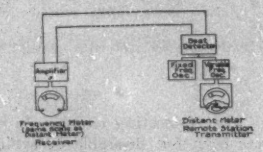


Fig. 1—Transmission Over Wire Conductor

The electron tube oscillator immediately suggests itself as a method of frequency control. It has been proposed by St. Clair, and others, that a condenser be attached to the instrument which it is desired to telemeter and that this be connected in the circuit of an oscillator in such a way as to influence the frequency at which it will oscillate. One of the special features of such a method is that it is not restricted to the telemetering of electrical quantities, as are some systems. It is controlled simply by mechanical or angular displacement and may thus readily be employed in connection with any measuring or indicating device furnishing a deflection.

The range of frequency which may be used depends both upon the permissible dimensions of the control condenser and upon the characteristics of transmission of a-c. energy over the channel to be employed. If we furnish a measuring instrument, such as a voltmeter, wattmeter, etc., of conventional type and of robust construction, it will be found that a condenser of the order of 0.0005 microfarads can readily be mounted on the movement of such a meter without interfering in any way with its accuracy or operation. Such a condenser is capable of controlling frequencies of the order associated with carrier current or radio circuits. A condenser suitable for controlling very much lower frequencies would be too bulky to attach to any ordinary meter.

The use of a high frequency, varying according to the meter position, as the vehicle for transmitting the instrument reading, would be attended by difficulties both in transmission and in furnishing a direct indication at the receiving station. With frequencies of this order, transmission would be very largely affected by the change in frequency resulting from the meter movement. For transmission over wire conductors, the attenuation would be considerable. Transmission of carrier can be readily obtained over high-voltage power lines, at one definite frequency, by properly tuning the coupling circuits and by selecting a frequency which conforms to the constants of the transmission line. But since this involves a number of adjustments, all depending upon frequency, it would be very difficult indeed to transmit carrier having a widely varying frequency. The result would be that wide variations in signal strength would occur with changes in the instrument reading. Furthermore, no simple instrument which will give a direct indication of a high frequency, is available.

Thus it is necessary to employ a frequency which can readily be transmitted over a metallic conducting circuit without either serious attenuation or marked effects due to resonance, and for which a direct reading frequency meter can easily be furnished. This therefore suggests a frequency of the order of hundreds, rather than thousands. Such a frequency may be transmitted readily by a simple wire circuit.

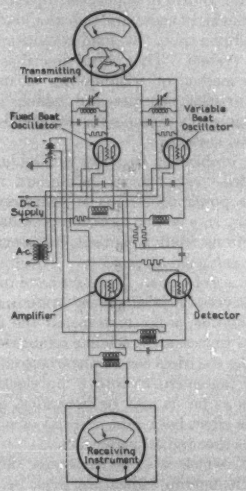


Fig. 2—Diagram of Connections

If it should be desired to transmit the telemetering frequency over a high-voltage power line, by means of carrier current, this can be done by exactly the same methods as are employed for carrier-current telephony. The carrier wave is modulated with the telemetering frequency instead of by speech frequencies. In this way the telemetering frequency is not directly associated with any problems in connection with the transmission of the signals over the power network. That is,

it does not in any way restrict or interfere with the selection of the carrier frequency, which must largely be governed by line constants and characteristics, in accordance with which the carrier circuit must be adjusted and tuned.

### Telemetering Single Instrument Reading over Conducting Circuit

Fig. 1 shows the general arrangement which is employed. A small condenser is attached to the movement of the instrument of which the reading is to be telemetered. This condenser is connected to an oscillator so that the frequency of the latter varies according to the meter position. The frequency of the oscillator will be high—comparable with a carrier frequency—and the change in frequency corresponding to full scale deflection will be less than ten per cent. The force due to the electrostatic attraction between the

Fig. 3—Transmitting Instrument

condenser electrodes is, in comparison with the meter torque, negligible.

A second oscillator, operating at a frequency close to that of the first oscillator, has a fixed condenser, and therefore furnishes a constant frequency. A beat frequency is set up by these two oscillators and this is detected by means of a third vacuum tube. This beat frequency will be relatively low, and it will vary, in accordance with the instrument deflection, over a suitably extended range which may amount to a hundred per cent or more.

The beat, or telemetering frequency, is transmitted, over the connecting line, to the receiving station, where it operates a direct reading frequency meter. The frequency meter may be directly energized by the incoming signal or an amplifier may be provided. This will depend upon the nature of the line, its impedance, and on the energy level which it is permissible for it to carry.

The frequency meter will be furnished with a scale corresponding exactly with that of the distant instrument. It will indicate at all times exactly the position of the remote instrument and will follow all such changes and fluctuations as the damping of the transmitting instrument permits the latter to follow. The receiving instrument has the usual characteristics of such meters, that is, its indication depends upon frequency

Fig. 4—Receiving Instrument

only and, provided it receives more than the minimum power necessary to operate it, is not affected by changes in signal strength. Thus, any changes in the impedance or leakage resistance of the line do not affect the accuracy. Moreover, inductive interference is more likely to affect the signal strength than it is to produce any effects tending to change the frequency.

Fig. 2 is a complete diagram of the connections at both transmitting and receiving stations. Fig. 3 is a typical transmitting instrument and Fig. 4 one of the receiving frequency meters.

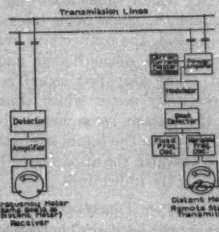


Fig. 5—Transmission by Means of Carrier Current

### Carrier-Current Transmission

If it is desired to transmit the instrument readings by carrier, either over special conductors, telephone lines, or high-voltage power lines, this is done by employing transmitting and receiving apparatus very similar to telephone communication equipment which is already familiar in central station engineering.

Fig. 5 shows a schematic diagram of the general arrangement for carrier-current telemetering. The

complete connections at the transmitter are shown in Fig. 6. The beat frequency is applied in the regular way, to the modulator, instead of a microphone speaking circuit. The carrier-current generator consists of the usual arrangement of master oscillator and power amplifier. There is thus sent out over the line a carrier wave of steady carrier frequency which is modulated by

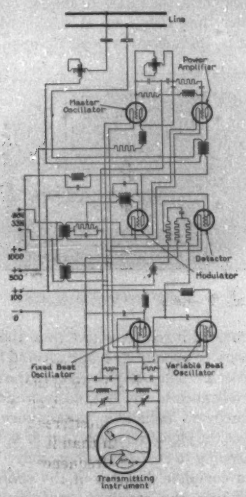


FIG. 6—DIAGRAM OF CONNECTIONS OF CARRIER-CURRENT TRANSMITTER

an audio frequency which varies according to the position of the instrument which is being telemetered.

At the receiving end, the connections are as given in Fig. 7. The carrier is demodulated and the audio signal amplified. The amplified signal is then taken direct to the frequency meter which thus reproduces the position of the distant instrument. It will be especially noted that again the signal strength—provided it be sufficient to energize the apparatus—has no effect upon the accuracy of the indication.

## MULTIPLE TELEMETERING

In many cases it will be desirable to telemeter more than one instrument reading from a remote station. There is a number of different arrangements which may be provided, depending upon the circumstances and requirements.

Two or three indications, for instance, may be sent over the same channel simultaneously by assigning to each instrument a different range of frequency. At the receiving station, these frequencies may be unscrambled by means of band pass filters. Thus, one instrument may work from 300 to 600 cycles, another from 800 to 1600, and a third from 2000 to 4000.

However, one cannot very conveniently read more than one instrument at a time and in the majority of cases it is not essential that this be done. Thus, in general, it is entirely satisfactory if the different readings be furnished selectively one after the other. In this way a larger number of instruments may be telemetered than could be done simultaneously.

A telemetering system is a convenient and desirable adjunct to any system of supervisory or remote control. Almost, one might say, a necessity, if the full value of the control system is to be realized. One very simple method of telemetering a number of different instruments over a single telemetering channel, is to make use of the supervisory apparatus in such a way that the operator can, at will, cause any distant instrument to be connected to the telemetering transmitter so that it assumes control of the indicating frequency. At the same time, a suitably scaled instrument will be connected to the telemetering receiver.

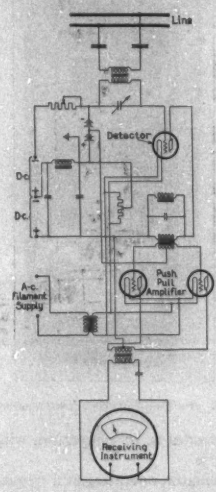


FIG. 7—DIAGRAM OF CONNECTIONS OF CARRIER-CURRENT RECEIVER

Another alternative is to employ a dial telephone installation in a similar way so that the operator, in order to obtain the reading of any remote instrument, will dial a specified number which will cause this instrument to be connected to the telemetering equipment.

For load dispatching and other important services where it is desirable for the operator to be able to see, at a glance, the state of the system in general, an arrangement has been devised by means of which, over a single telemetering channel employing one transmitting equipment and one receiver, a number of instruments at one

station may be continuously indicated in the load dispatchers office. This may be carried out with equal convenience either over a wire line or by means of carrier equipment over the power conductors.

According to this system, there is provided at the remote station, a continuously operating selector which automatically connects each instrument, one after the other, to the telemetering transmitter for a brief period. Twenty or more instruments may be taken care of in this way.

At the receiving station, there will be installed an equal number of instruments. These will all be frequency meters identical in construction but each will bear a scale representing the corresponding instrument

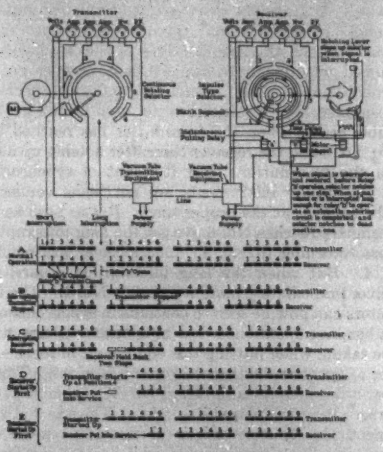


FIG. 8—METHOD OF SYNCHRONIZING MULTIPLE TELEMETERING SYSTEM

at the remote station. A second selector associated with the receiver is arranged to connect each receiving instrument to the telemetering receiver during exactly the correct period at which the corresponding remote meter is connected, by the transmitter selector, to the telemetering apparatus, and has control of the indicating frequency. Thus, each pair of instruments, one transmitting and one receiving, is given possession of the telemetering channel once in each complete cycle, which embraces all of the instruments. The receiving instruments which are employed with this system of telemetering have movements of the type which retain their position when deenergized. Thus, when they are operated in this manner, we get the following result. Each instrument indicates at all times the reading shown when it was last connected to the telemetering circuit. At regular intervals, each meter is corrected. Thus, if we assume that each instrument is energized for a second, which is sufficient for it to assume, and come to rest at, its corrected reading, each reading will be checked about every ten seconds if there are ten instruments. With other numbers of meters, the frequency of correction will vary accordingly.

The result will be that all the instruments, all the time, will show the state of the power system, at most, ten seconds previously. Thus a survey of the whole set of meters will furnish, very nearly indeed, as good an idea of the operation of the distant station as if one could see the remote instruments in actuality.

Clearly it is necessary to synchronize the selector at the receiving station with that at the transmitter. A feature of this scheme which is of special interest is the fact that, unlike many existing methods of synchronizing, it does not require a special channel for this purpose. No extra conductors, or additional carrier-current circuit are necessary. Nor is it necessary to perform any special operation when the apparatus is placed in service in order to synchronize the two selectors. Thus, it is no more difficult to operate multiple instrument telemetering over carrier or radio than over a wire line.

How this has been accomplished is shown in Fig. 8. This diagram has been prepared primarily in order to present an explanation of the principle on which the synchronizing system operates. Thus it does not purport to represent the type of apparatus employed nor the actual connections. In order to simplify the diagram, only six instruments are drawn, but it is to be understood that exactly the same principle of operation may be carried out with any greater number of meters.

At the transmitting station, the selector, continuously operated by any suitable means, connects the instruments one after the other to the telemetering transmitter. The energy sent out by the latter, either in the form of ordinary alternating current or carrier current, as may be employed, is interrupted for a brief period each time the selector steps from one segment to the next.

At the receiver, the selector has a similar number of segments. But instead of being continuously rotated, it is actuated by a step-by-step mechanism. Each time the telemetering energy is interrupted and instantly restored, operating the pulsing relay *a*, the selector notches up one step, thus transferring the received energy from one meter to the next in synchronism with the transmitter selector.

This is evidently entirely satisfactory if both the selectors are started up properly in step and if nothing happens which may interfere with this regular step-by-step operation. But it is well known that any simple notching scheme, without any additional synchronizing feature, is not suitable for continuously maintaining two different pieces of apparatus in step. In the event that the step-by-step mechanism should slip a notch, or should pick up additional impulses due to external inter-

ference, cumulative errors, which are inadmissible, are liable to occur. The present system has been devised with a view to providing, without any additional synchronizing channel, a method of preventing such effects from producing any cumulative discrepancies. This is accomplished as follows.

After the last instrument in the group has been telemetered, the transmitter selector returns to the first segment. But before it does so, the transmission is interrupted for a period somewhat longer than the normal break when transferring from one instrument to the next. The receiver selector is furnished with an additional time delay releasing relay *b*. This does not have time to re-set during the regular interruptions which occur when the transmitter selector moves from segment to segment. But during the long break which occurs immediately following No. 6, relay *b* operates. This completes what is called the "motoring circuit" through the motor magnet, which notches up the selector, and the inner range of segments on the selector which are furnished for this purpose. All of the segments are connected together except No. 1. This causes the selector to "motor," that is, it is continuously notched round until it reaches the blank segment No. 1, on which it stops. Thus, when the telemetering signal ceases entirely, or is interrupted long enough for relay *b* to re-set, no matter upon which segment the receiving selector may be, it is instantly returned to the first segment and meter No. 1 is connected to the receiver. It will normally be at rest in this position, therefore, when the apparatus is not in service.

The transmitter, it has been noted, always gives a long interruption immediately before moving on to segment No. 1. The receiver is automatically returned to the same position by the long interruption. Therefore, immediately following this interruption, both selectors are in synchronism and meters No. 1, both transmitting and receiving, have possession of the telemetering channel.

In Fig. 8 an attempt has been made to indicate graphically the operation of the selectors. The interrupted lines indicate when the telemetering energy is, respectively, being sent out by the transmitter and is energizing the receiver. The numbers indicate the segments which are occupied by the selectors and show when the two are in synchronism.

*A* shows entirely normal operation, the transmitter is on segment No. 1 and the receiver also is connected to the first instrument. After the first meter reading has been telemetered and the instrument at the receiving station has been energized for about a second, long enough for it to come to rest in its corrected position, the transmitter selector moves on to No. 2. In so doing, it instantaneously interrupts the signal which causes the receiver selector to notch up on to No. 2 also and the second instrument reading is telemetered. In the same way, each of the meters at the receiving station is corrected one after the other and finally No. 6 is reached. After this, the long interruption occurs and both selectors return to No. 1.

In order to better indicate the operation of this system of synchronizing, it is assumed in *B* that the transmitter selector is stopped for an instant by some form of interference. It is assumed that it is stopped while the signal is being sent out, and that this continues until the transmitter is allowed to continue its operation. It will be seen that when this occurs, the receiver is not thrown out of synchronism but that it remains on the same segment as the transmitter until this is released, when both continue in the normal manner.

In *C* it is assumed that the receiver suffers some form of interference due to which it ceases properly to notch forward. A transient short circuit on the transmission channel or loss of signal through some other cause might produce this effect. This is shown as having occurred when both transmitter and receiver are on segment No. 1. The interference does not affect the transmitter which continues to step around. The trouble ceases when the transmitter has reached segment No. 3 and the receiver thereafter notches up along with the transmitter. But it is out of synchronism and the proper instruments are not being connected to the receiver at the proper time. But as soon as the transmitter reaches No. 6, we get the long interruption before returning to No. 1. The receiver has reached No. 4. But when the long interruption occurs, the receiver immediately motors round to No. 1. The two selectors can now be seen to continue in synchronism.

It has been mentioned that no special measures have to be taken, when putting this equipment in service, in order to synchronize transmitter and receiver. This is done automatically as shown in *D*. It is assumed that the receiver is first placed in service. The selector is on segment No. 1, on which it always stops when de-energized. Since there is no incoming signal, it remains in this position. The transmitter is now started up. It may have stopped on any segment last time it was used. It is shown as having stopped at No. 4. As soon as it commences successively to connect the different instruments to the telemetering transmitter, the receiver starts to notch up, but out of step because it started from No. 1. It continues out of synchronism until the transmitter reaches No. 6, when the receiver has reached No. 3. The long interruption now occurs and both transmitter and receiver now start in synchronism on No. 1.

*E* shows what happens if the transmitter be started up first. The receiver is switched into service just at the instant when the transmitter happens to be on No. 5. As soon as the latter reaches No. 6, and returns to No. 1, the receiver falls automatically into step in the manner which has been described.

Thus we have an arrangement in which the receiver and the transmitter may independently be started up (it does not matter which is first placed in service) without paying any attention to the question of syn-

chronism. Within a few seconds the receiver will automatically fall into step with the transmitter. In the same way, if, while the telemetering apparatus is in service, the receiver may be thrown out of synchronism by line disturbances or interference, as soon as normal transmission is resumed, without any attention from the operator, synchronism is automatically restored.

Fig. 9—Installation at Amsterdam

## Description of Apparatus

In order to study the operation of this system under service conditions, an installation has been made in the neighborhood of Schenectady. Instrument readings in a railway substation at Amsterdam, N. Y., and at another substation at Glenville are transmitted by means of carrier current to a receiving station on the outskirts of Schenectady.

Fig. 10—Installation at Glenville

For this installation, two transmitters and two sets of receiving equipment were specially built. No attempt was made to arrive at a finished design. The necessary circuits and apparatus were merely assembled in a convenient form for carrying out an extended field test.

## Transmitting Equipment

Fig. 9 shows a view of the apparatus installed at Amsterdam. A view of the Glenville installation is shown in Fig. 10. Fig. 11 shows a closer view of one of the transmitters, both of which are substantially similar except for the instruments and certain details in connection with the power supply.

While the apparatus furnished is able to take care of as many as 20 instruments, it was felt that for the purpose of these tests, it would be sufficient to install three only. The carrier-current transmitter incorporated in this equipment is sufficiently powerful to send the telemetering signal a distance upward of 100 miles if necessary. For the purpose of this test, it was convenient, however, to transmit a shorter distance so that both ends of the line might readily be accessible. Amsterdam is about 20 miles from Schenectady.

The three instruments, one after another, are successively connected to the carrier-current transmitter by

Fig. 11—Carrier-Current Telemetering System

means of the special selector. This is illustrated in Fig. 12. While the general principle of operation by means of which the successive transmission of the different instrument readings is performed, is substantially that described with reference to Fig. 8, it is found convenient in practise to employ at the transmitting end a selector mechanism somewhat similar to that shown, in Fig. 8, at the receiving station. That is to say, this selector is not, in fact, continuously operated by means of a rotating drive, but is notched up successively by means of an automatic vacuum tube timing circuit. It connects the telemetering circuit to each instrument in turn for a definite period, after which it is instantly transferred to the next instrument. When the last instrument has been telemetered, it introduces a time delay exactly as described with regard to Fig. 8. The first indication is then repeated, this cycle of opera-

tion being continued indefinitely. This time delay is controlled by a vacuum tube, condenser, and high-resistance circuit of the type in which the duration of the time delay depends upon the time taken for the condenser, which is connected to the grid, to discharge through this high resistance.

Since one of the most important characteristics of this equipment, which it has been particularly important to study, is the constancy of the relation between the beat frequency of the oscillators and the position of the instrument condenser, there was introduced into this equipment a convenient method of keeping a check upon this feature throughout the test. While only three instruments are to be seen upon the panel, there are transmitted four successive indications. Three of these are the instruments shown, the fourth one is simply a fixed capacity. The fourth indication, therefore, should invariably be the same frequency.

Fig. 12—Transmitting Selector

## Receiving Equipment

The receiving equipment is illustrated in Fig. 13. This consists of two identical carrier current telemetering receivers, one of which, that shown on the left, receives the carrier-current transmission from Amsterdam. The right hand receiver is tuned to the carrier-current transmitter at Glenville. The power supply for the two receivers is controlled by switches mounted upon the left hand panel. Reading from left to right, the instrument indications are as follows:

| Left Hand Panel Amsterdam | Right Hand Panel Glenville |
|---|---|
| A-c. feeder current | D-c. trolley volts |
| A-c. feeder volts | D-c. current west track |
| A-c. feeder kilowatts | D-c. current east track |

Below each of these sets of three instruments may be seen a fourth instrument. This is not provided with any scale but is marked at one position only. This corresponds to the frequency sent out by the fixed condenser mounted in the transmitter. Thus, it has been possible to study very easily the constancy of the vacuum tube beat frequency circuit. So long as this instrument remains at the marked position, this forms a definite indication that the readings of the other instruments are exactly correct.

It also gives a definite indication that the receivers are in synchronism with the transmitters. Should the receiver get out of synchronism, this instrument will be energized with a frequency corresponding to one of the other instruments which will cause it to move away from the normal position.

Fig. 14 shows a picture of the selector at the receiving station. This selector works exactly in accordance with the one described with respect to Fig. 8.

## Operating Characteristics

The results obtained with this test installation have clearly shown that this system offers an entirely practical method of telemetering.

Fig. 13—Installation at Receiving Station

The outstanding characteristic which these tests were designed to disclose is the relation between the transmitting instrument deflection and the beat frequency. And especially, the extent to which this relation shall accurately be maintained over long periods of time. The performance of the apparatus in this respect has proved very satisfactory. The fact that both the beat oscillators are operated from the same plate and filament supplies seems largely to be responsible for this result. Thus, variations in these sources tend to produce more or less equivalent changes in both oscillators

and, therefore, affect to a minimum extent the beat frequency. Fig. 15 shows the effect upon the beat frequency of voltage variation of the plate and filament supplies. From these curves it can be seen that this system of telemetering may be operated from power supplies having poor voltage regulation without any serious inaccuracy from this cause being encountered.

Since the instrument used at the receiving station is a frequency meter, the reading of which is unaffected by the carrier current signal strength, it is likewise immune from any variation in amplitude due to the performance of the vacuum tube circuits incorporated in the receiver. Thus it is independent of wide variation in the voltage of the power supply from which the receiver is operated.

This installation has been in service for twenty-four hours daily for several months and has maintained a high degree of accuracy, comparable with the performance required of directly indicating instruments, throughout this period.

### Conclusion

The outstanding features of the electron tube telemetering system may be summarized as follows.

1. Accuracy not affected by resistance or leakage of conductors.
2. No moving parts other than meter movements.

Fig. 14—Receiving Selector

3. Continuous indication given all the time. Follows all fluctuations registered by transmitting instrument.
4. Can readily be transmitted over power lines by means of carrier current or by radio. Accuracy not affected by signal strength.
5. No synchronous power required.
6. It is not limited to the telemetering of electrical quantities but may readily be applied to any deflection instrument as, for instance, steam pressure, water level, temperature, etc.
7. Does not require instruments, either for transmitting or receiving, of unconventional type. No follower mechanisms necessary.
8. It is equally suitable for the telemetering of single or multiple indications.

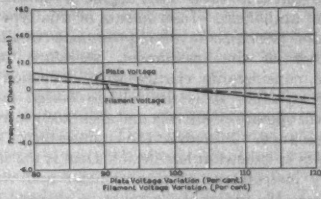


Fig. 15—Beat Oscillator Characteristics

*Multiple System*

a. Large number of indications given over one channel with single equipment.

b. No special synchronizing channel required.

c. Synchronism automatically established and maintained.

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# (Part II)

***Synopsis.***—*Discusses the problems of totalizing, graphic recording, and the telemetering of watthour or integrating meters. A new thyratron circuit is described, which furnishes a direct current directly proportional to the frequency at which the circuit is excited. By means of this circuit, a number of varying frequency telemetering signals may be totalized by adding together the d-c. outputs of the thyratron circuits. The resultant current is then proportional to the sum of the several frequencies.*

*The use of this thyratron circuit in a field installation, furnishing totalized indications, is described.*

*In addition, the problem of transmitting watthour indications is generally discussed. A method of transmitting watthour readings by means of the electron tube varying frequency system is described. Signal frequencies proportional to individual dial readings of the watthour meter, are sent out. The advantages of this method are, that, by sending out individual dial readings, high accuracy is obtained; and when the dial reading of a watthour meter is transmitted, the telemetering channel is not required except when the readings are actually being observed.*

### Introduction

In the first part of this paper the author described the general principles of an electron tube telemetering system of the varying frequency type. The present section will deal with some further developments of this system showing how it is applied to the requirements of totalizing, graphic recording, and the telemetering of watthour or integrating meters.

These special requirements affect principally the means for indicating, at the receiving station, the varying frequency signal which is a function of the position of the transmitting instrument.

In the initial installation, described in Part I, standard frequency meters, having special windings suitable for the range of frequency used, were employed for this

purpose. While they were found to operate quite successfully in this installation, instruments of this type have certain limitations which become more apparent in connection with totalizing and graphic recording.

A minor disadvantage of the usual type of frequency meter is that it involves some degree of difficulty in the design of amplifiers. Instruments of this type usually operate on principles involving resonant circuits. The impedance of the instrument, therefore, tends to undergo considerable change with deflection of the moving system. It is difficult to design amplifiers which will operate effectively and accurately into a varying impedance. Moreover the engineering of such instruments is somewhat less flexible than is the case with ordinary instruments of the ammeter and voltmeter type where the range may readily be changed by suitable shunt and series resistances. It is less easy to alter the operating range of a frequency meter. Thus in a telemetering system there would be a tendency toward a lack of flexibility in respect of the frequency ranges used.

Frequency meters do not as a rule develop a very high torque. An instrument of such volt-ampere consumption as may conveniently be furnished by an amplifier would not be suitable for directly driving the pen of a graphic recorder. The better known types of graphic frequency meter employ some form of motor operated follower mechanism for operating the pen.

Totalizing instruments of the ammeter and wattmeter type are well known. What is required for furnishing totalized indications with a varying frequency telemetering system is an instrument or its equivalent which will give a reading proportional to the sum of a number of different frequencies.

On looking further into this problem, it is found that no immediate means appear to be available for making a frequency meter which will totalize in this manner. The reason for this is that while ammeters and wattmeters are instruments which furnish a torque proportional to the electrical quantity which they are intended to measure, all known types of frequency meters operate on a different principle. No frequency meter is known which furnishes a torque proportional to frequency. Direct reading frequency meters of the pointer, as distinct from reed, type instruments, are what is called "position" instruments rather than "torque" devices. That is to say, they do not generate a torque in opposition to a control spring. Often they have no control spring. These instruments assume a position on the scale at which no force acts upon the moving elements, which position is an indication of the frequency.

Thus the only apparent method of totalizing the readings of such instruments would be some electromechanical scheme by means of which the position or deflection of the pointers might be summated. Or, alternatively, a system involving synchronously rotating rotors and stators. Neither of these methods appears very attractive or likely to lead to a simple and inexpensive equipment.

The totalizing of readings of "torque" type instruments is simple. Readings of current in d-c. circuits can readily be totalized by connecting the several circuits in parallel so that the total current flows through a single ammeter. Readings of instruments such as a-c. wattmeters can be as easily totalized, by mounting a plurality of meter movements on a common shaft so that the resultant torque generated is the sum of the contributing torques. In each case the deflection of the instrument is a measure of the total load. But we cannot do this with "position" type instruments such as frequency meters.

Therefore, the method of attack which suggests itself is to explore the possibility of devising an instrument or circuit by means of which frequency may be measured without the use of a "position" instrument.

Consideration of the fundamental nature of the effects which are measured by the "position" and "torque" types of instrument may be of interest. If there can be discerned any common ground between these effects, it may furnish us with a clue as to how we may set out to solve this problem. The "torque" type instrument gives a deflection proportional to the strength of the current or power which actuates it. The frequency meter indicator on the other hand is, or should be, entirely independent of the magnitude of the alternating current energy with which it is supplied. It seems difficult to reconcile these differences.

Frequency is cycles per second. That is to say, it represents the number of events, one cycle being exactly like every other cycle, which occurs in a given time. The essential feature which makes the term "frequency" significant is that all of the events are exactly similar.

Let us compare this with the action of, for example, a d-c. ammeter. This furnishes a torque proportional to a field strength, which is constant, and the current to be measured. Therefore, the torque is proportional to the current. We commonly regard a current as something which flows continuously. But, we may express a current as being the flow of so many coulombs per second in a circuit. In other words, current is the coulomb frequency. A coulomb is a definite quantity of electricity, or it is so regarded. The d-c. ammeter, then, gives a torque which is proportional to the number of events occurring in a given time, each of them being identical, and being in fact the passage of one unit of charge.

We are beginning to note some aspects of similarity between the two arrangements.

It is seen that with a "torque" type instrument, we can measure the frequency with which definite charges are allowed to pass. It is important that these charges be of uniform magnitude. We could not express current as "coulombs per second" unless all the coulombs were precisely identical. But, if we know the value of

the charge and can read the current which flows as the result of so many charges being released per second, we can determine the frequency with which they are released.

From this reasoning, it is clear that if we could arrange that each cycle of our a-c. frequency could be made to release a finite charge of electricity and if the charges so released can be caused to pass through a direct-current measuring device of the "torque" type, we shall have attained our object. A very brief search through our present resources in the way of tube circuits and devices will uncover an arrangement which will accomplish precisely what is required.

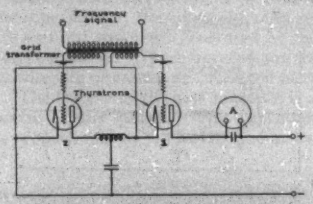


Fig. 1—Principle of Thyratron Frequency Indicating Circuit

## Thyratron Frequency Indicating Circuit

The fundamental principle of this circuit is as follows. During each a-c. cycle, a condenser is first charged through a d-c. current measuring instrument, from a fixed source of d-c. voltage, and then discharged. The current read by this instrument will therefore be the product of the charge carried by the condenser and the number of times per second that this charge passes through the instrument. The charge will be the product of the condenser capacity and the d-c. supply voltage. These being fixed, the instrument will give a reading directly proportional to frequency.

Fig. 1 illustrates this principle. The circuit includes 2 three-electrode gas-filled tubes of the type known as thyratrons. It will be recalled that in this form of tube a negative voltage applied to the grid can prevent the flow of current through the tube. When the grid is made positive with reference to the cathode, current may flow, the magnitude being determined by the anode voltage and by the impedance of the circuit. Once this current has become established, however, the grid has no further controlling action. If the grid potential be again made negative, no change in the current results. If the current be reduced to zero by any other agency, for instance, if the circuit be opened at some other point, or if the circuit has such characteristics that the current which flows through the tube is a transient, and automatically ceases to flow of its own accord, then the grid resumes control and no further current can flow until the grid be again raised to a positive potential. It is this latter condition which obtains in the present circuit.

The two thyratrons are referred to as No. 1 and No. 2, respectively. The condenser is connected so as to be charged through tube No. 1 from the d-c. source. Tube No. 2 is connected across the condenser so as to form a path through which it may be discharged. The measuring instrument is arranged to read the current drawn from the d-c. source. The grids of the tubes are provided with a negative bias.

The a-c. voltage of which it is desired to indicate the frequency is connected to a grid transformer having two secondary windings. These are connected, with opposite polarity, to the grids of tube No. 1 and tube No. 2, that is to say, at any instant when a positive voltage is applied to tube No. 1, the grid of tube No. 2 is made negative, and vice versa.

Let us then assume that, at a given instance in the a-c. voltage wave, the grid of tube No. 1 goes positive. Current flows from the d-c. source into the condenser until it is fully charged up to this voltage. The current then ceases. No current can flow in tube No. 2 because the grid is at a negative potential at this instant. The constants of the circuit, that is, the value of the condenser, the value of the series resistance represented by the instrument, and the tube drop must be so selected that the charging of the condenser is completed within one-half cycle of the a-c. frequency.

Let us follow the cycle of events. Assume that about a quarter of a cycle later, the a-c. voltage passes through zero and the voltage applied to the grid of tube No. 1 as well as that applied to the grid of tube No. 2 is also zero. Current has ceased in tube No. 1. No current has been flowing in tube No. 2. Both of the tubes have a negative bias due to the bias voltage and therefore no current flows in the circuit. A quarter of a cycle later the grid of No. 1 tube will be negative and the grid of No. 2 tube will be positive. No further current, therefore, can establish itself in tube No. 1, but the condenser discharges through tube No. 2. This current ceases when the condenser is completely discharged. A quarter of a cycle later, both secondary windings of the grid transformer will be furnishing zero voltage and both grid bias voltages will apply a negative bias to both tubes. All flow of direct current from the supply ceases

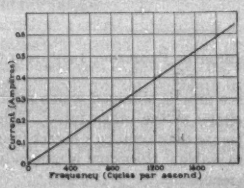


Fig. 2—Operation of Thyratron Frequency Indicating Current

until, as the cycle repeats itself, the grid of No. 1 again goes positive. The curve shown in Fig. 2 shows the linear relation between frequency and current in this circuit.

A feature of this circuit which is of interest is its flexibility in respect of frequency range. With any given instrument the relation between the current which gives full scale deflection and the frequency indicated, depends upon the value of the capacity which is used. Thus the apparatus may be adjusted to operate over any desired frequency range, within wide limits, without any change in the instrument, but merely by varying the capacity of the condenser employed.

While the operation of the form of circuit shown in Fig. 1 is more readily explained, a modification which has been developed by Mr. B. D. Bedford has superior operating characteristics. This is shown in Fig. 3. As in Fig. 1, the current flowing through the ammeter is directly proportional to the frequency applied to the thyratron grids.

The advantage of this arrangement is that the condensers are charged and discharged through a resistance but they are so connected that when one tube is charg-

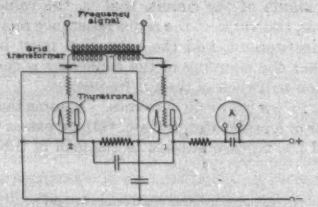


Fig. 3—Improved Frequency Indicating Circuit

ing a resistance drop is obtained which applies a negative plate voltage to the other tube. This makes it possible to operate the circuit to a higher frequency and makes it more stable if the signal is unsteady or is subject to interference.

It has been mentioned that if the instrument reading is to be proportional only to the frequency, the supply voltage from which the thyratrons are operated must be constant. If a source of power having sufficiently close regulation is not available the measuring instrument may be compensated so that reasonable variations in the voltage will cause no error.

Fig. 4 shows such an instrument used with the circuit shown in Fig. 3. It is of the ratio type having two windings, one of which carries the current of the thyratron circuit and the other a compensating current. The reading of the instrument being proportional to the ratio between these two currents no error is introduced if the voltage does not remain exactly constant.

Both indicating instruments and graphic recording meters of this type have been developed by Mr. St. Clair of the General Electric Company. The indicating instrument is shown in Fig. 5 and the graphic meter, which has a directly operated pen, in Fig. 6.

With this thyratron circuit any number of incoming frequencies, each a function of a meter deflection, may readily be added together merely by connecting all three thyratron circuits so that the total current flows through a common meter. Three such signals are shown totalized in this way in Fig. 7, each individual reading being given by three corresponding meters and the total being shown by a fourth instrument.

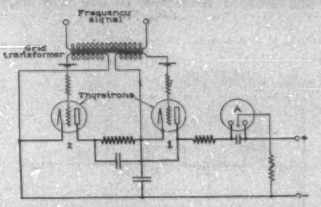


Fig. 4—Compensation for Voltage Variation

While this circuit is especially suitable for totalizing, it also presents advantages over the ordinary frequency meter even when no totalizing reading is required. It has flexibility because the frequency range may be altered without change in the meter. It permits graphic recording. Moreover the amount of power required to drive the thyratron circuit, since only grid excitation is required, is very small. Thus the thyratron circuit to a large extent takes the place of any amplifier that might be used to step up the incoming

Fig. 5—Indicating Instrument

signal, whether wire line or carrier current, to the energy level required to operate a frequency meter. The thyratron circuit requires only a low plate voltage, in comparison with what is necessary when a vacuum tube amplifier is used, and is capable of much larger power output.

## Watthour Indications

There are two principal differences between indicating and integrating instruments which affect the problem of telemetering. First, watthour metering requires a

higher order of accuracy, and, second, the constructional features of the instruments involved are different.

There are several different ways of telemetering integrating meters by means of the electron tube system. It is believed that a brief discussion of the possibilities in this connection, and of the problems involved, may be of interest.

There are two definite methods of handling the telemetering of watthour readings. One way is to transmit a signal proportional to the watts and to integrate this at the receiving end. This method has, up to the present, usually been employed. For instance, in systems operating on the frequency-impulse system impulses are sent out which are generated by the rotation of the watthour meter. These impulses are transmitted either by wire line or carrier and received at the remote station. The frequency of these impulses is a measure of the watts, at any instant. The total number of impulses is proportional to the watthours, and these may

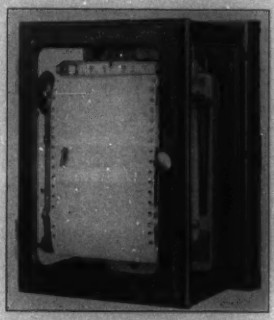

Fig. 6—Graphic Instrument

be integrated by the usual arrangement of gear train and counter, at the receiving station.

A similar system may be used in an electron tube telemetering scheme. If we employ a rotating watthour meter at the transmitting station, we can generate a frequency proportional to the meter rotation by a variety of different means. For example we may make a simple contact device which will generate interruptions of the required frequency or we may use a beam of light and a photo-tube and holes in the meter disk.

If we use as a transmitting instrument an ordinary wattmeter we may use the standard beat oscillator controlled by means of a condenser mounted on the instrument exactly as if we were transmitting kilowatts. Either of these two schemes will emit a frequency proportional to the kilowatts.

At the receiving station, we may do either of the following. We may operate a small synchronous motor from the received frequency and drive therefrom the counter. Or we may employ the circuit shown in Fig. 1, which furnishes a d-c. current proportional to the frequency, and may cause the d-c. current to flow through a standard d-c. type ampere hour meter.

It is important to note that, if we transmit a reading proportional to the kilowatts and integrate this at the receiving station, we must have the exclusive use of the carrier current or other channel by means of which the signal is transmitted. And if this channel be inter-

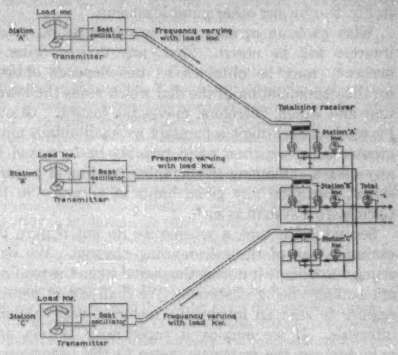


Fig. 7—Totalizing Connections

rupted, due to a system outage or other emergency, the integrated reading will be in error by an amount equal to the energy registered by the meter transmitted during the period of the outage.

Thus for carrier-current applications it may be desirable to transmit, instead of a signal proportional to the kilowatts integrated at the receiving station, a frequency proportional to the kilowatt hours already integrated at the transmitting end.

It has been pointed out that this electron tube telemetering system is essentially a deflection translating

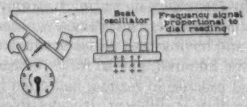


Fig. 8—Principle of Watthour Meter Transmission

device which is capable of transmitting the position of any kind of instrument. A watthour meter consists of a rotating meter element driving by means of an integrating train of gears, a number of dials which read units, tens, hundreds, and thousands or other suitable denominations. Thus if we may transmit by means of the telemetering system the position of each of the dial pointers we can make available at the receiving station a facsimile indication of the readings of all of the dials.

All that we have to do is to provide any suitable contrivance by means of which a condenser, of the same

value as would be attached to the movement of an indicating instrument for the purpose of telemetering its reading, is caused to vary its capacity in accordance with the indication of the pointer. We cannot mount a condenser directly on the pointer since this makes a complete revolution and we require that the capacity be a minimum when the pointer is indicating between zero and one and a maximum when it is between 9 and zero. But we can do this by means of a cam as shown in Fig. 8 or by any other suitable scheme.

With such an arrangement two features of special interest will be noted. First, any desired order of accuracy may be obtained as this depends entirely on the denomination of the dial which reads the lowest unit and which, therefore, moves the fastest. Clearly by reading each digit separately we shall obtain much greater accuracy than could possibly be furnished by any means embracing the complete reading in a single signal, assuming any given limits of accuracy in the telemetering system as such.

Second, with such a scheme we do not require the exclusive use of the telemetering channel. We only require to occupy it during the period when the readings are actually being observed. We shall not in general require to read an integrating meter at very frequent intervals. If we employ a supervisory system and only connect the watthour meter to the telemetering system when required, one dial at a time, the telemetering channel will be available at all other times for reading other instruments. It follows also that we shall experience no errors due to line interruptions as the integrated reading whenever it is transmitted and received shows the dial reading at that time. In a continuous automatic multiple telemetering system, of the type described in Part I of this paper, any number of watthour meter dials may be included in the complete series of indications along with wattmeters, voltmeters, ammeters, and any other indicating instruments which it may be desired to telemeter.

At the receiving end, the dial pointer positions may be shown by frequency indicating instruments exactly similar to those used for indicating any other telemetering signals and having their scales graduated from zero to ten, to one hundred, and so forth. Since, however, conventional practise in reading deflection instruments and circular dials is different, it is possible, depending upon the skill of the personnel involved, that it might be desirable in some cases to furnish the standard frequency indicating instrument movement with suitable gearing so as to give a circular dial reading.

## Field Installation

In order to obtain field experience relating to the thyratron totalizing type receiving circuit, arrangements were made for further field tests on the installation described in Part I. For this purpose two thyratron frequency indicating circuits were substituted for the original vacuum tube amplifiers. One of these indicates the signal from Amsterdam and the other from Glenville. Arrangements were made for operating the system in two different ways for these tests.

According to the first set-up, the system was arranged to operate, with the thyratron frequency circuits, with the multiple selector system described in Part I. The same three readings from Amsterdam and from Glenville were provided by means of d-c. ratio instruments instead of the frequency meters used in the original installation.

By means of change-over switches arrangement was made to cut out the multiple system and to receive instead a single indication, continuously, on each carrier channel. The selectors at Amsterdam and Glenville were likewise cut out and a single transmitting instrument at each station connected to the transmitter. The two incoming signals are each indicated, continuously, by separate instruments. In addition the two signals are totalized and the combined reading is recorded by means of a graphic instrument of the d-c. ratio type.

Fig. 9—View of Modified Receiving Installation

Fig. 9 is a view of the modified receiving installation. In addition to the circuit changes the general arrangement of the apparatus has been altered. All the instruments are mounted upon a separate panel such as might be installed in a load dispatcher's office. This may be seen on the right of Fig. 9.

On the meter panel the three readings from Amsterdam and the frequency check meter are on the upper portion. Immediately below are the four similar instruments which give the readings from Glenville. At the bottom of this panel are the instruments which are used when the equipment is used for totalizing.

To the right of the meter panel are the two tube equipments. The upper one contains all carrier-current and telemetering tubes, relays, and circuits, operating on the Amsterdam channel. Below is a similar unit which receives the signals from Glenville.

## Discussion

**E. J. Rutan:** When Mr. Fitzgerald first described briefly his electron tube telemetering system in the paper presented at the Winter Convention in 1929, it was felt he had developed a system having considerable possibilities. Since that time, he apparently has had an opportunity to improve the system, and obtain operating data from an actual installation.

In the paper presented here, he has given us some of these details, together with a discussion of some of the difficulties and his methods of overcoming them. Reading the paper from the standpoint of a user of such equipment, there are several points on which more data than have been given in the paper would be desired.

In any system of measurement, especially a telemetering system, it is necessary to have detailed data in regard to accuracy. It seems in the development of telemetering systems so many schemes have been proposed that it is difficult to judge the suitability and reliability unless the accuracy performance is known. In fact, many systems proposed for telemetering do not deserve any consideration whatsoever because the accuracy is so poor compared with the well developed existing systems. Although Mr. Fitzgerald's paper gives details, and in places is extremely frank in acknowledging certain difficulties which he encountered, it is felt that his statements under the caption "Operating Characteristics" in Part I of the paper could be made more specific. It is to the paragraphs in this section that I feel the operating men will look in order to judge the quality of the scheme proposed. I am sure that Mr. Fitzgerald has the data from the trial installation which he made which would enable him to give us the accuracy with which he can transmit indications of voltage, current and power. He states that the performance was very satisfactory. This could be made much more specific.

As has been indicated in the paper, one of the important factors in determining the accuracy of the system is the constancy of the oscillating circuits at the transmitting end, for any variation in these circuits will be multiplied 10,000 to 20,000 times in the beat frequency, and affect the accuracy of the indication to the same extent. From the trial installation, he, no doubt, could read directly this effect on the indicator which he used to determine whether his system was functioning correctly. He could advise us what percentage variation he obtained on this indicator during the period of his test.

In considering the installation of the telemetering system, it is also desirable to have data on the maintenance required. From the trial installation, Mr. Fitzgerlad could probably give us some data in regard to the type of maintenance which this system required. In the event that tubes may need replacement, is it possible to substitute a new one without any change in accuracy? What frequency of inspection for the selecting device is necessary in order to obtain satisfactory operation? These questions are raised because very often the maintenance costs for the installation will greatly influence the selection of the type of telemetering system to be used.

An advantage of this system is that the receiving instruments retain their position when they are denergized, but this may become a disadvantage in the event of failure of some part of the system. No indication will be given to the operator because the instruments will hold their last indicated position. I wonder if Mr. Fitzgerald experienced any of this difficulty during his tests, and what steps were taken to provide some signal indicating that the system was faulty?

In the conclusions of Part I of the paper, certain statements are made concerning the outstanding features of this system which are, perhaps, a little too broad. They seem to imply that other telemetering systems do not have similar advantages. These will be taken up individually.

He stated that this system has no moving parts other than the meter movements. This same characteristic applies to most of the successful telemetering systems now in use.

He also states that this does not require instruments of an unconventional type. The transmitting instrument which he shows in Fig. 3 is considerably different from the standard switchboard instrument.

The advantages claimed for the multiple system in general are also available in a number of the successful telemetering systems now in operation.

In regard to Part II of the paper, many interesting adaptions of the system have been indicated, but without indicating that they have been put into actual operation, except in the case of one type of installation. Here again the accuracy data are incomplete.

**W. B. Kouwenhoven:** For a number of years I have been interested in the reading of watthour meters at a distance and Mr. Fitzgerald's vacuum tube scheme brings nearer the day when the Public Utility may dispense with its meter readers.

Mr. Fitzgerald, however, presents very little experimental data in his paper and there is a number of questions upon which additional information would be helpful. Among these are:

1. In the installation described in the paper, what range of frequency is used in the oscillating circuit of which the capacitor attached to the instrument pointer forms a part and what is the range of frequencies transmitted to the receiving station?

2. Is the telemetering device described simply an indicator or does it give the distant reading with precision? Data comparing the scale reading of the frequency meter for both increasing and decreasing deflections of the master meter would be of interest.

3. A full description of the variable 0.0005 $\mu$ f. capacitor attached to the instrument pointer would be of value and interest. I should also like to know the dielectric that is used in its construction and to what extent do temperature variations affect its capacitance?

4. In applying this method to a watthour meter Mr. Fitzgerald shows it for a single dial only. In case the method was provided for reading each of the four dials commonly used would it be necessary to use the selector equipment mentioned?

5. Is this method limited in its operation by the type of equipment, such as transformers, voltage regulators, etc., included in the circuit between the transmitting and receiving stations?

6. What effect does the presence of harmonics in the circuit have upon the accuracy of the equipment?

**C. Lichtenberg:** Telemetering forms one more element in the chain of automatization. It permits essential electrical indications and measurements to be automatically transmitted hundreds of miles using conventional communication circuits. The more recent developments have reduced or almost entirely eliminated the errors due to the size and length of the lines connecting the transmitters and receivers. They have also increased the number of readings which may be automatically and continuously sent over one pair of connecting lines from one to twenty.

The systems described by Mr. Fitzgerald may be used on wire channels, carrier channels or radio channels. Each of course, has its field and limitations at the present time. The limits are of at least two kinds. These are cost and comprehensiveness.

The cost is quite definite. It can be readily determined for each set of conditions. It consists of the cost of the terminal apparatus and of the connecting lines. The cost of the terminal apparatus varies only with the type and number of indications to be sent and received while the cost of the connecting lines depends primarily on the distance between transmitting and receiving points.

If the distance is less than fifty miles and the number of readings to be transmitted is two or three, then wire lines in conventional communication channels will be found least expensive. If the distances are greater, then carrier channels may be found more expedient. Radio channels, however, do not seem at

present suited, since they require too much manual attention to permit of their economic use. It is believed, however, that radio developments may soon reach a point where its channels may prove to be valuable in transmitting telemetering information.

Comprehensiveness is the second important factor. Suppose an individual located in Chicago is connected by telemetering equipment with Milwaukee, 85 miles north, South Bend, 85 miles east, and Peoria—125 miles southwest. With present day limitations of intelligence transmission, the individual at Chicago, utilizing the telemetering equipment would have difficulty in making the best use of it without further information regarding local conditions at Milwaukee, South Bend, and Peoria. He might obtain total system load readings and distribute this information, as is being done successfully at the present time in metropolitan Chicago by the Commonwealth Edison Company. However, the cost of doing this over longer distances at the present time seems out of proportion to the results obtained. Consequently, until such time as better and less expensive methods for intelligence transmission are available, it would seem as though telemetering, excepting for limited applications, is a little in advance of the art.

The field of application of telemetering, however, would be considerably broadened if it could be made available to transmit electrical measuring instrument readings over communication channels without interfering with speech communication. At the same time, it is necessary that this be done at a cost not to exceed 5 to 10 times the cost of the readings or the apparatus to obtain the readings locally. Mr. Fitzgerald's paper indicates the probability of such development which operators will no doubt welcome as another element in reducing the cost of electrical energy and extending its field of application.

**R. T. Pierce:** The work described in Mr. Fitzgerald's paper is a very definite contribution to the advancement of the telemetering art. The process makes use of a medium of transmission which has been recognized for some time as being ideal when the limitations of the transmitting and receiving apparatus were overcome.

I would like to review briefly an analysis made during the development of the current balance system of telemetering. It was recognized that the limitations imposed on a telemetering system hinged around the transmitting unit. We therefore considered each electrical quantity which might be used and which I will list with a discussion of each.

*1. Voltage.* This may be subdivided into three groups

(A) That system which produces a voltage proportional to the value being read and which is duplicated by a voltmeter at the receiving end.

(B) That system which produces a voltage proportional to the value being read and which is duplicated at the receiving end by a recording potentiometer producing a balancing voltage so that no current flows in the wires between the transmitting and receiving end.

(C) That system which produces a heating effect proportional to the value being measured, measures the heat by means of thermocouples, and transmits the thermocouple voltage to the receiving end where it is measured by a recording potentiometer.

The trouble with all of these methods is that the line resistance very definitely affects the accuracy of the system. In the straight voltage method changes in line resistance have more of an effect than with either of the other two. The distance which these can transmit is limited. A constant control voltage is necessary.

*2. Current.* If a current is produced proportional to the value being measured it can be transmitted independent of line resistance to the receiving end. This makes quite a simple system for medium distances. The inaccuracies aside from the apparatus involved are due to line leakage. The distance is limited by the voltage allowed on the transmitting wires and the leakage error permitted. The control voltage need not be constant.

*3. Watts.* A wattage proportional to the value to be measured could be produced and transmitted over three wires to the receiving end. This, however, combines the errors of the voltage and current methods and is impractical.

*4. Frequency.* This method was used on the installation of the telemetering system on the Chicago, Milwaukee & St. Paul R. R. electrification. The apparatus used for transmission and reception was complicated and expensive. It was independent of distance and line resistance. Later several impulse methods were devised which were quite simple except in cases where indications were desired. For watthour transmission and reception the impulse method is simple and accurate.

*5. Phase Angle.* Under this heading we included all Selsyn motor schemes which changed a phase condition to produce the desired results. This system has a very definite application for short distances but does not apply to telemetering installations for controlling the distribution of power on large or interconnected systems. The main limitation to long distance work is the number of wires between the transmitting and receiving stations.

Mr. Fitzgerald's paper describes a system which is an added contribution to the frequency type. The expensive transmitting and receiving apparatus used on the Chicago, Milwaukee & St. Paul R. R. installation prevented this system from being more universally adopted. The impulse methods have simplified the apparatus involved and still retain the advantages of being able to transmit over unlimited distances. The electron tube or beat type is a further simplification of the impulse types and for this reason I consider it to be an important contribution to the art.

To obtain indicating or graphic readings at the receiving end with the frequency method of the impulse type it has been quite common practise to charge and discharge a condenser through a D'Arsonval meter element. Relays are used on the low frequency impulse method but with the high frequency beat method it is necessary to resort to gas valves or Thyratrons. The principle, however, is the same in both cases although the instrument design problem is simpler in the case of the higher frequency. The objection to either of these is that a constant voltage is needed to charge the condenser and the condenser has temperature errors.

A brief comparison of the various methods used most as to their suitability for different measurements will give a picture of how they fit into the art.

The first problem is the totalization of power readings. With the current and voltage methods this can easily be done by connecting the incoming circuits so the current or voltage values are added together in one meter. In the impulse method the impulses are added up and combined into one receiver. With the beat method the current charging a plurality of condensers passes through a common meter as shown on Fig. 7. Totalization therefore is no particular problem for any of these systems.

Watthour meter readings at the receiving end are obtained with the impulse method by placing a counter in the circuit to add up the impulses. Such readings can also be obtained with the current balance method. None of the voltage methods have ever attempted this to the writer's knowledge although it could probably be worked out. Transmitting from a watthour meter is outlined in a general way in Mr. Fitzgerald's paper but no mention is made of receiving readings in terms of watthours with any degree of accuracy. Adding the high frequency beats is more of a problem than in the case of the impulse method.

Alternating current or voltage can easily be transmitted with the current balance or voltage methods. Ampere-hour meters with commutators and contacts can be used to transmit current with the impulse method. A special high-torque induction

ammeter or voltmeter can undoubtedly be made like the wattmeter shown in Fig. 3.

Direct current amperes or volts may be transmitted easily using the current balance or voltage methods. This has not been worked out commercially to the writer's knowledge in any other system.

The position of a water level float or like measurement has been transmitted for short distances by the Selsyn motor method. Also such readings have been transmitted over long distances by the current balance method. There is also a possibility of working this out readily with the beat principle. However there is often no control voltage available at the transmitting end. This can be supplied from a battery in the current balance method where as the others require an alternating current source.

It is quite evident that the beat system as described by Mr. Fitzgerald is readily applicable to the most important readings needed in power system control and operation with the exception of watthour meter readings. It has advantages over the other methods in the flexibility with which it adapts itself to various mediums of transmission. An induction meter element as shown in Fig. 3 is required to deliver sufficient torque to handle the variable condenser. Such a condenser could not be added to standard indicating instruments without large errors which eliminates the possibility of universally applying it to all measuring problems. However it is a very definite step in the right direction and the limiting features will undoubtedly be worked out as more experience is obtained with its use.

**A. S. Fitzgerald:** Mr. Lichtenberg gives a very instructive survey of the present status of telemetering. He shows how the cost of the transmission channel is an important factor, and points out the advantage of employing a communication circuit, the cost of which need not entirely be borne by the telemetering service. The question of transmitting telemetering indications over communication channels without interfering with speech is therefore important and merits further investigation. Impulse systems and direct current systems can be used in this way. The transmission of readings by means of a frequency system, without interference, is probably quite feasible. It is a matter of common experience that a telephone conversation can be carried on effectively with a high order of interference noise, provided that the interference frequencies lie outside of the frequency band necessary for the transmission of intelligence. I think it is quite likely that a telemetering channel and a speech channel could be carried by the same circuit if the telemetering frequency be kept either above or below the speech frequency band.

It will be appreciated, of course, that a carrier current telemetering channel may be superimposed upon a communication circuit without any mutual interference at all. It is common knowledge that additional communication channels are furnished in this manner by the telephone and telegraph companies. It should be pointed out that this arrangement avoids the cost of the high voltage coupling equipment which is necessary in order to establish a carrier circuit over transmission lines. All that is required is a carrier current transmitter, which need only furnish a relatively low output and a carrier current detector at the receiving end.

It is regretted that Mr. Rutan and Mr. Kouwenhoven find the paper somewhat lacking in respect of performance data. I am sure, however, that they will appreciate that, in preparing a paper, it is necessary to keep in mind the question of space in the JOURNAL and to leave out a great deal that one would like to include. Thus, in the present paper it was felt better to restrict it in scope mainly to a description of how these various circuits work. As pointed out in the paper the installation described was entirely of a developmental character. Performance data on such equipment is, it is felt, of somewhat limited value to practical engineers. It will not be long, I hope, before we shall be able to have some information of the performance of a commercial installation, and this will be of much greater interest.

However, it may be of interest to discuss a little more the question of accuracy. Suppose we consider, for a moment, for what different purposes we may wish to read instruments. These are mainly, system operation and accounting.

In operating a system, we often have to take action, sometimes immediate action, as the result of what the instrument indications tell us. But whether we open a tie-line or parallel another generating unit is determined by general conditions of the system which usually do not require a high order of accuracy to ascertain. It is more important that we get the information promptly than that we use instruments of laboratory accuracy. It has been estimated that errors of as much as five per cent in a telemetering system would, for the majority of indications in which load dispatchers are interested, be acceptable in an equipment reliable and reasonable in cost.

The other purpose for which instruments are observed is for system accounting, and station economy. Energy or watthour readings are of most importance in this connection. Here it is not so necessary that the readings be obtained promptly nor is it required as a rule to obtain them very frequently. For this reason, telemetering has probably less application in this connection, on the same principle that one sends a letter instead of a telegram if one is not in a hurry. For this reason the subject of watt-hour telemetering was only touched on briefly in the paper.

However, in the case of watt-hour telemetering, accuracy is of primary importance. It is possible that I have not entirely made my meaning clear to Mr. Pierce, with regard to the question of transmission of energy readings since he suggests in his discussion that the beat system is not readily applicable to watthour meter readings. As pointed out in Part II of the paper it is one of the special features of the system of transmitting dial positions that with any given over-all accuracy of the telemetering transmitter and receiver, any desired accuracy in transmission of watt-hour readings may be obtained by transmitting an appropriately small unit of energy on the lowest reading dial.

For transmitting the readings of the several dials, any of the methods indicated in the paper for handling more than one telemetering indication may be used.

Mr. Rutan asked some specific questions about the performance of the development field installation, and the percentage variation which the frequency check instrument indicated. This instrument only had a single mark in the middle of the scale. However, during several months operation, and of course, excluding those trouble shooting periods associated with any new development, we found that this instrument was never more than two or three pointer widths off the mark. You had to stand close to the instrument to see if it was correct or not. I would say we were getting an accuracy within two or three per cent.

With regard to the question of changing tubes the answer to this is that it all depends upon the tube. Generally speaking, if you use tubes intended for broadcast receiving, you will be liable to have to check the beat frequency when you change a tube. However, for the telemetering equipment we used tubes furnished for electron tube applications and which are manufactured to closer limits, and we did not encounter any serious difficulty in this respect.

The instrument shown in Fig. 3 admittedly does look rather different from existing switchboard instruments. But the movement is that of a standard curve drawing instrument. As a matter of fact this has an enormously greater torque than is required to carry a condenser of 0.0005 $\mu$f. Mr. Pierce may be interested to know that a condenser of the desired size was successfully mounted on a standard switchboard instrument in the

laboratory. This condenser caused no serious errors in the instrument readings. However, this arrangement did not lend itself to production manufacturing and therefore the curve drawing movement was employed instead. This is a great deal larger than is actually necessary but manufacturing facilities were not available for any intermediate size.

The dielectric of the condenser, as can be seen in Fig. 3, consists of air.

Perhaps Mr. Rutan has not quite grasped my intended meaning in the concluding summary. He says, for instance, that the advantages claimed for the multiple system are also available in a number of existing telemetering systems. But are they multiple systems? Will they transmit a large number of indications over a single channel?

The beat oscillators each operated at a frequency around 20 kilocycles and the maximum beat frequency was approximately 1500 cycles.

Mr. Kouwenhoven's questions five and six refer to the channel by means of which the telemetering signal is transmitted. As described in the paper, this may be carrier current, wire line, telephone lines, etc. It is presumed Mr. Kouwenhoven's questions apply to carrier current. The limitations applying to the transmission of telemetering signals over a carrier current channel do not differ from the conditions applying to carrier current telephones or carrier current systems in general. Harmonics in the power system, voltage or current would have no effect upon a carrier current system. It is conceivable that in cases where the beat frequency is transmitted by a conducting circuit, harmonics might cause trouble; if due to inductive interference they could get into the telemetering circuits.

# Development of a Two-Wire Supervisory Control System

## with Remote Metering

BY R. J. WENSLEY* and W. M. DONOVAN*
Associate, A. I. E. E. Non-member

*Synopsis.—This paper describes the conditions leading up to the development of the two-wire supervisory control system. It enumerates the outstanding requirements of supervisory control systems in general and indicates a number of the advantages of the two-wire system. It provides a brief description of the operation of the system.*

THE first installation of supervisory control equipment on a commercial basis was made on the system of the Cleveland Railways Company approximately seven years ago. This installation is still operating in a highly satisfactory manner and has been added to from time to time, so that it still ranks among the larger installations of this nature.

From this beginning, there has come into existence a number of different forms and types of apparatus which may be included under the general classification of supervisory control equipment. An intimate association with the development of a large number of these systems has made possible a thorough study of the requirements as outlined by operating companies throughout this and other countries.

In the search for a suitable type of apparatus which would be both compact and reliable, recourse was had to the products of the telephone manufacturing companies engaged in the design and construction of automatic telephone exchanges and similiar equipment. Here it was found possible to obtain relays having satisfactory characteristics which were compact and at the same time of sturdy construction. There were also available various types of selector switches which were equipped with step-by-step mechanisms which could be used for transmitting and receiving trains of impulses.

Shortly after the first installation of supervisory control equipment for the Cleveland Railways Company, it was decided that an investigation should be undertaken to determine the possibility of simplification and reduction in space requirements. The suitability of a system of supervisory control which would operate through the medium of telegraphic signal codes transmitted from one station to the other was also considered. Codes of a similar nature are widely used in the automatic telephone industry.

It should be noted that the situation in connection with the remote control of power equipment is somewhat different from that encountered in the selection of the proper number in a telephone exchange. Being connected to the wrong party is disagreeable for all of us; but it is quite evident that this condition is not nearly so serious in connection with communications as would be the case if we were to operate the wrong circuit breaker in a power station. Obviously, there must be some means of insuring the reception of the correct signal at the remote station.

To meet these requirements, there was developed the code visual type of equipment, which was originally known as the "switch" type to differentiate it from the "all-relay" type previously developed.

The code visual supervisory control equipment was designed and manufactured with the rotary type selector switch as a nucleus. Inasmuch as the particular type of switch selected for use was equipped with

FIG. 1—VIEW OF CONTROL PANELS

25 steps, or contacts, a series of impulses totaling 25 was considered to be the most suitable for the application.

The equipment was so designed that this series of impulses consisted of 22 short impulses or dots, and three long impulses or dashes. The first two long impulses might be included in the series at any point, but the last long impulse must always be the 25th in a correct series of impulses. Thus, if the 25th impulse of any series were not a long impulse, the final circuit could not be completed to cause an operation.

The code visual type supervisory control equipment in its commercial form required three wires between the dispatching office and the substation. These consisted of a common wire, a control wire and a supervision wire. By means of circuits well known to the telegraphic art,

*Both of Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

the code visual equipment could be operated over two line wires between the dispatching office and the substation; but such an arrangement was not considered commercially feasible because it required frequent attention and delicate adjustment.

In order to provide the most reliable check upon the correctness of the signal received, it was determined that the most satisfactory system would be one making use entirely of relays.

Considerable interest was also expressed in the possibility of reducing the line wire requirements from three wires to two wires, particularly by those operating companies who lease their communication circuits from the local telephone company. Inasmuch as the communication circuits are leased on the basis of so many dollars per circuit mile, it is evident that a system requiring three wires will represent twice the expense in line wires that a system requiring two wires will, since it is necessary to lease four wires, even though only three are required.

It may be of interest to indulge in a little simple arithmetic to illustrate the financial advantage of a supervisory control system requiring only two wires over a similar system requiring three or four wires. The average cost per circuit mile for leased wire circuits obtained from the telephone companies in various parts of the country is approximately $42.00 per year. Assuming a nominal distance of five miles between the substations, the yearly cost for a single circuit would be $210.00. Now considering a 12 per cent return upon the capital investment to be a fair average, the expense for a two-wire line will represent a capital investment of $1750.00. Obviously, if three wires are required, it will be necessary to lease two circuits, thus doubling the expense and representing a capital investment of $3500.00. From this it is evident assuming the two systems are equivalent in other respects that the operating company can well afford to expend something more for a supervisory control equipment which requires only a single circuit rather than two circuits between the dispatching office and the substation.

There are a number of other requirements which have been found desirable by various operating companies during the course of development of supervisory control. These have been given careful consideration in the design of the two-wire system.

An ideal system of supervisory control should have the following characteristics:

1. The equipment must be simple in construction and operation.
2. It should occupy the minimum amount of space consistent with satisfactory operation.
3. It must be flexible in design so that the control key units may be mounted upon a desk or a panel. The units may be arranged in groups or as a part of a miniature bus layout.
4. It must present a neat appearance and be suitable for installation in line with the usual form of power station switchboard.
5. It should require the minimum number of line wires between the dispatching office and substation consistent with reliable operation.
6. It should require a minimum amount of attention and maintenance at regular intervals.
7. It should be protected from damage due to excessive voltages on the supervisory control lines between stations.
8. It should not be possible to obtain any false operation of apparatus units due to unusual conditions in the supervisory control equipment itself, or upon the control wires between stations.
9. It should be possible to obtain selective remote metering indications without requiring extra wires.

A study of the general trend of the specified requirements will indicate that the latest development in the field which is known as the "visicode" system approaches most nearly the ideal supervisory control system.

This design, operating over two line wires, utilizes the same type of telephone relays which has been used

Fig. 2—Arrangement of Control Board

since the entrance of supervisory control systems into the commercial field. These same relays have been used in automatic telephone exchanges for approximately a quarter of a century. The relays are all of standard construction and are given a definite factory adjustment which requires no change under service conditions, inasmuch as they are given a thorough test and inspection at the factory before shipment.

The visicode supervisory control equipment consists essentially of a dispatching office unit, with its associated control escutcheons, and a substation unit, with its associated interposing relays and signaling equipment. The dispatching office unit and the substation unit are similar in construction and in design of the fundamental circuits. Each unit is composed of transmitting relays, receiving relays, and line transfer relays, together with the required in-

dividual point relays, according to the size of equipment.

The transmitting relays are composed of a relay chain which actually provides the means of sending out the impulses, and a series of selection relays to determine what particular portion of the code is to be transmitted by the relay chain. The receiving relays may be divided into the group receiving relays, the unit receiving relays and the operation control receiving relays. The line transfer relays consist of those relays which provide for the transfer of the line connections from the transmitting relays to the receiving relays, and vice versa, at the proper time in the operation of the equipment.

In controlling an apparatus unit at the distant station, the first operation at the dispatching office is the energizing of an individual point relay by depressing the control key at the bottom of the proper escutcheon. This in turn causes the operation of the local line transfer relays in such a manner as to interrupt the line circuit, thus releasing the apparatus at the local station and at the remote station from the normal position of rest.

At the local station, the interruption of the line circuit causes the equipment to be prepared for the transmission of the first series of impulses. These impulses cannot be transmitted, however, until the line circuit has been completed at the remote station. At the remote station, the interruption of the line circuit causes the equipment to operate in such a manner as to connect the first set of receiving relays to the line circuit in preparation for receiving the first series of impulses.

After the transmission of this series of impulses, the line transfer relays at the local point disconnect the transmitting relays and connects the first set of receiving relays at this station. Simultaneously, the line transfer relays at the remote station operate in such a manner as to disconnect the first set of receiving relays from the line between stations and connect the transmitting relays in such a manner as to transmit the first series of impulses from this station as soon as the receiving circuit has been set up at the local station.

At the conclusion of the first series of checking impulses, the line transfer relays at the remote station operate in such a manner as to disconnect the transmitting relays and to connect the second series of receiving relays. At the same time, the line transfer relays at the local station act in such a manner as to disconnect the first series of receiving relays and to connect the transmitting relays preparatory to transmitting the second series of impulses from this station. This series of impulses is sent out as soon as the receiving circuit at the remote station is prepared to receive it.

The completion of the second series of impulses transmitted from the local station causes the line transfer relays to operate, disconnecting the transmitting relays and connecting to the line circuit the second set of receiving relays. The line transfer relays at the remote station also operate to disconnect the second set of receiving relays and to connect the transmitting relays preparatory to sending out the second series of impulses from this station.

Upon the completion of the series of checking impulses from the remote station, the line transfer relays at that station disconnect the transmitting relays and connect the operation control receiving relays to the line. At the local station, the line transfer relays disconnect the second set of receiving relays from the line and connect the transmitting relays to the line preparatory to sending out the operation control impulses.

At the local station, the completion of the third series of impulses permits the line transfer relays to disconnect the transmitting relays and connect the third set of receiving relays which correspond to the operation control receiving relays at the distant station.

The line transfer relays at the remote station disconnect the operation control receiving relays from the line, at the same time causing the operation of the apparatus unit and connecting the transmitting relays to the line preparatory to transmitting the third series of im-

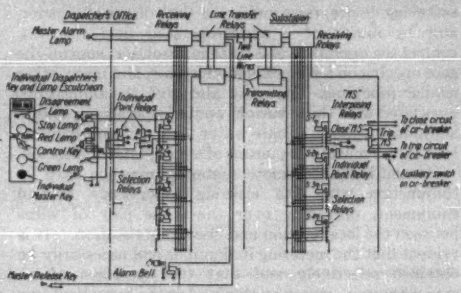


FIG. 3—SCHEMATIC DIAGRAM OF FUNDAMENTAL PRINCIPLES OF OPERATION

pulses as soon as the apparatus unit has changed position.

When the third series of impulses or indication code has been transmitted from the remote station to the local station, thus indicating that the apparatus unit has actually changed position, the line transfer relays at both stations are actuated in such a manner as to disconnect both transmitting and receiving relays from the line and restore the equipment at each station to its normal condition.

In case the operations were originated at the remote station, the functioning of the equipment would be the same as that described above, except that in this case, the remote station would be the first to transmit a series of impulses. Furthermore, at the conclusion of the third series of impulses transmitted from the remote station to the local station, the equipment at the remote station would be prepared to receive the third series of impulses from the local station and the local station would be prepared to transmit the third series of im-

puises, only when the proper circuit is set up by the operator at the local station.

After this circuit is completed by the operator at the local station, the third series of impulses is transmitted from the local station to the remote station if desired, thus causing the operation to take place, after which the third series of impulses is again transmitted from the remote station to the local station, thus indicating the change of position of the apparatus unit.

In case the operator at the local station did not desire to cause an operation of the apparatus unit at the remote station, the equipment at both stations could be restored to normal by depressing the release key. This same release key may be used at any time during the cycle in order to cancel an operation which has been started but is not to be completed. Release is instantaneous with the pressing of the key.

Practically any operation can be performed by means of the visicode supervisory control equipment which does not require the simultaneous use of more than two wires between the local station and the remote station. We may close and trip a circuit breaker or similar switching device, raise and lower the voltage of a generator by means of a motor-operated field rheostat, control the operation of a voltage regulator, control the gate opening on a waterwheel generator, and many other similar functions. We may also give the indications associated with these various control operations, and in addition, we may indicate water level and approximate load upon a machine by means of step-by-step indication.

Current-balance remote metering may be used in conjunction with the visicode supervisory control equipment, operating over the same pair of wires between the local station and the remote station. It is evident that the metering indications will necessarily be obtained selectively and that the operation of an apparatus unit cannot be obtained at the same time as a metering indication. However, an automatic operation which may have occurred during this time will be indicated immediately upon the release of the metering circuit. Furthermore, a change in position will be indicated even though the apparatus unit may have returned to the original position.

By means of current balance remote metering equipment, we may obtain accurate indications of current, voltage, kilowatts, and any other type of indication which may be obtained by the use of a Kelvin type of instrument.

In order to obtain a selective remote metering indication, we assign a standard point for this purpose so that whenever this particular point is selected, the line wires are connected to the remote metering circuit and are disconnected from the transmitting and receiving relays at each station. In order to release the remote metering circuit so that other operations may be performed, the operator at the local station depresses the release key, thus opening the line circuit and causing the supervisory control equipment at both stations to be restored to the normal condition.

## Discussion

**J. E. Goodale:** The New York & Queens Electric Light & Power Company is operating three substations over supervisory control equipment and has had experience with this equipment for several years. The two later stations are of 30,000-kv-a. capacity each and the supervisory control consists of relay equipment similar to that described in the paper, although a larger number of wires is used. A careful record of operation of the supervisory control systems for the year 1929 showed for the two stations a total of approximately 124,000 operations of which 13 were incorrect and in most cases the cause of the incorrect operations has, we believe, been corrected.

We believe that there are some things which it may be necessary to do in operating a substation which cannot be accomplished over a two-wire supervisory system. We have found it desirable, for example, to operate our induction regulators over the supervisory system from the control station, and while this operation is being performed to read the voltage on the lines being regulated. So far as we can see this could not be accomplished with the two-wire system. The same reasoning would, of course, be applied to synchronizing, because two simultaneous readings would be required for this. With the system which we now have, if the supervisory chain should for any reason get out of step and stop at any point, we can reset the equipment at the starting point. With a two-wire system it seems that this cannot be accomplished unless an additional wire is added.

There is, of course, a saving in cutting down the number of control wires. On our own system, owing to the importance of the load supplies by the supervised substations, we have installed our own control wires. The control cable used consists of 10 pairs of No. 18 paper-insulated wires in a lead sheath. We have had at least one case where the control cable to one of the substations was burned apart by a manhole fire, but no incorrect operation or indication resulted. Consideration is being given to equipping our particular substations with two sets of control wires over different routes. This procedure, if adopted, would make a smaller number of wires used for control very desirable, particularly if the control wires were leased from the telephone company.

As I understand the system of supervisory control described in the paper, a transfer relay operating at each point is required. It would be interesting to know how this feature affects the speed of the equipment compared to the equipment now in use. In the three-wire supervisory system the equipment can be divided into individual groups, but so far as I can tell from the paper this is not the case with the two-wire equipment. In case of trouble with the supervisory equipment, it would seem to be less difficult to locate what was wrong if the system could be divided into groups, particularly if the system were a large one.

Fig. 3 shows an individual point relay connected to the auxiliary switch of the oil circuit breaker. We have found that supervision of the trip coil and its connections is desirable. If a relay were directly in series with the trip coil, it would eliminate this individual point relay, obtain trip coil supervision and give a correct indication regardless of the position of the breaker. The scheme shown in the paper would indicate that the oil switch was in the closed position if the breaker happened to be of the truck type and were pulled out into the aisle.

Anyone intending to install and operate one of the supervisory systems described by the paper would be interested in:

First: Whether or not the supervisory system described is trip free or whether the trip-free feature is to be obtained by the use of external relays;

Second: Whether or not it is desirable to have a panel in the supervised station for the remote control and supervision of the oil circuit breakers, this panel to be exactly similar to the one that is installed in the dispatcher's office. It would seem

that the switch layout and panel should be a one-line diagram of the station;

Third: What is the best method of obtaining the direct current for the operation of the supervisory control, and is it desirable or necessary to keep it separate from the station batteries at both the dispatcher's station and the substation?

**C. A. Mayo:** I find in making a comparison of costs and using the figures in Mr. Wensley's paper of $42.00 per year per circuit-mile for leased wires which for four wires represents a capital investment of $3500.00, our capital investment for an equivalent 5 miles is $3150.00 which is somewhat less. Not only is the investment less but we have available 28 conductors for use in other ways such as, private telephone lines, voltage indication of regulated circuits and the control of R. O. series circuits along the cable route.

Our first installation was in 1922 and I believe was one of the first, if not the first of this type of system to go into operation with both control and indication. As with any other new piece of equipment we had our difficulties, but these were soon cleared up. At first we tried to operate with the ground for the common return, but due to excessive stray ground currents this had to be abandoned, and substituted by a wire in the control cable.

In the beginning false operations and indications did occur but soon after the first installation the possibility of false operation was practically eliminated. At present the system fulfills the requirements and is entirely satisfactory. Our second installation took place in 1923 and the other three followed, the last being installed in 1928.

I think the comparison of costs of an attended substation as against the unattended substation with supervisory control is worthy of note. We figure that an attended substation would cost us approximately $5500.00 per year while the unattended substation with supervisory control costs us approximately $2000.00 per year. This last figure includes carrying charges on the investment, maintenance, repairs and janitor service for the station. This shows a considerable saving and is much more satisfactory.

The development of a two-wire supervisory control system is certainly a step in the right direction since it means a reduction in the cost of both installation and operation.

In conclusion I would just like to add that I feel there are many installations for some type of supervisory control which could be justified from an investment standpoint and would be entirely satisfactory.

# Centralized Control of System Operation

BY JAMES T. LAWSON*
Member, A. I. E. E.

***Synopsis.***—*This paper considers the application of centralized control of system operation of the Public Service Electric and Gas Company in New Jersey. A brief history of events leading to the installation of supervisory system operation is given, with a detailed description of the apparatus and the methods used to carry out the indications, together with a statement as to what is being accomplished in improving the service.*

* * * * *

IN the early days of the generation of electrical energy there was little need of load dispatchers or system operators. Then, each power station supplied its own local territory, usually at 250 or 500 volts direct current or 1000 or 2400 volts alternating current. The operating man in charge of the power station or distribution system could direct the handling of apparatus and feeders without any trouble. Power stations were not run in multiple and each one could be operated in a manner best suited to it.

Gradually, as consolidation was effected and territories enlarged, several plants were tied together, and in time, voltages were raised. The method of allowing superintendents or chief engineers to operate the distribution systems and the stations according to their own individual ideas led to confusing, inefficient operation, and had to be discontinued.

This forced in a group of men, who would be available at all hours to guard the operation of the system as a whole.

Such a scheme was first started in our system in 1900, to handle d-c. railway feeders. At this time, the operator did the work as a side line to other duties and his entire equipment consisted of a small plug board, somewhat like a cribbage board, with the names of the stations and substations lettered on the left-hand side and the feeder numbers across the top. A series of holes was drilled across the board to match. By placing pegs in the proper holes, it was possible to keep track of the railway feeder operation.

Later, this scheme was extended to follow up the operation of the a-c. system, both for railway and lighting. At this time there was no attempt at parallel operation of power stations.

In 1906 parallel operation of the stations became necessary and centralized control of system operation imperative and the first load dispatching office was then started in our Marion Station, Jersey City. The office controlled the operation of the power stations, and distribution and transmission systems, in Hudson, Bergen, Passaic, and Essex Counties, or in the Northern Division.

The operating board consisted of a wooden drawing board, an elaboration on the original plug board about 6 by 12 ft., painted white and marked with single wire diagrams of the transmission lines and station and substation busses, and showing symbolically the main apparatus in each station and substation. The diagrams of transmission lines, apparatus, and busses were placed on the board by using gummed paper cut in narrow strips, and gummed letters and numbers.

Wooden plugs, colored red and white, were used, placed in holes drilled in the board. But few private telephone lines were in use.

In 1909 and 1914, load dispatching systems were established in the Central and Southern Divisions. At this time the three divisions were not electrically connected and we thus had four load dispatching offices. The work increased rapidly, and as the system expanded and the divisions were tied together, the future seemed to point to the need of one central load dispatching office to control the operation of the entire system as a unit, not only within itself but in its relation to connections which might be effected with other companies.

Accordingly, plans were made to consolidate three of the offices and move them into a centralized office at Newark; this was accomplished in 1926.

A load dispatcher must be familiar with every operating detail, and an accurate and up-to-the-minute diagram of the bus layout of each station and substation is necessary. The load dispatcher's diagram of busses, and substation and generating station apparatus, is known as a "Pilot Board." Our first pilot boards were made of wood, using gummed paper for the diagrams and small wooden plugs inserted by hand in holes drilled in the board to show the switch and apparatus positions. These were changed to a type of board using instead of plugs, a scheme of small colored lights manually controlled by the load dispatcher from his desk. (See Fig. 1.)

These types of pilot boards are accurate only in so far as the plugs or lights are changed in response to telephone messages, or orders given or received. Therefore they are not always an accurate visual record of the system. Time is lost in waiting for each station or substation operator to report switch positions and switch movements, especially in times of stress and trouble.

A board which automatically shows the position and movement of the switches not only serves as a diagrammatic record but also enables the load dispatcher to follow the switch operations as he directs them, and, more important in times of trouble, gives him an instantaneous indication of system conditions.

*Assistant to General Superintendent of Generation, Public Service Electric and Gas Company, Newark, New Jersey.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

From these indications, without waiting for reports from generating station and substation operators, he is in a position to act immediately toward restoring service and maintaining normal system conditions.

Accordingly, when it was decided to centralize the load dispatchers' office, an automatic pilot board was considered; but the cost for the entire territory was so great that it was decided to have only automatic indication from the stations and substations in the vicinity of Newark, the remainder to be manually controlled.

The location of the system operator's and load dispatcher's office is quite important; it should be as close to the records and operating department's facilities as possible. The office was therefore located in the company's main office building in Newark, N. J., convenient to every operating record and personnel facility.

The usual red and green indicating lamps are employed to show the positions of the various oil circuit

Fig. 1—Manually Controlled Load Dispatcher's Pilot Board

breakers in the generating stations, substations, and transmission system. For the substations in the Essex Division, together with the Essex, Marion, and Kearny generating stations, the Elizabeth and Bayway substations of the Central Division, Athenia switching station in the Passaic Division, and Hudson switching station in the Hudson Division, the indications are automatic, and the apparatus used to accomplish this is the distributor type of supervisory control and remote indicating equipment. There are 42 distributors in all, located in 21 substations and in Marion, Kearny, and Essex generating stations. Some of the smaller substations do not have distributors, the positions of the oil circuit breakers being indicated over direct wire connections.

Each distributor will automatically indicate from 50 to 100 switches, depending on whether or not supervisory control of the switches is desired in conjunction with automatic indication. Therefore, one distributor will usually take care of a subatation while two or more are needed for the generating stations.

The positions of the oil circuit breakers in substations not equipped with automatic indicating apparatus are shown by means of small control switches, manually operated, that light red and green lamps, the information for keeping these indications correct being obtained by the load dispatcher by telephone from the substation operators.

Provision has been made for four load dispatchers' telephone positions, with an extra position for the chief load dispatcher. Each operating position has a capacity of 40 telephone lines, and in addition, a special monitor type switchboard has been provided for the chief load dispatcher with multiple connections to each of the 160 lines furnished by the four operating load dispatchers' positions. All of these lines are not in use at the present time, ample provision having been made for future growth.

The load dispatcher's office consists of two rooms. The office proper contains the remote metering panels, telephone switchboards, pilot board, etc.; the second room contains the apparatus, batteries, motor generator sets, etc., for obtaining automatic indication of the switches in the substations and power stations.

The positions of the various oil circuit breakers and disconnecting switches in the system are shown on the load dispatcher's board by means of colored lights. Red and green lights indicate the closed and open positions of oil circuit breakers, and white lights with a horizontal or vertical black line across the lamp, the closed or open positions of disconnecting switches. A group of three lights is used for an oil circuit breaker, (the red and green referred to above), and in addition, a clear white light, the function of which is to indicate that the oil circuit breaker has changed its position. This white light is extinguished by a small push-pull, single-pole double-throw switch, thus compelling the load dispatcher to acknowledge the operation of the oil circuit breaker and also giving him notice that an oil circuit breaker has operated, since under normal operation the board is operated with all white lights unlighted. In the arrangement used, the white light is on top, the red and green lights directly below in the order given. Underneath the green light, the oil circuit breaker designation is painted on the face of the board. So far as practicable, the various oil circuit breakers and disconnecting switches are shown in their correct positions relative to one another. While all oil circuit breakers in the transmission system are indicated, only such disconnecting switches as perform a switching function are shown. Disconnecting switches which serve only to isolate other apparatus from the system are not shown on the load dispatcher's board, since in most cases such isolating disconnecting switches are stick-operated, so there is no simple means of obtaining automatic indication. The load dispatcher is supplied

with simplified wiring diagrams of each station and substation, which show all such isolating switches as well as other necessary information not feasible to show on the indicating board.

This system requires two separate sources of energy at the load dispatcher's office; 125-volt, three-wire direct current is required to operate the distributor motors and the relays of the system; 24-volt direct current is required for the indicating lamps. For this latter service, a 5-kw., 24-volt motor-generator battery-charging set is used with a 24-volt storage battery floating across its terminals. This storage battery has a capacity of 60 amperes for eight hours. For the 125-volt power, two 70-volt, 1-kw. d-c. generators are driven by one motor with a 60-cell storage battery floating across the generators. This battery has a capacity of 20 amperes for eight hours. Both batteries are of the sealed-in rubber-jar type, commonly referred to as the automobile-type of storage battery, and are contained

Fig. 2—Batteries, Motor-Generator Sets, and Control Panels

in the apparatus room. This type was selected so that it would not be necessary to construct a separate battery room. Spare battery and motor-generator equipment is provided, ready for service.

Each battery, with its charging set, is controlled from a separate panel, shown in Fig. 2. These panels are so constructed that on failure of a-c. power, the charging set is disconnected on both the a-c. and d-c. ends. As soon as a-c. power is available, the charging set starts automatically, and when the d-c. generators reach full voltage, a contactor closes, connecting the d-c. terminals to the bus on the back of the panel. Both motors are 220-volt, three-phase, 60-cycle squirrel-cage. The power equipment is shown in Fig. 2; from left to right are the 120-volt battery, 120-volt charging set, 120-volt panel, 24-volt charging set, and 24-volt battery.

Fig. 3 shows some of the relay and distributor cabinets. The cabinet at the left is a 100-relay cabinet, there being 50 relays on the reverse side of the cabinet. The second from the left is a combined distributor and relay cabinet. The third and fourth from the left show cabinets with a capacity of three distributors each, although the two middle distributors have been removed. These clearly demonstrate the method in

Fig. 3—Relay and Distributor Cabinets

which a distributor is connected to the cabinet. It illustrates also the ease with which a distributor may be taken out for inspection or repair. A later type of relay distributor is shown in Figs. 4 and 5.

One or more distributors are located in each power station or substation, depending on the number of switches involved. Each pair of distributors is tuned

Fig. 4—Improved Relay and Distributor Panel, Front View

to run at exactly the same speed. They are connected by leased telephone wires, so that an indication of a switch movement on the station or substation indicator is communicated to the distributor in the load dis-

patcher's office and in turn to the lamps on the pilot board. Some 300 mi. of leased telephone lines are used for switch indicating purposes.

A general view of the front of the load dispatcher's board is shown in Fig. 6, and a rear view in Fig. 7. The board is constructed of ebony asbestos panels, 42 in. by 51 in. by ¾ in., with a dull, lacquered finish. In order that changes and future installations may require only that receptacles be mounted and wired and the designations painted on the front of the board, the panels were so drilled that any arrangement of lights could be obtained without further drilling.

As shown, the panels are mounted two high, making the present size of the board 31 ft. long and 8 ft. 6 in. high. It is supported on a steel base and wood sill, raising the base of the panel 18 in. from the floor.

Fig. 5—Improved Relay and Distribution Panel, Rear View

This was necessary in order that the view of the bottom rows of lamps might not be obstructed by the special two-position, low-back telephone switchboards. Future extensions of the board will be in the nature of semicircular wings on each end, so that the ultimate size of the board can be 42 ft. long.

As shown in Fig. 6, the room is arranged for four load dispatchers and one chief load dispatcher; the chief load dispatcher's desk is shown in the foreground. The control key switches for the white "acknowledgment" lights and the manually-operated indications are in black shallow cabinets alongside the dispatchers' desks. Fig. 7 shows the rear of the load dispatcher's board. The terminal racks at the right are for making cross-connections between the cables going to the control key cabinets just mentioned and the groups of lamps. Strips of black paper have been pasted over the unused positions on the board, so that any light which may be behind the board will not mar the appearance or affect the visibility of the lamp indications.

The Public Service Electric and Gas Company

Fig. 6—Load Dispatcher's Pilot Board, Front View

supplies the more populous sections of the State of New Jersey with electric light and power. That portion of the state served from the New York State line on the east to the Delaware River below Camden on the west is outlined on the map of the State of New Jersey, in Fig. 8. The territory is 110 mi. long and covers an area approximately of 1700 sq. mi. as compared with

Fig. 7—Load Dispatchers' Pilot Board, Rear View

8224 sq. mi. in the state. This area includes about 88 per cent of the population of the state, which exceeds 3,500,000; electric meters, December 31, 1929, numbered 886,797. The portion of the territory directly

supervised and operated from the Newark Terminal load dispatchers' office is shown in the clear area. The stations and substations which have automatic indication on the load dispatchers' board are located within or adjacent to the City of Newark. Indications from the other stations and substations are controlled by manually operated miniature switches manipulated

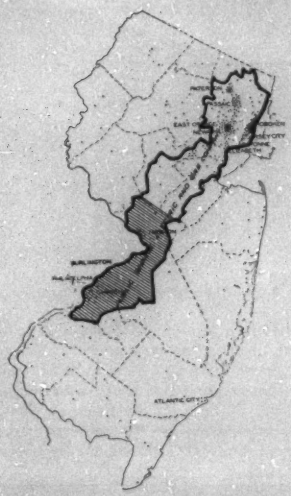

FIG. 8—MAP OF NEW JERSEY SHOWING THE TERRITORY OF THE ELECTRIC AND GAS COMPANY. THE UNSHADED PORTION IS OPERATED BY NEWARK LOAD DISPATCHING OFFICE

by the load dispatchers from information obtained by telephone. The territory indicated by the shaded area on the map is known as the "Southern Zone," and has no automatic indication equipment installed.

The entire Public Service territory is supervised from the Newark load dispatching center, although the southern area, or shaded portion of the map, is operated directly from a load dispatching office at Burlington.

In the entire system, there are 131 Public Service and industrial substations, nine switching stations, and five generating stations. Of this number, the Newark Load Dispatcher has direct supervision over and operates 87 substations, eight switching stations, and four generating stations, leaving 44 substations, one switching station, and one generating station in the Southern Zone.

Associated with the load dispatcher's board, and using the same equipment, supervisory control apparatus has been installed in an adjoining room to obtain complete remote supervisory control of six automatically operated unattended substations. In these six remote controlled substations, we combine the supervisory indications for load dispatching purposes with the supervisory remote control of the automatic substations.

The following table shows the number of automatic indications on the load dispatcher's board.

| Station or substation | No. of indications on L. D. B. | 26,400 or 13200 v. O.C.B's. | 4150 v. a-c. three-phase circuits | 600-volt d-c. circuits | Rotating machines |
|---|---|---|---|---|---|
| *1 Essex | 209 | | | | |
| 2 Hudson | 46 | | | | |
| *3 Marion | 174 | | | | |
| *4 Kearny | 100 | | | | |
| 5 Miller St. | 8 | 8 | 18 | 10 | 2 |
| 6 Norfolk St. | 7 | 7 | 20 | 9 | 2‡ |
| 7 Clay St. | 6 | 6 | 14 | | |
| 8 Montclair | 5 | 5 | 15 | 4 | 2‡ |
| 9 Bloomfield | 7 | 7 | 12 | | |
| 10 Race St. | | | | 2 | 1 |
| 11 Lakeside Ave. | 6 | | | | |
| 12 Washington Ave. | 7 | | | | |
| 13 Central Ave. | 6 | | | | |
| 14 Irvington | 11 | | | | |
| 15 Waverly | 6 | | | | |
| 16 City Dock | 29 | | | | |
| 17 Harrison | 9 | | | | |
| 18 Elizabeth | 11 | | | | |
| 19 Bayway | 11 | | | | |
| 20 Plank Road | 5 | | | | |
| †21 Federal Ship | 2 | | | | |
| †22 Crucible Steel | 3 | | | | |
| †23 Submarine Boat | 2 | | | | |
| 24 Athenia | 81 | | | | |
| | 751 | 33 | 79 | 25 | 7 |

Notes

*Generating stations—Others are substations.

†No. distributors used—Indications by direct leased wires.

‡Also two steps of field control on each motor-generator set.

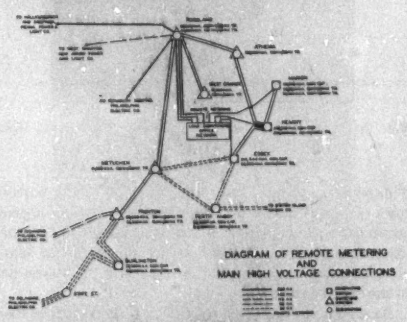


FIG. 9—DIAGRAM SHOWING INTERCONNECTIONS WITH OTHER COMPANIES AND REMOTE METERING SCHEME

In addition to the indication board, there is certain accessory equipment to aid the load dispatcher in keeping informed at all times of the status of the system. This includes an automatic radio clock, for receiving the Arlington time signals, a master frequency clock, a graphic frequency recorder, and graphic wattmeters of the generating stations. The frequency recorder has a

scale which can be read easily to five one-hundredths of a cycle. Three of the recording wattmeters indicate, by means of remote metering, the kw. load on the generators of the three stations, Essex, Marion, and Kearny, and the fourth is a totalizing wattmeter which gives the total of the three station wattmeters. Additional space is provided for instruments of this type as future need for them may arise. Some of the future requirements along these lines are instruments to record and indicate by means of remote metering the interconnected loads supplied or purchased from other companies. Fig. 9 shows the scheme of remote metering which will record the interconnections about to go in service.

Apparatus for recording telephone conversations to and from the load dispatchers' office is installed, enabling the operators to record the actual conversations which take place.

Perhaps the most important factor in the operation of any system is the ability to maintain perfect and continuous telephone communication between the load dispatcher and every station and substation operator. To provide this, a private telephone system is maintained over leased wires having no connection with any other public service telephone exchange. By means of this system, the load dispatcher is able to keep in close touch with the entire operating personnel. Throughout the state, there are some 850 mi. of telephone wires for this purpose, all leased from the local telephone company.

To back up the private telephone wires, each station and substation has a second wire through the local public service exchange to be used in case the private wire fails. In times of emergency, the load dispatcher's calls take precedence over any other calls on these wires.

The load dispatcher's duties make it imperative that he be thoroughly informed on every condition in every part of the system. A complete set of maps and records is kept showing the routes, lengths and sizes of transmission lines and cables, and the capacity of all generating and substation apparatus.

It is difficult to estimate the value of a load dispatching system or the value of one type of load dispatching equipment over another; these, we believe, are matters of local importance and must be judged by the individual utility which may wish to employ the several methods. No doubt load dispatching can be, and is, handled with simple as well as elaborate equipment,—a matter of opinion. Our experience in using the simplest as compared with the elaborate leads us to believe that the automatic indicating equipment, backed up with accessory apparatus, gives the best results as regards safety, service, and economical handling of station load.

After an experience of three years with the automatic indication system, we have not changed our opinion.

With the completion of the 132-kv. transmission system and the existing and approaching interconnections with other companies, the advantage of centralized control of system operation to this company has become more apparent.

The 132-kv. transmission system has made it possible to schedule the loading of generating stations so as to obtain operating economy. These load schedules would be almost impossible to follow effectively if the system were not controlled at a central point.

At the end of the current year, 1930, this company will be interconnected with three other companies, and there will be operating agreements with each, governing the interchange of power. This interchange will fall into several classes and each class will be regulated by different conditions and restrictions. It is evident that centralized control will be required to procure reliable action, to take advantage of effecting economies, and to avoid penalties which might result from the lack of coordination.

During 1929, the load dispatchers issued a total of 238,986 operating orders in connection with switching changes; and of this total, only one operating mistake resulting in interruption to service is chargeable to the load dispatcher. This one interruption occurred at a time which caused no inconvenience to the customer; in fact, it was not noticed or reported. We feel justified therefore in having incurred the cost of installing and maintaining the automatic indicating system.

The author wishes to acknowledge the help in preparing this paper given by H. W. Codding, Public Service Production Company, who designed and constructed the load dispatchers' board, and W. C. Mangels, System Operator, Public Service Electric and Gas Company, both members of the Institute.

## Discussion

**C. A. Mayo:** It seems to me that the subject of supervisory control has many applications and is becoming more popular every day. The rapid increase in substations and the daily growth of interconnections demand something of this nature to automatically centralize the control of such a system.

I would like to describe our own system which in some respects is similar to the system of the Public Service Electric and Gas Co. of New Jersey. Our system is not as expansive since we have five substations located within a radius of less than five miles of our Malden station, which is our operating center. These substations are supplying light and power to a population of approximately 250,000. Being located within five miles of Boston it is chiefly a residential area.

These substations are all automatically operated and unattended. Each has an ultimate capacity of 10,000 kv-a. By means of our supervisory system we have control and continuous indication of some 100 switches on high- and low-tension circuits also both a-c. and d-c. street circuits.

There is another feature in which we differ from the New Jersey installation and that is that we are leasing no wires from the telephone company, but have our own control cables installed. These cables are the standard 16-pair, 32-conductor paper-insulated lead-covered, as used by the telephone company.

**H. W. Codding:** Mr. Lawson has reviewed the history and development of the load dispatching system, including methods and equipment, as used by the Public Service Electric and Gas

Company of New Jersey. He has shown the development of the system from a small beginning to its present elaborate layout and has given the reasons for each step of the development.

There is a big step between the system at the time of the first 13-kv. lines and the present 132-kv. and 220-kv. transmission lines. The 13-kv. lines, now largely replaced by 26-kv. lines, which were considered such a great advance at the time of their first construction, are now coming to be looked upon as hardly more than distribution feeders. While at the present time the load dispatcher is still concerned with the 26-kv. lines, as well as the 132-kv. and higher voltage circuits, there is reason to believe that in a not distant future, the operator of each generating station or switching center will have the responsibility of keeping his 26-kv. lines energized in the same way as the substation operators at present are expected to keep their 4000-volt a-c. feeders or 600-volt d-c. feeders energized. When this time comes, the load dispatcher will become more of a supervising official who will concern himself more with matters of load control than that of supervising the switching of lines and transformers. One result should be a saving in time in case of outages of 26-kv. lines, in that the substation operator will be able to reclose such lines without waiting for instructions from a central load dispatcher. At times when a large number of lines is out due to lightning or other causes, delays of several minutes must necessarily occur where several substations are affected, due to the impossibility of the load dispatcher receiving reports of outages and issuing necessary orders to have the lines affected energized. While it is always somewhat dangerous to make predictions concerning future events, yet the changes that have already been made in load dispatching methods indicate that some such method of operation is likely to be the next step.

In order that the load dispatcher may have an accurate record of the system, some type of load dispatcher's board such as described in Mr. Lawson's paper, together with the necessary automatic equipment required to secure proper indications, is necessary. Since the use of this equipment enables the load dispatcher to have before him an accurate record of the system, which is correct at all times, the cost of installation and the operating cost are justified under the present conditions. However, with the growth of the system into a number of groups of substations, each fed from a suitable switching center, the transmission network would become considerably simplified and the cost of the load dispatcher's board and its leased telephone wires might be eliminated, or, certainly, considerably reduced without sacrificing any of its helpful features.

**C. Lichtenberg:** Centralized control became a recognized requirement of successful system operation as soon as electricity supply was furnished from two or more stations. The first step was to install a system operator, load dispatcher, or power director at some central location. He was then provided with telephone and telegraph communication with the other stations and substations. Later he was provided with system diagrams of one form or another in order to permit him readily to record changes in the system arrangement and to issue orders for system operation. Still later, means were provided to record automatically system arrangement on a system or similar diagram board. This indicated, first manually, then automatically, the position of switches and circuit breakers at all times.

One type of such an automatic supervisory indicating and control system is described by Mr. Lawson. He gives a very interesting record of its performance and some refreshing comments in connection therewith. His "experience in using the simplest as compared with the elaborate leads us to believe that the automatic indicating equipment, backed up with accessory apparatus, gives the best results as regards the safety, service, and economical handling of station load" is a typical response from an operating engineer of one of the large companies. It shows quite clearly that automatic supervisory control and indicating equipment has reached such a stage of development as to warrant its application wherever feasible to improve system operation and performance.

The broadening application of automatic supervisory control and indicating equipment will depend upon the results of development and the product of the manufacturers as well as the application and plans of the operating companies. The principles of the automatic supervisory control and indicating systems are sound. Several well tried ones are now available and they possess many desirable features. A full knowledge however of these features together with the operating requirements of an electricity supply system is necessary in order to permit successful application. Where this is done, more economical operation and better continuity of service results.

**D. W. Proebstel:** The centralizing of load dispatching operations is without doubt an economic thing to do where systems are made up of several important interconnected divisions. The automatic indication in the dispatcher's office of the switching operations is however a refinement, the value of which depends upon the switching complexity and the number of switching operations.

It is often the thought of those who select a location for the load dispatcher's office that it should be in the main office building "as close to the records and operating departments facilities as possible." This in many cases is a mistake. The operating department together with the load dispatchers's office should be placed at a point within the system where their functions and where automatic features of control and indication of switching operations can be attained in the simplest and most effective way.

The author stated that no indication was provided for disconnecting switches. This brings up the subject of safety to construction or repair men who might have work to do on a circuit. No circuit is safe unless the line disconnecting switches are open. Therefore, the load dispatcher, in giving clearance of a line to a workman, can only pass along the word of the station operator that a certain line has been cleared. From this view point the automatic indication of the oil circuit breakers provides the load dispatchers with only a portion of the necessary information. That portion of information is no doubt very desirable for other reasons than clearing a line for repairs. Assuming that there are no operators where supervisory control is used, it would seem that personal inspection of the switching apparatus would be necessary before permitting work on a circuit.

The experience that the Public Service Electric and Gas Co. has had with this system during the past three years has proved its worth because it has without doubt been a great factor in maintaining a high standard of service.

# Automatic Power Supply for Steel Mill Electrification

BY ROBERT J. HARRY[1]

Non-Member

*Synopsis.—In the production of steel, the use of electrical energy is growing rapidly. This paper outlines the present operating conditions in the Monongahela Valley System of the Carnegie Steel Company. The use of automatic switching for certain portions of this power supply has proved both economical and satisfactory.*

* * * * *

WE read and hear so much these days of the extensive electrification programs of the public utilities that (electrically speaking) we are apt to overlook what is going on inside the fences which surround the modern steel mill. The utilization of the by-products incidental to the manufacture of steel, such as gas from the blast furnaces, coke dust, tar, etc., provide a source for the generation of electricity more than sufficient to meet the demands of the steel manufacturers. In most plants, all of the available sources of heat have not been utilized, owing to the fact that the demand is not so great as the supply. With the increasing demand for power, we shall see all of the available sources used and waste heat boilers will be installed wherever any hot gases are found to be passing out to the surrounding atmosphere without giving up their precious B. t. u's.

During the past few years we have seen electric drives replacing steam drives, both for main rolls and auxiliaries, so that we find many instances where a quarter of a million motor horsepower is installed in a single steel plant.

In the next few years, we shall see electricity employed in a new field which will require every available kilowatt that can be produced. The author refers to heating steel by electricity. Statistics show that this method of heating is cheaper when done under the proper conditions. It is the purpose of this paper to discuss the power system which supplies the five large U.S. Steel Corporation Steel plants in the Monongahela Valley about 10 mi. above Pittsburgh. These plants are Homestead Steel Works, Edgar Thompson Steel Works, Duquesne Steel Works, National Tube Company, and the Clairton Works.

Until about a year ago, only Homestead, Edgar Thompson, Duquesne, and National Tube Company were electrically connected. This connection consisted of a pair of 500,000-cir. mil circuits at 6.6 kv. Due to the great distances between plants, the transmission for this voltage was not very efficient, and as a result, it was impossible to transmit the required amounts of power without an abnormal voltage drop. The ability to help out an adjacent plant in case of power shortage, as well as the much better load factor that could be obtained by operating with all plants tied together, presented an economic advantage; therefore about three years ago it was decided to rebuild the system and extend it so as to include the Clairton works.

On account of this tie line operating in an industrial section where conditions are not favorable for insulation, it was some time before an operating voltage was decided upon. At first it was recommended that 22 kv. be adopted, but finally it was decided to use 44 kv. With this voltage efficient transmission can be obtained for even greater distances than at present encountered. While higher voltages were considered, it was agreed that 44 kv. was as high as could be operated with any guarantee of continuous service. The successful operation of this line leads us to the conclusion that higher voltages could be successfully employed.

Two circuits were installed, and in order to secure continuity of service under the worst conditions, it was decided to use No. 0000 copper. This enables either line to transmit at high efficiency the capacity of the largest unit on the system, which is 15,000-kw. This contingency could arise at three of the plants where 15,000-kw. units are installed. The transmission system could therefore meet this condition with one circuit out of commission.

In order to obviate the necessity of frequent periodic cleaning of line insulators, it was decided to over-insulate the line and, by means of arcing horns, reduce the flashover to ground, thereby bringing the voltage stresses on the line to a point well below the flashover value of the equipment in the substations. The line insulator units consisted of five suspension insulators whose combined rating is as follows: dry arc over without horn-gaps, 338-kv.; wet flashover, 170-kv.; dry flashover with horns, 175-kv.; wet flashover with horns, 175-kv. This compares with the manufacturers' recommendation for 44-kv. service of three units in series. It was thought that the above combination, would operate indefinitely without cleaning insulators. In some locations, however, the dirt conditions are so bad that occasional cleaning of insulators had been resorted to, and necessitated the installation of sectionalizing line switches to facilitate this procedure.

Fig. 1 shows the 44-kv. transmission system as it is at

1. Of the Alliance Machine Company, Alliance, Ohio. Formerly with the Carnegie Steel Company

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

present, and gives the distances between substations. When the two circuits are in commission, the system is always operated with the knife switches, which connect up the two 44-kv. lines on the high-voltage side of the transformer bank, in the open position. These switches are installed for emergency and single-line operation.

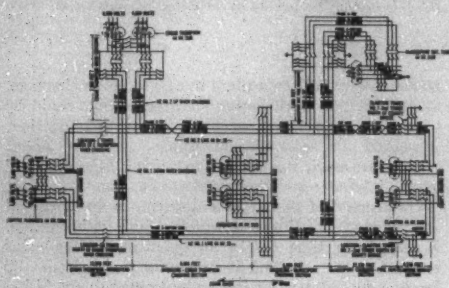

Fig. 1—44-Kv. Transmission System of the Monongahela Valley—Carnegie Steel Company

Many schemes of relaying were proposed, but none seemed to meet all of the conditions that might reasonably be expected to occur, better than did straight overcurrent and ground relays. Results of these operating experiences of more than eighteen months have been all that could be expected, and the reliability of the line has been established. In the construction of this line it was necessary to cross the Monongahela River at three points, the longest span, 2300 ft., occurring where the lines from the Edgar Thompson Works crosses the river to tie in with the line connecting Homestead and Duquesne.

The neutral on the 44-kv. side of the transformers is solidly grounded at all substations. The five substations are equipped with a total of nine 9000-kv-a., three-phase, Y-delta transformers. Two of these transformers are located at Homestead, two at Edgar Thompson, two at Duquesne, two at Clairton, and one at National Tube Company. The transformer capacity at the various plants was determined by the shortage which would be created by the failure of the largest generating unit in the plant. These transformers are equipped with tap-changing devices with conveniently arranged mechanism for changing the three phases simultaneously, and are located close to the floor. An indicating dial is also installed, as well as provision for locking in any tap position. The oil circuit breakers must be open during tap changes. It was not considered necessary to add to the cost of equipment by installing tap-changing equipment which could be operated under load. The high-tension bushings have a normal rating of 73 kv. with a dry flashover value of 240 kv. and wet flashover of 200 kv. The low-tension bushings have a normal rating of 25 kv. with a dry flashover value 100 kv. and wet flashover of 40 kv. All of the transformers are so designed that blowers can be installed to increase the rating, but only at Homestead was this extra equipment actually installed. With the blowers in operation, supplying 5000 cu. ft. of air per min. at three-ounce pressure, and the temperature of the atmosphere 40 deg. cent., a 25 per cent continuous rating above normal, or 11,250 kv-a., is guaranteed. With a larger blower, much greater capacity can be obtained. The blowers were installed on the Homestead transformers to meet the conditions arising from the shut down of one of the 15,000-kw. turbines when load conditions were at a maximum.

Current transformers are installed in the three high-tension bushings and ground bushing of the 9000-kv-a. transformers, and in the low-tension lines for differential protection. Current transformers are also installed in the bushings of the oil circuit breakers for line protection.

In order to satisfy the telephone company engineers, it was necessary to transpose the 44-kv. lines between the Duquesne and Clairton works where the power line paralleled the telephone lines.

Three of the substations are typical outdoor type, while two are indoor type. It has been found that in order to prevent the rapid deterioration of the radiators, it is necessary, where the transformers are located outside near blast furnaces, to resort to frequent painting. This may be a good application for rustless steel.

Before the five plants were connected together, it was necessary to make a study of short circuits in each plant to ascertain the proper size of circuit breakers.

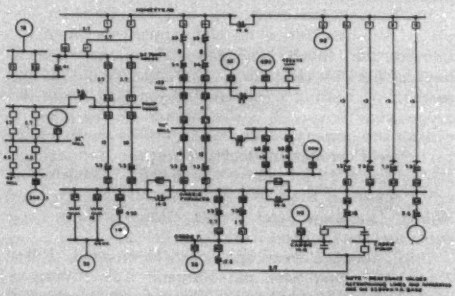

Fig. 2—Single-Line Diagram of Homestead & Carrie Furnace Works of Carnegie Steel Co. 6.6-Kv., 25-Cycle

In some of the plants, radial feeders with proper current limiting reactors are installed, while at other plants loop circuits are employed. In order to reduce the short-circuit values to a point where the circuit breakers could meet the thermal and interrupting capacities, it was necessary at some of the plants to insert reactors in the station bus.

At the Homestead Works, a loop system is in operation. When completed, it will be as shown on Fig. 2. At the Carrie Furnaces, only two turbo generators are installed at present, although provision has been made for a third unit. The oil circuit breakers have sufficient capacity to meet the proposed increase in generating capacity. Reactors having a continuous capacity of 2000 amperes are installed in both front and back busses, and oil circuit breakers installed to short-circuit the reactors when operating conditions require. The

Fig. 3—View of Tower Substation on the Homestead Loop System

size of this equipment permits the transfer of the entire capacity of a 15,000-kw. generator to any part of the bus for distribution either through switch or reactor. Under normal operating conditions, the feeder circuits are so arranged that very little power is transmitted through the bus reactor.

Since continuity of service is of prime importance in the operation of steel mills, adequate protective relay equipment was installed to provide selectivity in case of fault, and at the same time not involve too much complication. Four parallel feeder circuits were installed between the Carrie Furnaces generating station and the New Structural Mills. These circuits are equipped with current balance, back-up overload, and ground relays. Owing to the large amount of synchronous equipment fed from each substation, selective relay action is obtained. The induction type overload relays have a high setting and function in case of bus faults.

Reactors were installed at strategic points in the loop system so that only that portion of the system in which the fault occurs is affected, sufficient voltage being maintained in the other parts of the system to prevent losing the synchronous load. While the above reason would be sufficient to warrant the installation of reactors, their economic value is of considerable importance. The reactors installed in the loop stations between the bus and feeder circuits permit the use of small oil circuit breakers with the same margin of safety that obtains with the use of larger breakers on the other side of the reactor. This can be illustrated by the fact that the loop bus at the d-c. power house is equipped with breakers having an OCO + OCO rating of 36,000 amperes at 6600 volts, while the feeder breakers on the other side of the reactor have a big safety factor with an OCO + OCO rating of 8500 amperes at 6600 volts. When it is considered that there are 22 small feeder breakers installed in this location, the economy made possible by the use of reactors is very apparent. The reactors also prevent the extremely heavy currents with their resultant stresses from getting to the small feeder circuits and equipment connected to them.

The loop circuits are of overhead construction, located on towers, and involving two river crossings. The towers at the loop stations are of special design, and in addition to supporting the lines, have a three-story building with a 30-ft. by 25-ft. floor area located in the bases. Figs. 3, 4, 5, and 6 show views of one of these combination towers and substations. The lightning arresters are outside valve type and are accessible from the roof. The oil circuit breakers (Fig. 6), are located on the third floor, the reactors (Fig. 5) on the second floor, and the ground floor provides sufficient space to house power and lightning transformers.

The oil circuit breakers are of the metal-clad lift type which permits of unit assembly at the manufacturers'

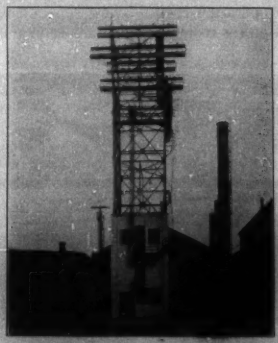

Fig. 4—Another View of Tower Substation on the Homestead Loop System

plant, and provides for easy additions in the field. All substations can easily take care of the distribution of 10,000 kw. which provides for future installation. In the substations, 32-volt storage batteries are installed for tripping the oil circuit breakers and to provide a source of light in case of power failure. Since nothing would be gained by closing the breakers before power was restored, a motor-generator set with automatic switchboard to provide 250 volts direct current for

closing the breakers was installed. This motor-generator set is small, and 250 volts emergency is obtained in a few seconds after the 6600-volt lines are energized.

At the New Structural Mills, an automatic substation is installed. It consists of three 1500-kw. motor-generator sets operating at 500 rev. per min., the motor

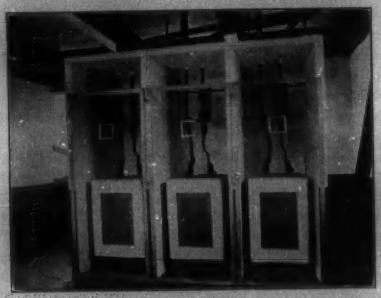

Fig. 5—Views of Tower Substations on the Homestead Loop System

being of the standard synchronous type arranged for compensator starting and the generator being compensated shunt-wound.

The reason for making this substation automatic was to reduce operating costs. These sets, located in the large mill motor room building, are shown in Fig. 7.

Fig. 6—Views of Tower Substations on the Homestead Loop System

The figure shows but two sets, the third set having been added recently. Provision was made in the switchboard shown in Fig. 8 and foundations provided for this contingency. This room, a general view of which is shown in Fig. 10, also contains seven main roll drive motors, with their motor-generator sets and auxiliaries.

The duties of the two men employed in this room require them to spend considerable time in the basement where the air conditioning equipment, fans, truck type oil circuit breakers, etc., are located; and they are therefore unable to spend much time at the motor-generator sets. Because of this, it was considered safer to depend on the automatic features, which are continually on the

Fig. 7—Two 1500-Kw. Motor-Generator Sets in the Homestead Substation

alert and ready at all times to do their assigned duty, rather than upon an operator who may or may not be on the scene when trouble occurs to the equipment.

There were many automatic features which could have been installed, but which were omitted on account of the added cost and complications not warranting their

Fig. 8—Automatic Switchboard for the Control of the Motor-Generator Sets

The third set is now in operation, the control boards replacing the blank panels in the picture

installation, and because two men are always in the building.

The substation is equipped with the following features:

1. Individual, truck-mounted, line-starting and running oil circuit breakers, and starting auto-transformers are provided for each motor-generator set, and one common cell housing for the necessary potential transformers is provided for all sets.

2. The normal d-c. control is taken from a constant source.

3. Push-buttons are used to start all units.

4. After the unit has attained synchronous speed, a three-element regulator balances the generator voltage against line voltage and then connects the generator to the bus. The regulator then operates to maintain constant voltage on the d-c. bus. A load-limiting element regulates the load that can be taken from the generator.

5. The d-c. feeders open only on short circuit and reclose automatically after a suitable time element and the removal of fault.

6. Equipment is installed to protect against:

(a) Single- and reversed-phase starting; (b) a-c. undervoltage; (c) a-c. overload; (d) field failure; (e) wrong polarity; (f) reverse power; (g) overheated motor winding; (h) hot bearings; (i) d-c. and a-c. ground protection; (j) overspeed; (k) d-c. overload; (l) overheated starting compensator; (m) overheated generator windings; (n) undervoltage connection to d-c. bus.

The results obtained from more than four years of operation have been entirely satisfactory and we do not

Fig. 9—Underground Installation of Mill Table Controllers

in any way regret the decision in favor of the automatic equipment. To date, no automatic features have been discontinued and no failures or emergencies have made necessary the installation of additional protective or automatic equipment. While some minor troubles were experienced when the station was first put into service, after all adjustments had been made the reliability of the equipment has met our most optimistic expectations. Some faulty operations of the feeder breakers have occurred where the acceleration currents drawn by large motors approximate short-circuit conditions, and the impulse coils on the feeder circuits find it very difficult to differentiate between these conditions when they have practically the same steep wave front.

One item which must be kept in mind when making installations of this size, is the bracing of the d-c. bus bars. Bus short circuits which occur on feeder circuits close to the substation produce tremendous stresses which will destroy the bus structure unless very rigidly braced to withstand the stresses.

In cases where one station is tied to one or more other substations by suitable tie lines, these tie lines should be equipped with high-speed breakers. These breakers should have a very definite tripping current which will permit sending over these lines all the current the station can in safety put out and provide for normal interchange of power. In case of substation outage, currents of much greater magnitude would be involved,

Fig. 10—General View of Automatic Substation at Homestead

Two of the three present sets with automatic switchboard may be seen in left foreground

and the high-speed breakers would separate the good substations from the faulty one before the standard circuit breakers would have time to function. This equipment would prevent many of the d-c. total outages.

It has been found that, where electric equipment is isolated from the mill equipment and installed in buildings where it can be kept clean, little trouble can be expected. This is true not only of substation and mill motor equipment, but holds equally true for auxiliary equipment. Where possible, mill auxiliary controllers are grouped and installed in houses or in tunnels directly under the equipment. Fig. 9 shows a typical installation of a group of controllers for mill tables. This type of installation provides for easy inspection and maintenance.

The reliability of the equipment entering into the construction of the modern automatic substation, and the greater protection obtained from the use of modern relays which possess almost human intelligence and indefatigable alertness, will result in the installation of a greater number of these equipments in the steel plants.

## Discussion

**C. Lichtenberg:** The title of Mr. Harry's paper is a most fitting one. It is indicative of the present day trend toward automatizing. It describes the application of automatic switchgear to an important steel mill where continuity of electricity power supply is measured directly in terms of production cost.

One item is of particular interest. It is the mention of some faulty operations of the feeder equipment which occurred when the acceleration current drawn by large motors approximated short-circuit conditions. This may have been due to inherent limitations in the design or in the application.

Discrimination between normal and abnormal current rushes is exceedingly difficult when the impulse ratios approach each other. However, the development of the art is producing solutions which meet the requirements indicated by Mr. Harry.

The testimony, "Results obtained from more than four years of operation have been entirely satisfactory, and we do not in any way regret the decision in favor of the automatic equipment," is very encouraging. Operating engineers the world over are turning to automatic switchgear to solve the service continuity problem. They are finding that electrical devices which operate in response to circuit conditions are inherently very much more prompt, and in general more reliable than humans. Of course, this is not just accidental. It is the result of close cooperation and collaboration of the manufacturers and the operators during the past 15 years. In this period they have spent much time, money and energy, as well as inventive talent toward making automatic switchgear simpler and more reliable, at the same time keeping the cost within limits, so as to make "automatics" more economical than the conventional equipment.

**R. J. Harry:** Mr. Lichtenberg states that relays are now being developed having greater discriminating characteristics than those formerly used. This will undoubtedly result in fewer faulty operations and also bring this type of equipment more into favor. Automatic equipment has already reached such perfection that it is much more reliable than human attendants and few substations are being installed at present that do not contain some automatic features.

As automatic switch gears become more simplified and consequently more reliable, it will undoubtedly, to an increasing extent, crowd out the non-automatic type.

# 1000 Kw. Automatic Mercury Arc Rectifier Substation

## of the Union Railway Company of New York

BY W. E. GUTZWILLER[1] and O. NAEF[1]

Non-member Associate, A. I. E. E.

*Synopsis.—A 1000-kw., 625-volt automatic mercury arc rectifier substation, installed by the Union Railway Co., of New York, in May, 1929, is described in general in this paper together with the account of the automatic and remote control features of the substations. The principle reasons for the adoption of the mercury arc rectifier are mentioned and operating and performance data for the first ten months' operation are presented.*

* * * * *

### Introduction

In May, 1929, the Union Railway Company of New York put their first automatic rectifier substation in operation. This substation contains a 1000-kw., 625-volt rectifier set, which is supplied by 13,200-volt, three-phase, 60-cycle current. Its control is a combination of automatic load responsive and remote control. Provision is made for operation of the set on either 25- or 60-cycle.

The installation is noteworthy, inasmuch as full benefit has been derived from the many advantages the mercury arc rectifier has over rotating converters. Such advantages are adaptability to automatic and remote control, operation on two frequencies, small weight and space, and absence of special foundations,—all resulting in low installation costs.

A description of this installation is given herein, with particular reference to automatic control.

### Deciding Factors in the Choice of Automatic Rectifier

The 1000-kw. automatic rectifier substation in question supplies power to the street-car system of the Westchester Square Section, Bronx, N. Y. Previous to the installation of this rectifier, the d-c. power for this section was supplied from the Union Railway Company's substation at West Farms, located approximately three miles from Westchester Square. This substation is manually operated and contains 5000 kw. in 25-cycle rotary converters.

Due to a steadily increasing load in the Westchester Square Section, these converters, which are over 15 years old, could not for much longer handle the increased demand from this section, so that the railway company decided to install additional converting capacity. It was estimated that at least 1000 kw. of additional machine capacity was needed to take care of the present and future power requirements in this section. In order to reduce feeder losses to a minimum, it was decided to place the new converting equipment in the Bronx Gas & Electric Co.'s transformer substation at St. Peters and Westchester Avenues. This substation is located right in the center of the Westchester Square Section, where additional power was required. The new unit was to be equipped with full automatic control and provided for remote operation and indication from the railway company's station at West Farms.

For this new substation, both rotary converters and mercury arc rectifier were considered, but after a careful investigation the choice fell in favor of the rectifier. The principal reasons for the Union Railway Company's choice of a mercury arc rectifier were as follows:

A 1000-kw. rectifier set could easily be installed in an available corner space in the above mentioned substation, while considerably less rotary converter capacity could have been accommodated in the same space.

While all the converting equipment of the Union Railway is of the 25-cycle type, 60-cycle converting apparatus had to be provided for this new substation, as only 60-cycle power was then available. Inasmuch as it was questionable, however, whether 25- or 60-cycle equipment would be used to greater advantage at some future time, it was highly desirable to provide the new converting equipment for operation on 25- and 60-cycle. Here again the mercury arc rectifier proved to be the ideal apparatus, since it is not affected by the frequency of the supply system. The rectifier transformer, of course, had to be designed for operation on both frequencies.

Since the space in the substation had to be rented from the power company, and also in view of the expiration of the power contract, it was desirable to install the new equipment at a minimum cost. In this respect the mercury arc rectifier also met all requirements, as it needs no special foundation; it could be set on the existing substation floor without any reinforcement. The rectifier required no ventilating ducts nor openings in the walls or roof for ventilation, (such as is the case with a rotary converter), as practically all its losses are carried away by water.

Due to the stationary character of a rectifier, automatic and remote control is very simple and the costs of the control apparatus are low. Due to the simplicity of the control, only very few conduits for control wiring

1. Both of American Brown Boveri Co., Inc.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

had to be provided. The conduits, as well as all the low-voltage power cables, could be installed over head, thus obviating any changes whatsoever in the building structure. Remote control from West Farms Substation, approximately three miles away, could easily be provided without much extra expense. Only eight control wires were required for remote control and

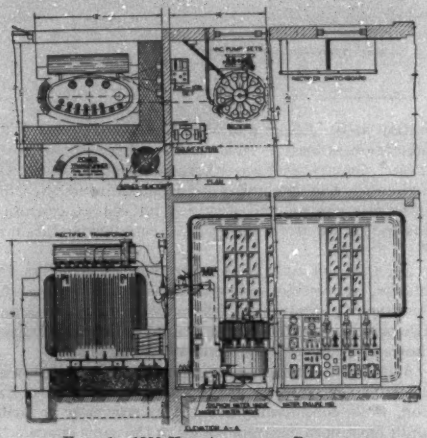


Fig. 1—1000-Kw. Automatic Rectifier

indication. From Fig. 1 showing the substation layout, it can readily be seen that the rectifier apparatus fully utilizes the available space, yet sufficient clearance exists between the apparatus for inspection.

## Description of the Equipment

The 1000-kw. automatic rectifier plant consists of one 1000-kw. nominally rated rectifier unit. Energy is taken either from the 13,200 volts, three-phase, 60-cycle station main bus or from the station auxiliary bus and converted to 625 volts, d-c. The rectifier and its transformer are capable of carrying the following loads, based on the nominal rating of 1000 kw. at 625 volts, at 25 or 60 cycles:

| Load in percentage | Ampere | Duration |
|---|---|---|
| 100 | 1600 | Continuously |
| 150 | 2400 | 2 hours |
| 200 | 3200 | 1 minute |

All apparatus pertaining to the rectifier plant, including automatic and remote control apparatus, cables, bushings and busbar material were furnished and installed by the American Brown Boveri Co., Inc., with the exception of the two 13,200-volt oil circuit breakers. These breakers were already available in the substation.

Since mercury arc rectifiers and their standard auxiliary apparatus of similar types have been described before, this apparatus shall be mentioned in the following only in a general way.

The rectifier cylinder is of the 12-anode type and is cooled by fresh water. The anodes are water cooled. Fig. 2 shows the rectifier cylinder. As the rectifier tank when in operation is under d-c. potential, it has been surrounded by a protective screen.

The rectifier receives energy from an oil insulated, self-cooled, tubular type outdoor transformer. The transformer is provided on the primary side with one plus and one minus 3½ per cent full-capacity tap and ratio adjuster for no-load operation. The secondary is connected in double six-phase star. Due to space limitation, the interphase transformer which usually is built into a separate tank, has, in this case, been built directly into the rectifier transformer. The transformer is designed for operation on either 25- or 60-cycle, 13,200-volt, three-phase current. At 60-cycles, the transformer has an impedance of 4.5 per cent. When operated on 25-cycle, it is necessary to connect an external reactance of 3 per cent in series, in order to protect the transformer. Fig. 3 shows the rectifier transformer from the low-voltage side, completely assembled. On account of the 25-cycle rating and the built-in interphase transformer the over-all dimensions of this transformer are somewhat abnormal.

The pumping equipment for exhausting the air from

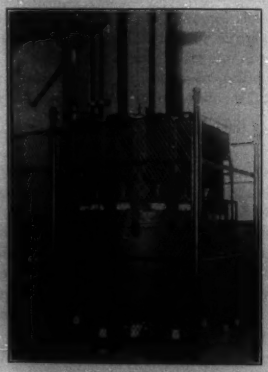

Fig. 2—1000-Kw. 625-Volt Mercury Arc Rectifier

the rectifier cylinder consists of a water-cooled mercury vapor pump, connected in series with a motor-driven rotary oil pump, all mounted on a common frame.

The ignition and excitation apparatus is mounted on a common angle iron frame and operated from a single-phase and low-voltage auxiliary supply.

The vacuum measuring device, as well as all the automatic control apparatus, are operated from the same a-c. supply. The power for the rectifier auxiliaries is taken from a 220-volt, 60-cycle, two-phase, three-wire circuit, which is separately metered.

On the d-c. end, the rectifier is connected to the bus through a single-pole, 3000-ampere solenoid-operated breaker, with overload and reverse current trip.

Two 2000 ampere automatic reclosing feeder breakers connect the rectifier bus with the load.

The rectifier switchboard consists of five 24-in by 90-in. slate panels. Fig. 4 shows the rectifier switchboard. Starting from the left hand side, the first

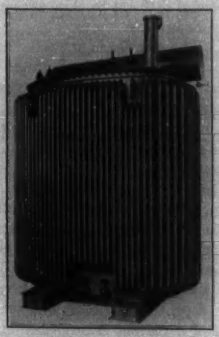

Fig. 3—1000-Kw. 13,200-Volt, Three-Phase, 2 x 6 Phase 25/60-Cycle Rectifier Transformer

panel contains the apparatus for automatic starting and stopping of the rectifier set. The second panel contains the rectifier indicating instruments, the vacuum measuring device, drop annunciators, receptacles, and plugs

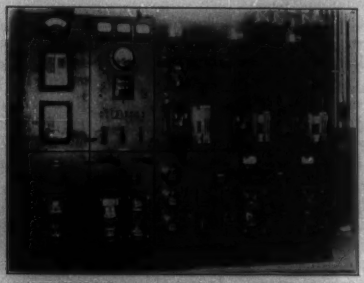

Fig. 4—Rectifier Switchboard of 1000-Kw. Automatic Substation

for various methods of control, control switches for rectifier auxiliaries and circuit breakers; also, the automatic control apparatus for the vacuum pump set. The third panel contains the rectifier d-c. breaker and knife switch, breaker-control relay, and induction type overload relays. The fifth and sixth panels each contain a feeder breaker with knife switch, ammeter, and automatic feeder reclosing apparatus.

For overvoltage protection between anodes, each secondary phase of the rectifier transformer is connected through a damping resistance to a horn-gap arrester. The other side of each arrester is connected to the common neutral of the transformer.

The rectifier set is provided with a filter equipment designed for the purpose of suppressing the ripple in the d-c. output of the rectifier to a point where it will not cause objectionable interference with telephone circuits. The equipment consists of a series reactor connected in the negative lead of the rectifier and three shunt filters, tuned for 360, 720, and 1080 cycles, which are the most disturbing frequencies for communication circuits. The series reactor offers a high impedance to the alternating currents of above mentioned frequencies and limits them to such values as can be

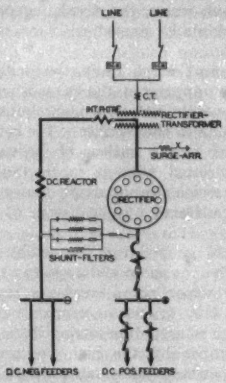


Fig. 5—1000-Kw. Automatic Rectifier

economically taken care of in the shunt filter. Each shunt filter is a resonant branch for one of the above mentioned frequencies and therefore provides a short-circuit path for the particular frequency for which it is tuned. The series reactor is located outdoors while the shunt filter with necessary fuses and knife switches mounted on a pipe frame, are located indoors within the enclosing screen of the rectifier.

Fig. 5 shows the single-line diagram of the rectifier plant.

## Description of Automatic and Remote Control

Since the automatic control of this rectifier plant is typical for a railway substation of this type, a more detailed description of the control is given hereafter: The following paragraphs will describe not only the method of control actually in use in this substation, but also the method which would be employed should one or more units be added to the present installation. In addition, certain features which are not being utilized

now, but are available and may be of importance in the future are described.

The following description of the automatic controls will be divided into five groups; namely, control of auxiliaries, control of the rectifier, plant or master controls, a-c. feeder control and d-c. feeder control. The remote control, being a particular feature of this substation, is dealt with in a separate paragraph.

*I. Control of Auxiliaries.*

The auxiliaries of a mercury arc rectifier consist of the excitation-ignition set, the cooling equipment, and the vacuum pump set. The excitation-ignition set is energized by the closing of the a-c. breaker and maintains the excitation arc so long as the a-c. breaker is closed. In the same way, the magnet water valve controlling the rectifier cooling water is opened by the closing of the a-c. breaker. Where recooling is used instead of fresh water, the circulating pump and fan motors are similarly started with some modification in the control.

*Vacuum Pump Control.* Unlike the excitation-ignition set and cooling apparatus, the vacuum pump operates independently of the rest of the plant, but so as to maintain the vacuum in the rectifier. The contact-making vacuum meter is the nucleus of the vacuum pump control. Associated with it is the vacuum pump control relay, which also takes care of several protective functions necesitated by the nature of the vacuum pump set.

The gases are pumped from the rectifier in two stages by a mercury vapor pump and a rotary vacuum pump. The mercury vapor pump creates a high degree of vacuum, but only against a comparatively low back pressure. The rotary pump carries off the gases drawn from the rectifier by the high vacuum pump. A reservoir and an automatic valve are placed between the two stages so that continuous operation of the rotary pump is unnecessary. On the other hand, the high vacuum pump must operate continuously.

Since the vacuum attained by the rotary pump is insufficient for safe rectifier operation, this pump must never be permitted to operate alone. Therefore, should the high vacuum pump fail for any reason, such as failure of auxiliary power or water failure,—the mercury vapor pump requires a continuous flow of cooling water while in operation—both pumps are shut down. When the trouble is cleared, normal operation is automatically resumed after a preliminary heating of the high vacuum pump lasting approximately a quarter of an hour. The reason for this time delay is that the mercury vapor pump cannot produce a sufficient vacuum before it reaches the proper temperature.

*II. Control of the Rectifier.*

The control of the rectifier means the actual starting and stopping of the rectifier. In starting, the oil circuit breaker is closed first, energizing simultaneously the ignition-excitation and the rectifier cooling water valve. The d-c. breaker closes last, whereupon the rectifier immediately takes its share of load. The starting requires one to two seconds. In stopping, the oil circuit breaker opens first, tripping the d-c. breaker and stopping the excitation and the water at the same time.

*A-C. Closing and Reclosing.* The oil circuit breaker is controlled by the a-c. closing and reclosing relay, which makes three attempts to close the breaker, either on initial starting or after opening on overload. The third unsuccessful attempt to close automatically locks out the oil circuit breaker.

*Protection.* The rectifier is protected against sudden or continuous overloads, reverse current due to backfire, operation with poor vacuum, excessive temperature, and cooling water failure.

Induction overload relays provide short-circuit protection, while a thermal overload relay takes the rectifier out on continuous overload for the length of time required to restore normal temperature.

When a backfire occurs while the rectifier is paralleled with other machines, the reverse current trips the d-c. breaker, which in turns opens the oil circuit breaker through a special high-speed interlock. This interlock is extremely simple and effective. A current transformer trip coil on the oil circuit breaker is connected in the circuit of a current transformer in the primary of the rectifier transformer. When the d-c. breaker is closed, this trip coil is short-circuited by a contact on the d-c. breaker. When the d-c. breaker is tripped by backfire this short-circuit is removed and the current transformer trip coil will trip the oil circuit breaker. The interlock and tripping do not depend on auxiliary or control bus voltage and therefore attain the highest dependability.

The rectifier is locked out when the vacuum pump is unable to maintain proper vacuum, which indicates a leak in the rectifier or trouble in the pump. Lockout also occurs in case of excessive temperature in the rectifier cylinder, if beyond the control of the overload protective devices. Lockout can only be reset manually. Water failure merely trips the d-c. breaker after an interval of about one minute and holds it open until the flow is restored.

*III. Plant Control.*

The plant control includes all devices and circuits which are used to stop and start the plant. The plant control in this substation, consists of load responsive and remote control. In case of load responsive control, either low voltage on the bus or the occurrence of low current will start the time-delay, start-and-stop relay. If these conditions persist over a period adjustable up to 60 sec. in case of low voltage, and 15 min. in case of low current, this relay will give the start or stop signal to the a-c. closing and reclosing relay. Instead of, or in addition to the load responsive control, a time switch may be provided.

Where there are two or more units in a station, one unit is generally controlled by the master elements

(*i. e.*, load responsive control, remote control, clock or manual control) while the others are switched in or out according to the load on the first unit. These units are then designated as leading and lagging units respectively. Should the leading unit be locked out, the signals from the master elements are automatically transferred to a lagging or reserve unit. This method of control is known as the "transfer-lockout" control. Any one, or a combination of the master controls may therefore be used, and can be obtained by the manipulation of a selector switch. Any unit may be made a leading, lagging, or reserve unit by means of the selector switch.

*Remote Control.* In this installation, the plant can be controlled by the supervisor at West Farms Substation. He has continuous indication of the positions of all breakers and can, at will, assume control or relinquish it to the master controls in the station, without the necessity of having someone change the position of the selector switch.

*IV. A-C. Feeders.*

The station is supplied by two a-c. feeders which may furnish the power singly or jointly. For simplicity of control, and to avoid the use of an additional breaker for the rectifier, an electrically operated change-over switch is so connected to the auxiliary contacts of the two feeder breakers that when either breaker or both breakers are closed, it is in a position corresponding to "breaker closed" and only when both breakers are open is it in a position corresponding to "breaker open." For control purposes therefore, this change-over switch may be regarded as a "phantom" rectifier a-c. breaker whose position indicates whether the power is on or off the rectifier. The control relays for the rectifier mentioned in Paragraph II operate directly on the a-c. feeder breakers. Where mention is made of the rectifier a-c. breaker or oil circuit breaker in connection with the automatic controls in this substation, the phantom breaker is understood.

Due to the fact that the substation is very close to a ring bus the automatic reclosure of the a-c. feeder breakers has not, so far, been permitted, on account of the voltage dips which might occur when the breakers close on short circuits. Manual control switches in series with the closing contacts of the reclosing relay are therefore provided on the company's control board located in the same substation. The breakers, then, cannot be closed, unless the manual control switches are operated and the reclosing relay is in its closing position. Tripping can be accomplished either by the rectifier control and protective relays or by the power company, independent of each other.

During the past ten months of the operation of the rectifier plant, no disturbances which could have resulted in an automatic reclosure on short-circuit have occurred. There is no question but that the Union Railway Company will soon be permitted to derive the full benefit of its automatic equipment.

If desirable the a-c. feeders can be arranged for "preferred feeder" control. The change-over from the preferred to the emergency feeder is done automatically in this case and when the trouble is cleared the supply of power is transferred back to the preferred feeder. Either feeder can be made preferred by means of a selector switch. This type of preferred feeder control is also applied when power is supplied at 60 cycles over one feeder and at 25 cycles over the other feeder. In this case, a series reactor is installed in circuit with the 25-cycle feeder for transformer protection and for maintaining the same regulation of the rectifier d-c. voltage as at 60 cycles.

*V. Automatic Reclosing D-C. Feeders.*

There are two automatic reclosing d-c. feeders in this substation. The feeder breakers are normally closed. When tripped by overload, the d-c. feeder reclosing relays will attempt to reclose them a predetermined number of times at predetermined time intervals. After the scheduled number of attempts have failed to close a breaker, it is locked out.

A city ordinance requires that the supervisor have the ability to disconnect any trolley feeder when called on to do so. For this reason the feeders are also equipped with remote control, so that they can be locked out and reset by the supervisor.

*Remote Control.* Since the remote control plays such a prominent part in this substation, it is thought advisable to devote a few words to the system employed.

The remote control station is at West Farms Substation, about three miles away. The connections between the two stations are made over a telephone cable. The scheme requires a 110-volt battery at each end of the cable, a polarized relay in the substation for each breaker to be controlled, and one at the remote station for each breaker for which indication is desired. One wire is required for each relay; that is, one for the indication and one for the control of each breaker. There is one common wire joining the mid-points of the two batteries. Where only one battery is available, two extra wires must be used.

The breakers controlled are the a-c. feeder breakers and the two d-c. feeder breakers. Indication is provided for the phantom a-c. rectifier breaker, the d-c. rectifier breaker and the two d-c. feeder breakers. Eight wires are therefore needed for the complete remote control of the station. The remote control plays the same part in the control of the plant as the other master elements, except that its signals predominate all but the protective relay signals. It therefore controls the position of the a-c. closing and reclosing relay, which, in turn, controls the breaker of that a-c. feeder which has been selected for reclosing operation.

In connection with the remote control, mention might be made of an inexpensive scheme of remote metering, devised and installed by the railway company. The scheme utilizes the d-c. voltage drop across the series reactor of the telephone interference equipment, to give

an indication of the rectifier load at West Farms. A millivolt meter at West Farms, calibrated with the line drop, indicates the load on the rectifier in amperes. The voltage drop across the reactor consists of a d-c. component and several a-c. components. In order to reduce the a-c. component in the current through the millivolt meter, a small reactor was installed in the leads. The accuracy of this remote metering equipment has been found entirely sufficient for practical purposes.

*Operation and Performance Data.* The rectifier unit has been in successful operation since May, 1929. The set is in service daily from 6:00 a. m. to 10:00 p. m. Every Sunday morning, at times of low load, the set is taken out of service for cleaning and a short inspection.

Up to March 1, 1930, a total a-c. input of 2,334,800 kw-hr. had been metered on the rectifier. No d-c. watthour meters are installed in this plant. It follows from this input figure that the average monthly power consumption was 233,000 kw-hr. which corresponds to a daily load factor of 45 to 50 per cent.

Over the same period, the metering of the rectifier auxiliary power indicates a consumption of 17,300 kw-hr., corresponding to 0.75 per cent of the total rectifier input.

No official efficiency measurements have been carried out on this set, but measurements taken with available switchboard instruments indicate that the guaranteed efficiences are met.

Measurements of the cooling water consumption of rectifier and vacuum pump are available only up to October 10, 1929, and indicate that up to that date 77,500 cu. ft. of water had been consumed, corresponding to 0.068 cu. ft. per kw-hr. rectifier input. Assuming the load factor to be the same over a period of 12 months, as computed from the first 10 months of operation, the yearly cooling water consumption, for this rectifier set, will amount to approximately $190. This figure is based on a water cost of $1.00 per thousand cu. ft.

Through trolley wire and feeders, the rectifier set is operating in parallel with rotary converters of the neighboring substation. The rectifier is taking the proper share of the system load and no difficulty whatsoever has been experienced in parallel operation.

As already mentioned, a filter equipment has been installed for suppressing the a-c. ripple in the rectifier output. This filter equipment has been working satisfactorily and no complaint of telephone interference in communication circuits has been received.

## Conclusion

In the foregoing article a 1000-kw. automatic mercury arc rectifier installation has been described, with particular reference to its automatic control. The installation is a practical example to show that a rectifier can, without too much complication, be provided for automatic and remote control, that it can be installed in a very limited space without any changes to existing building and floor. Furthermore, the rectifier can be provided for operation on 25 and 60 cycles, where power at both frequencies is available, or may be considered in the future.

# Miniature Switchboards

## A Modernization in the Design of Operating Switchboards for Electric Power Stations and Substations

BY PHILIP SPORN[1]

Member, A. I. E. E.

***Synopsis.***—*This paper points out the general progress made in the design of electric power systems and contrasts with it the lack of progress in the field of control switchboards. It is shown that due to this lack of progress a situation confronts many systems today where switchboards are so large that excessive amounts of space are necessary for their housing and further expenditures are later necessary in order to integrate these large switchboards so as to bring them within proper supervisory control of a limited number of operators. A development in miniature switchboards is described embracing and containing all the fundamental requirements of a control switchboard and yet with no greater space than 4 in. of panel width for complete control and supervision of one feeder. A description of the instrument, control switches, and auxiliary relays is given as well as the method in which all these elements have been assembled. Drawings and photographs of actual installations showing the possibility of developing a switchboard along the lines described, that will handle 60 feeders and yet bring it within the range and operating control of a single operator, are given. The advantages of the new development are, as brought out: Compactness, ease of operation, closer supervision, ease of erection, good appearance, and modernity.*

### I. Introduction

THE progress made in the design of central stations, substations, and switching stations in the past two decades is too well known to those associated with the electric light and power industry to require any extended description. There has been tremendous improvement in the design of boilers, turbines, transformers and similar and related equipment, as well as development and extension of the maximum economic sizes, resulting in each case in larger, more compact units, with decrease of the space required per kw. All this, as may perhaps not be apparent, is part of a general movement,—a part of a very pressing economic drive to obtain a kilowatt of capacity for less investment. That this is one of the most vital problems facing the electric power industry there can be no doubt; but, unfortunately, by the time it reaches the switchboard the importance of this vital movement is very often lost sight of.

It is only necessary to examine switchboards of today and compare them with those of 10 or 20 years ago to be impressed with the truth of this situation. Today we find switchboards perhaps with better wiring or with other refinements as compared with those which were built a decade ago, although substantially of the same type. Generally employed there is a panel—anywhere from 12 to 30 in. wide,—to control an individual circuit or portion of the apparatus. It is true that this particular circuit may be handling more power than was handled by a corresponding circuit 10 years ago, but this is exactly the sore point. The advance has been in the circuit itself; the switchboard design has not made a corresponding advance.

It is true that there have been some changes, but in the main there has been no fundamental progress. Thus we have seen the development of the back-to-back board, which has cut down the over-all length necessary for the control of a given number of circuits. On the other hand, in many instances the development of the idea of placing a bench board in front of the back-to-back board has resulted in requirements of greater cubage.

As a typical example of what this has led to, we can cite a case of one of the most modern steam plants placed in service within the last month or so, with two 58,000-kw. units and one 15,000-kw. unit, where a control room approximately 97 ft. by 30 ft. was provided. After allowing for an ultimate layout of approximately 600,000 kw., the control room is found to be very definitely and uncomfortably crowded.

The general result due to this lack of progress in switchboard design may be said to have been, that the boards for the average station or substation have grown in size and reached a point where an ordinary operator, or even a group of operators, can not comfortably take care of a single board. Or if they did take care of it, because of the size of the board they would lack a proper view of the various parts of the system at all times which in case of emergency or trouble when full knowledge is particularly essential might prevent a proper carrying out of duties.

In consequence, we have seen developed the electrically operated dispatcher's boards, only multiplying the links in the chain. As a result of the sprawling design of the primary switchboard, we have come to a control board to integrate the primary board and to place the fundamentals in connection with its control in a sufficiently small space to be fully controlled by the operator in charge. That this has meant an economically wasteful development in two directions is apparent.

### II. Modernizing Fundamentals

It was recognized that in order to get away from this

1. Chief Electrical Engineer, American Gas & Electric Co., New York, N. Y.

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cumbersome arrangement of switchboards, and provide a board on which all necessary instruments and control switches could be placed so that they would be entirely in view and under the hand of one operator, it would be necessary to develop a complete new line of small meters and small control equipment. Accordingly, the problem was attacked from this angle and a great deal of work was done in the development of such

Fig. 1—A-c. Ammeter for Miniature Switchboard

meters, control switches, and indicating devices. This miniature equipment has been designed to be mounted on very small panels, and the resulting miniature board is capable of doing everything that could be done with the conventional but larger sized switchboard equipment.

Instrument elements have been developed for a-c. or d-c. ammeters, voltmeters, and wattmeters and kv-a. meters, which can be mounted in a standard case

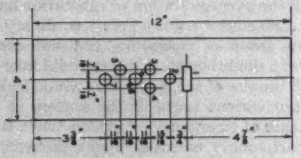


Fig. 2—Panel Showing

1. Card holder
2. Synchronizing receptacle
3. Green lamp
4. Red lamp
5. White lamp
6. Control switch
7. Operating key

having a front 4 in. wide by 4½ in. high and a body approximately 3½ in. square and from 6 to 10 in. deep. The scales on these meters are approximately 3½ in. long and are white with black markings. The needle pointer is furnished with a black tip. The front of this meter is drilled at each corner and supports the whole meter, thus allowing of direct mounting, with four machine screws. The volt-ampere burden for these instrument elements is in general somewhat lower than for the standard instrument elements. Fig. 1 shows a photograph of one of these instruments.

The control equipment and indications are taken care of by the use of a red light, a green light, and a white light, a control switch, a synchronizing receptacle, and an operating key or push button. The control switch itself is a development of the control switch used on supervisory equipments. The equipment is so wired that to close the circuit, the control switch is placed in the closed position, thereby closing a contact which is in series with a contact of the synchronizing receptacle and the operating key. When the operating key is depressed, the closing circuit is energized. The tripping is taken care of by placing the control switch in the open position in which position its tripping contact is wired through the operating key so that when the key is depressed, the oil circuit breaker is tripped. Fig. 2 shows a panel on which this equipment is mounted and an elementary wiring diagram may be seen in Fig. 3.

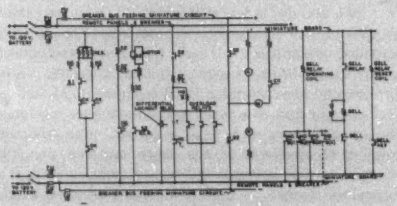

Fig. 3—Schematic Diagram for Typical Panel Showing Breaker Wiring

1. $\frac{H\ G}{C}$ Interposing closing relay
2. $\frac{H\ G}{T}$ Interposing tripping relay
3. $\frac{H\ G}{B}$ Series alarm relay in trip circuit
4. *S I* Synchronizing receptacle
5. *C K* Control switch
6. *O K* Operating key
7. *C C R* Control contactor
8. *T C* Trip coil

However, in connection with this control switch it has been necessary so far to use two interposing relays; one to handle the closing current, and one to handle the tripping current for the oil circuit breaker. A new control switch is being developed with adequate contact capacity so that the interposing relays will not be necessary. The interposing relay is a small instantaneous circuit-closing relay. The synchronizing receptacle consists of a telephone type jack and the wiring is shown in the elementary diagram of Fig. 3 and the arrangement of contacts as in Fig. 4.

## III. Assembly

The development of these instruments, control switches, indicating lamps, and other devices has resulted in a new type of switchboard structure. This structure is fabricated from electrically welded steel plates. The two forms which have been developed, so

far, consist in one case of an upright rectangular cabinet fitted with a desk top extending from the panels at a height of about 30 in. from the floor, and in the other, of a number of individual sections which bolt together

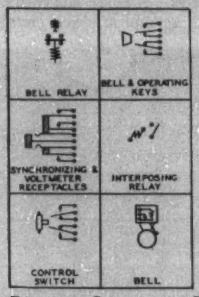


FIG. 4—DETAILS OF SWITCHES AND RELAYS

to form a polygonal arrangement with the switchboard on the inner side, attached to which is a desk top similar to that for the other design. This latter type, providing for the development of the panels on a circle, makes it possible to assemble a number of panels in such a posi-

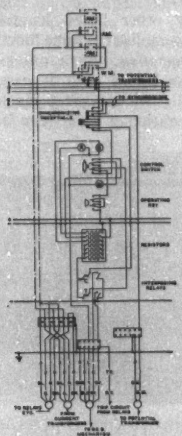

FIG. 5—BACK VIEW, WIRING DIAGRAM OF A TYPICAL FEEDER PANEL

tion that they can be more easily observed and controlled.

For both types of switchboard structure, the mounting is taken care of by cutting out sections from the steel fronts and providing frames to which the meters can be bolted directly. To this frame may also be bolted suitable small panels with the control switches, synchronizing receptacles, etc., mounted on them. A typical panel consists of the proper indicating instruments, control switch, indicating lamps, synchronizing receptacle, and operating key, etc., mounted vertically so that panel sections and meters are all flush. A wiring diagram is shown in Fig. 5 covering a typical

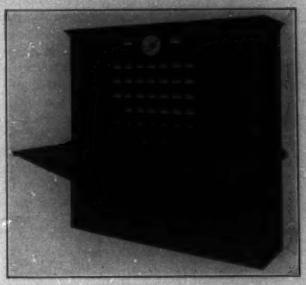

FIG. 6—ILLUSTRATION OF RECTANGULAR CABINET TYPE SWITCHBOARD

panel. The arrangement can be seen from Figs. 6 and 7, which are the photographs of two designs. Fig. 8 shows a plan view of a typical section for the polygonal arrangement, also a side and front elevation and Fig. 9 shows the method of grouping the sections.

## IV. DESIGN DEVELOPMENTS

Figs. 10 and 11 show two switchboards, Fig. 10 being a close-up view of the instrument and control

FIG. 7—PHOTOGRAPH OF MULTI-UNIT TYPE POLYGONALLY ARRANGED SWITCHBOARD

section of an installation made at the Beaver Creek substation of the Kentucky and West Virginia Power Company and Fig. 11 a photograph of the board to be installed at the 132-kv. Zanesville substation of the Ohio Power Company, both of which companies are subsidiaries of the American Gas and Electric Company. From Fig. 11, which is a three-quarter view

of the Zanesville board, it is evident how such a switchboard lends itself to complete supervision and ease of operation. The operator, from a swivel chair, can see all the instruments on the complete board and can easily reach all the control switches. The board shown in

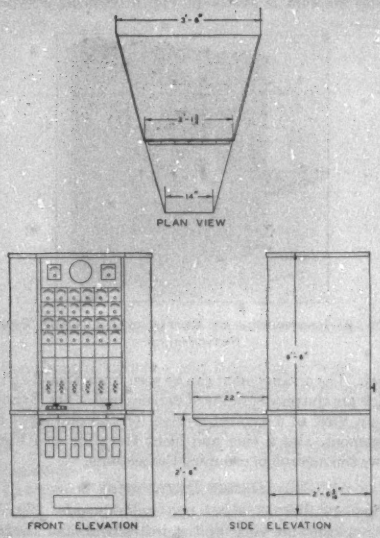


Fig. 8—Typical Unit for Zanesville 132-Kv. Substation Switchboard

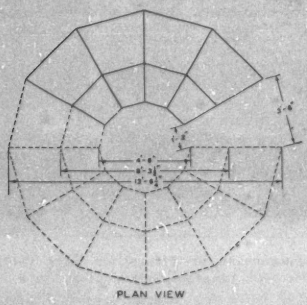


Fig. 9—Extent of Possible Development of Multi-Unit Board

Fig. 11 consists of four sections, totaling 24 circuits. Such a board can be expanded to eleven sections, as shown in Fig. 9; and 66 circuits can be controlled just as readily.

## V. Advantages

The advantages of the switchboard development described are almost self-apparent, but it may be well to summarize them here. They are:

*1. Compactness.* A board has been provided which takes up a small amount of space, certainly much less

Fig. 10—Close Up View of the Instrument and Control Section of the Miniature Board Installed at Beaver Creek

space than any other board heretofore developed attempting to accomplish the same functions.

*2. Ease of Operation.* As a natural concomitant, this compactness brings with it ease of operation. With no difficulty whatsoever a single operator can supervise the operation of 60 or more feeders and do so

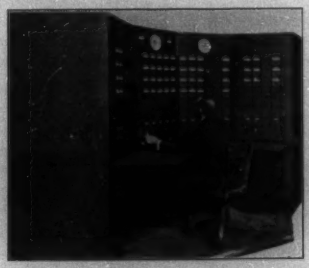

Fig. 11—Three Quarter View of Zanesville Switchboard Showing Ease with which It Can be Supervised

with a minimum amount of effort and a maximum amount of dispatch; further, due to the type of control switches employed, he can do this all while carrying on a telephone conversation or either giving or receiving instructions.

*3. Closer Supervision.* The small physical dimensions make it possible for the man actually operating the switchboard to exercise a closer degree of supervi-

sion; to know at a glance what has happened over the entire system supervised, and do so more easily than heretofore, without the intervention of other intermediate equipment. Besides, it saves the expense and complications of such additional equipment.

*4. Ease of Erection.* The board lends itself more readily than any other type of board to complete erection at the shop of the manufacturer and shipment complete as a unit. This makes it possible to install it more quickly and with less expense than a board which has to be disassembled or broken up into parts before shipment.

*5. Good Appearance.* By no means a negligible point in the favor of the new development is its excellent appearance. It cannot be claimed that most of the boards that have been built within the past decade or so have had beauty of appearance as their strong point; the new board most decidedly is a great advance in that direction.

*6. Modernization.* The advantages may be summarized in brief, as follows: The board is a definite step in modernization of an item of station and substation equipment that has too long been left to accumulate tradition and that has too long followed along old and weather-beaten paths. It is believed that the step taken at the present time will be helpful in the direction of further development and progress toward the modernization of an important item in electric plant and substation operation.

Acknowledgment is due to the switchboard engineers of the General Electric Company, who obviously did all the instrument and most of the other development work, and particularly to Mr. Chester Lichtenberg, without whose sympathetic cooperation this development would have been impossible. The author also wishes to acknowledge the help he received from Messrs. H. E. Turner and R. C. Miller, in the preparation of this paper.

## Discussion

**R. M. Stanley:** If a power station should be built according to the general practise of the past, with complete switchboard control equipment and, in addition, should there also be included supervisory automatic control, the resulting cost would, of course, be greater and, therefore, the use of automatic or supervisory control would be questionable, even though many of the advantages of such control were realized.

If, however, departures from conventional general design can be accomplished successfully and ways found to include automatic and supervisory control at no greater cost or, perhaps, considerably lower cost, their adoption can be justified. At Louisville, Kentucky, in the Louisville hydro plant built during 1926 and 1927, the following was accomplished:

It was found possible by the adoption of a miniature switchboard to eliminate from this station the following elements which would have been used if fairly modern standards of design and engineering had been followed;

1. A slate or steel benchboard controlling generators, exciters, power transformers and station auxiliary.
2. A vertical slate or steel switchboard containing watthour meters, relays, etc.
3. A control room of dimensions approximating 60 ft. long, 18 to 20 ft. wide and 10 to 12 ft. high.
4. Suitable foundations, concrete or structural work, for a portion of a power-house building of the size outlined.
5. Control wiring, conduits, shelving, lead covered control cable or other suitable means for connecting the control and relay switchboard with the apparatus to be controlled.
6. Suitable lighting, by electric illumination or by skylights, windows, etc., for the control room and suitable ventilation and heating for the comfort of the operators.

Unit control of generators and power transformers, by means of control cubicles located nearby, permitted a saving in building and control conduit and wiring. Without some centralized equipment, station operators would be obliged to walk the entire length of the plant many times daily. Centralized control—necessary in such a large plant—was accomplished by the use of a supervisory control cabinet or miniature switchboard, small in size and cost and requiring little space in the building, located near the middle of the generator room.

At the cubicles, voltage reduced by instrument transformers to about 10 volts, and currents reduced to about ¼ ampere, permit the use of 16-pair lead-covered telephone cable between control cabinet and each generator cubicle. These telephone cables are installed in 1¼-in. conduit and the combined cost is about 80 cents per ft. installed. One three-conductor control cable, ordinarily used between control switchboard and generator equipment, installed in 1¼-in. conduit, costs about the same per ft. The 16-pair cable does the same work as that of 16 control cables and conduits ordinarily used between a switchboard and generator equipment, and the saving should, therefore, be apparent.

These savings in control wiring and conduit more than offset the cost of extra automatic and supervisory equipment so that with building costs considered, the total plant cost was reduced very materially.

To generalize a little; automatic equipments have been applied to small apparatus to start when required, or to connect groups of small equipment to power supply when this supply has been restored after interruption. There now seems to be no reason why such equipment cannot be applied and devoted to the task of restoring power supply for various parts of a system and to keeping generating equipment operating, ready to be re-connected to the load in the shortest possible time.

When system troubles occur, operators often are at a loss to know what to do. System troubles cannot be instantly diagnosed and remedies cannot be instantly decided on. Oftentimes before the trouble can be analyzed the opportunity for action to correct conditions has passed. These things should be worked out in a deliberate manner, and remedial measures planned in advance. As we gain in experience in operating our systems, we can predict more closely what is going to happen, anticipate conditions, and be prepared to handle a situation within the very short interval of time which is allowed us, and the automatic equipment affords a medium to do this.

We have known a great many things about this sort of equipment but have not, until recently, realized much about how ready it stands to help us operate our systems if intelligently applied.

We have thought that its extra cost must necessarily preclude its use, but in this we have been wrong. It has, and probably will, if properly and intelligently applied—afforded a means of reducing costs. Our application in the Louisville hydro plant has, I believe, demonstrated the entire practicability of handling, automatically, large sized units in a large station and this, in connection with a system which is of average size combines all of the transmission, distribution and generating problems met with on representative power systems of today.

As to sturdiness and durability, the cubicles contain all of the standard switchboard indicating and recording instruments required for ordinary station records, and also contain relays

and automatic control contactors and other equipment. Between these cubicles and the generators, transformers are installed; standard current and potential and oil circuit-breakers control cable in iron conduit. There is, therefore, a complete and separate system of control in each case.

Superimposed upon this system is a miniature system operating at 10 volts and ¼ ampere, but entirely separated by current and potential transformers and relays respectively so that any breakdown of any part of one system cannot affect adversely the operation of the other. If the miniature system of one unit fails the unit can be operated from the cubicle. This has not yet been necessary and two and one-half years' use of this plant has apparently justified our selection and adoption of these ideas and methods.

In addition to reduction of fixed charges due to reduced installation and construction costs, operating costs are greatly reduced. Two men per shift operate the entire plant except when extra help is required on the outside at the racks where trash or ice accumulate.

**C. Lichtenberg:** Automatic supervisory systems have introduced smaller control devices and connecting wires into the power field. They have permitted a greater concentration of control equipment and have enabled more units to be placed conveniently under the control of a single supervisor. They have brought forth the so-called miniature switchboard.

A miniature switchboard may be defined as a small or concentrated switchboard using supervisory lamps and keys and small sized instruments. The lamps with their color caps are used to give indications of the positions of the devices controlled. The keys replace the conventional control switches. They control the operation of remote electrical devices through auxiliary relays and they may in time be replaced by miniature control switches. These will combine the present control keys and auxiliary relays without, however, appreciably increasing the space occupied on the panels. The instruments are of conventional design but with restricted scale length. This permits using conventional switchboard instrument accuracy with small size cases.

The adoption of the miniature switchboard permits radical changes in the design of stations and substations. It permits the elimination of the switchboard gallery as such, reduces conduit runs to a minimum and renders pull boxes unnecessary. It reduces the space requirements of a switchboard and its connections, and permits a marked simplification in station design. The switchboard will now contain only the control keys, or miniature switches, and a minimum number of instruments. Consequently, it will be very much smaller than the conventional switchboard. It will approximately require only about one-tenth the space of a conventional design of switchboard and will permit a very much more convenient operation of the units. It will permit the supervisor to maintain telephone communication with some remote point while at the same time reading instruments or operating devices in a maximum of 60 to 66 circuits.

The connections from the miniature switchboard to the remote electrical devices may be most conveniently made through conventional telephone cables. For greater safety it is recommended that the same standard of insulation be adopted as has been standardized by the American Railway Association for railway telephone and telegraph cables. The use of such cable with No. 19 B & S copper conductor is possible since the lamps and keys and the new miniature control switches are designed for 24-volt, 48-volt, or 60-volt operation. The miniature instruments may be obtained with 60-volt and 0.5-ampere windings. Consequently, lead covered cable without conduits may be installed between the miniature switchboard and the remote electrical devices. This markedly reduces the expense of control cable and conduits and permits greater flexibility in the location of the miniature switchboard and of the connections.

Besides marked reduction in installation cost, miniature switchboards have increased operating ease and testing facilities.

These boards are designed, as indicated in Mr. Sporn's paper, that they may be placed in circular formation. A maximum of 10 or 11 of these units may be placed in one group. This will give a seated individual the control of a maximum of 60 to 66 circuits. The circuits may be the control of individual oil circuit breakers or they may be the control of a complete hydroelectric unit as in the Louisville automatic hydroelectric station described by Mr. R. M. Stanley.

Many combinations of miniature switchboards will suggest themselves to designers. For example, one arrangement is the use of six-unit groups representing 180 deg. of a circle. These will take care of 36 circuits or of 36 machines. Six of such grouping arranged in two parallel lines with the concave sides facing each other may readily be used to control the largest station contemplated today. Such an equipment could easily be placed in a room or space about 35 ft. wide and 80 ft. long and still give ample room for the operators or supervisor.

The latest designs of miniature switchboards as exemplified in Mr. Sporn's paper indicate that the development is progressing rapidly and that today designs are available to meet most all conditions arising in stations and in substations. These designs should do much to reduce the cost of electricity supply undertakings and operation.

**H. B. Wood:** In the paper on miniature switchboards, the author has emphasized the desirability of simplifying the control board. This is especially helpful in minimizing operating errors.

The comparison of the miniature board with the ordinary type of control is not placed on an equal basis as the author has neglected to mention the space required for the relays, watthour meters, signal devices and other control apparatus.

To prevent operating errors, it is just as necessary to obtain circuit segregation on the board as in the bus and switching structures. A plan view of a miniature board is shown in the paper intended to provide for 66 circuits. With such a mass of identical devices the optical and mental grasp of the operator is exceeded and the identity of highly important equipment is lost and mistakes are apt to occur.

The control room should be simplified as much as possible, bringing to the board only the important features. Relays if mounted close to the instrument transformers will save a large amount of conduit and wire. Watthour meters, temperature recorders and curve drawing meters can be located elsewhere. Automatic devices have been developed to remove many duties from the switchboard operator.

In the miniature switchboards, devices of the telephone type are used. These devices including as they do added auxiliary relays are not sufficiently substantial or dependable for use in large high capacity plants. We need safer and more sturdy control equipment not reduced clearances and insulation.

**Philip Sporn:** Mr. Stanley discusses particularly the experience obtained with the control scheme used for the Louisville hydro plant of the Louisville Gas and Electric Company. The problem which confronted the designers on this particular job was one of providing centralized control with a minimum of space required and at a cost less than for the usual type of installation. This problem was solved by providing individual boards at each unit and by the use of a supervisory type board on which was grouped the control for all units. The solution as applied to the Louisville hydro plant, of course, is not strictly speaking a miniature switchboard application. The miniature board embodies a number of ideas developed in the Louisville hydro plant board but the development was carried in another direction and a great deal further.

The use of automatic equipment to minimize operating errors in times of emergency which Mr. Stanley suggested, has interest-

ing possibilities, but this too is out of the province of miniature switchboards as covered in this paper.

Mr. Lichtenberg's discussion constitutes in brief a description of what a miniature board really is.

Mr. Wood's discussion, I believe, comes the nearest to actual criticism of the ability of the board to perform what it is intended to do.

It seems to me that the thing which should not be lost sight of is the fact that the miniature board is really nothing more or less than a standard large sized control board greatly reduced in size. The mere fact that the board is small and that some of the devices on it have been the outgrowth of the development of supervisory control boards, as pointed out by Mr. Wood, does not mean that any part of this miniature board is less reliable than a corresponding part of a standard board.

The only additional devices in the control circuits are the auxiliary relays which are used. These are very simple, take up little room and are very positive in operation. Even these, however, we expect to be able to eliminate in the near future by using complete miniature control switches as mentioned by Mr. Lichtenberg in his discussion and also in the paper itself.

The fact that indicating and integrating meters and other indicating and recording devices are not mounted on the miniature control board does not detract at all from its value since it has been common practise for some time to use independent metering and control boards. It is even quite possible, in case it should be desired, to mount the necessary metering devices in the back of the miniature board units especially in the case of the circular arrangement where there is a considerable amount of extra room available. In connection with this it seems to me that one of the big problems facing instrument designers at the present time is that of reducing the size of indicating and integrating meters and of relays to meet a demand which is continually increasing for smaller devices of this kind. There is too, I believe, no real reason why these classes of devices cannot be reduced in size without any sacrifice in efficiency if the problem is approached seriously by the designers.

I do not believe that Mr. Wood's criticism concerning the probability of making mistakes by using the miniature board, where a large number of circuits is involved, is one that will be substantiated in actual practise. I believe that there is a much greater likelihood of mistakes occurring where an operator has to watch extensive control boards of the present type than there is where everything comes under his hand and eye as in the case of the miniature boards.

The grouping of circuits on the miniature boards can also be made extremely simple. For those who prefer to use a mimic bus, especially for boards used to control generating stations, this modification can be applied to the miniature board. Adequate communication systems for keeping an operator in touch with the boiler and turbine rooms can also be developed in miniature.

There is a great deal to be said as Mr. Wood points out for designing control equipment for sturdiness, but this does not mean, as has been so generally supposed in the past, large cumbersome boards with correspondingly large and ungainly devices mounted on them.

Concerning the reduction of clearances and insulation, there is certainly no reason why insulation and clearances as provided on these old style boards cannot be cut down. When the problem is attacked intelligently, proper insulation can be provided with considerably reduced clearances over those which have been used in the past. The tendency in general in control work, I believe, is going to be more and more toward the use of miniature equipment with the large savings which can be effected in reduction of space required to house such control, in the number of operators which it will be necessary to employ to adequately supervise any particular installation, and in the reduced cost of equipment itself which is going to become more and more apparent with the development of such miniature equipment.

# Mutual Impedances of Ground-Return Circuits

## Some Experimental Studies

BY A. E. BOWEN* and C. L. GILKESON†

Non-Member

Associate, A. I. E. E.

*Synopsis.—This paper describes some of the results of the work of the Joint Development and Research Subcommittee of the National Electric Light Association and Bell Telephone System on the mutual impedances of ground-return circuits.*

*The first part of the paper deals with some experiments which were performed to establish an experimental background for the testing of theoretical ideas. Different theories, one involving an "equivalent ground-plane," a second a d-c. distribution in the earth, and a third an a-c. distribution in the earth, are discussed in the light of the experimental results. While none of these is adequate to explain all the observed phenomena, each has a field in which it can be made useful.*

*The second part of the paper is devoted to a description of practical means for predetermining the mutual impedances of power and telephone lines. This involves an experimental determination of a curve of mutual impedance as a function of separation in the region of the proposed exposure and the calculation of the over-all mutual impedance between the proposed lines from this curve and the dimensions of the exposure. The results of trials of this method in two locations are given which indicate that it should be of sufficient accuracy for engineering purposes.*

* * * * *

### Introduction

THE magnitude of the inductive coupling between power and telephone lines is a factor of fundamental importance in problems of coordination to prevent interference between these two classes of lines. Accordingly, this is one of the subjects under investigation by project committees of the Joint Committee on Development and Research of the National Electric Light Association and the Bell Telephone System. It is the purpose of this paper to present the results of some work which has been done under the auspices of the Committee on one phase of this problem, namely, the mutual impedance of ground-return circuits.

The mutual impedance of two ground-return circuits is determined by measuring the ground-return current in one circuit (the "disturbing" circuit) and the open-circuit voltage at the terminals of the second circuit (the "disturbed" circuit). The vector ratio of the open-circuit voltage to the ground-return current is then defined as the mutual impedance of the two circuits.

For any normal or abnormal operating condition of a power system, the currents, either at fundamental frequency or at any harmonic frequency, in any of the lines can be resolved into components, some of which are entirely confined to the wires while another component flows in a circuit composed of all the wires as one side with the ground as a return path. The work which is described in this paper deals with the magnitude of the induced voltages on exposed telephone lines caused by the latter component. It has been directed to two ends, first, the establishment of an experimental basis for the study of the physical factors involved in the inductive coupling of ground-return circuits, and second, the development of practical methods to enable the advance calculation of the mutual impedances of power and telephone lines. The work is accordingly presented in two parts; first are given the results of tests made at a field laboratory in which testing conditions could be controlled, and second, tests in which the practical side of the problem was investigated are described.

### Cross Keys Tests and Theoretical Background

*Cross Keys Tests.* An extended series of measurements was made at a field laboratory operated by the subcommittee near Cross Keys, New Jersey, about 20 miles southeast of Camden. A single conductor, located about 34 ft. above the ground and 8500 ft. in length, was available for the disturbing circuit. For disturbed circuits, 500-ft. lengths of insulated wire were laid on the earth parallel to the disturbing conductor, at several separations, as shown on Fig. 1. Grounds were provided at the ends of each line. Ground-return current was transmitted over the disturbing line at 60 cycles from a commercial source, or at frequencies between 100 and 1000 cycles from a vacuum-tube oscillator with power amplifier. The measuring instrument was an a-c. potentiometer, equipped with suitable filters so that the observations

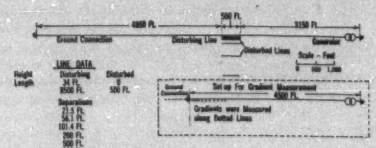


Fig. 1—Cross Keys Tests. Experimental Setup

*Am. Tel. & Tel. Co., New York, N. Y.

†N. E. L. A., New York, N. Y.

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were unaffected by the presence of harmonics in the disturbing current.

At several frequencies within the range from 60 to 1000 cycles the current in the disturbing line, the open circuit induced voltage in each of the short ground-return circuits, and the phase angle between these two quantities, were measured. The mutual impedances were derived from the ratio of the induced voltage to

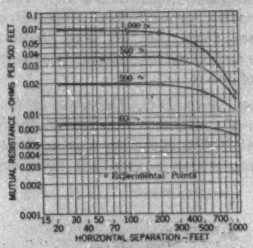


Fig. 2—Cross Keys Tests—Mutual Resistance

the inducing current, in accordance with the definition. The results of these tests are given on Figs. 2, 3, and 4. Fig. 2 shows the resistance components, Fig. 3 the reactance components, and Fig. 4 the magnitudes of the mutual impedances.

The measurements described above were made with the object of investigating the mutual impedances of ground-return circuits in which the ground connections

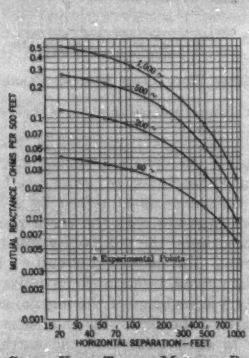


Fig. 3—Cross Keys Tests—Mutual Reactance

on the disturbing line are sufficiently removed from those on the disturbed circuit so that effects due to proximity of the grounds may be ignored. The results presented above were supplemented by observations demonstrating that the induced voltage in a parallel circuit was closely proportional to the length of the circuit and that the voltage induced in a ground-return circuit extending perpendicular to the disturbing line was exceedingly small.

As the points of grounding on the disturbed circuits approached those of the disturbing circuit this proportionality no longer existed nor was the voltage in a perpendicular circuit of negligible magnitude. A second series of tests was therefore conducted to determine the nature of this effect and the area in which it was of importance.

In these tests voltages were measured in very short disturbed circuits extended along radii converging on one of the ground electrodes on the disturbing line. At each location the circuit was made progressively shorter until the quantity measured per unit length was practically independent of the length. Thus the gradient of the mutual impedance, in the direction of the radius at the point of measurement was determined. These measurements were made only at a frequency of 60 cycles.

The resulting observations are shown in Figs. 5 and

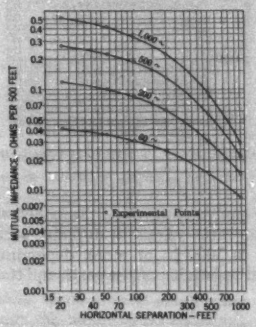


Fig. 4—Cross Keys Tests—Mutual Impedance

6. Fig. 5 shows the magnitude of the mutual impedance gradient along three radii, one radius being directly under the disturbing line, the second perpendicular to it, and the third along the extension of the line. Fig. 6 shows the corresponding phase angles. Under the disturbing line, as the distance from the grounding point is increased, the gradient approaches a constant value and the phase angle changes rapidly from a very small value to an angle approaching 80 degrees. Along the latter two radii, however, the magnitude of the gradient appears to decrease indefinitely and the phase angles are smaller.

A more complete analysis of the results of both groups of tests is given in connection with the discussion of theory which follows:

*Equivalent Ground-Plane Theory.* The equivalent ground-plane method of computing the mutual impedances of ground-return circuits utilizes a very simple

formula and has been in common use for a number of years. A derivation and discussion of the formula together with some experimental results are given in the report published by the California Railroad Commission in 1919.[1]

This method assumes that the returning earth current may be considered as flowing in a hypothetical plane surface of perfect conductivity located some distance below the actual surface of the earth. This surface is usually termed the "equivalent ground-plane." The

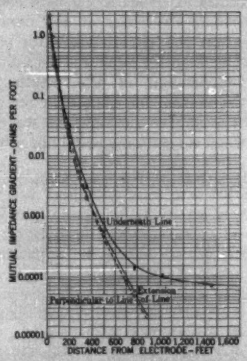


Fig. 5—Cross Keys Tests—Mutual Impedance

Gradient in vicinity of grounding electrode. Experimental curves

depth of the equivalent ground-plane below the actual surface of the earth varies in different locations from about 50 ft. to 5000 ft. or more, depending upon the character and resistivity of the earth and the frequency.

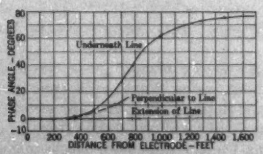


Fig. 6—Cross Keys Tests

Phase angle of mutual impedance gradient in vicinity of grounding electrode. Experimental curves

This method is subject to the objection that it fails to represent completely the observed phenomena. For instance, the method represents the mutual impedance only with a reactive term, while the experimental results indicated a substantial resistance component, particularly at the wider separations and higher frequencies. Furthermore, no attempt is made to explain the phenomena observed in the neighborhood of the ground electrodes. However, in one respect the theory leads to results comparable to those observed; the magnitudes of the mutual impedances as observed under conditions in which end effects are negligible can be checked reasonably well with a suitable choice of ground-plane. Comparisons demonstrating this point are made on Fig. 7, where it will be seen that the curve of experimental mutual impedance for a frequency of 60 cycles can be fitted very well by a calculated curve with a ground-plane depth of 835 ft. That the depth of the equivalent ground-plane depends on the frequency is seen from the fact that to fit the experimental curve at 500 cycles requires the use of a ground-plane depth of 385 ft.

*Method Assuming D-C. Distribution in the Earth.* For an earth of uniform conductivity, the distribution of the current in the earth for a ground-return circuit energized from a d-c. source has been employed by

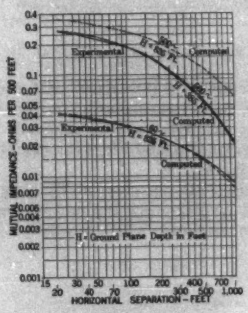


Fig. 7—Cross Keys Tests Ground Plane Theory

Comparison of measured and calculated values of mutual impedance

G. A. Campbell[2] to derive formulas for the mutual resistance and inductance of ground-return circuits. The mutual resistance is expressed by a very simple formula which involves only the earth resistivity and the distances between the points of ground connection on the disturbing and disturbed circuits. For the calculation of the mutual inductance formulas and graphs requiring only a knowledge of the mutual arrangement of the wire parts of the disturbing and disturbed circuits with respect to each other and the earth are given. The mutual inductance is independent of earth resistivity. While these formulas are, of course, strictly applicable only for direct currents, it is to be expected that at sufficiently low frequencies the ground-current distribution would not differ appreciably from that for direct current, and hence for these frequencies, the calculated d-c. mutual resistance and inductance should approximate the actual values. In the paper re-

1. For references see Bibliography.

ferred to, some experimental results at frequencies of 25 and 60 cycles supporting this point of view are presented.

The experimental curves of Fig. 2, which were obtained from measurements at Cross Keys on the 500-ft. disturbed lines near the middle of the 8500-ft. disturbing line, indicate a pronounced increase in

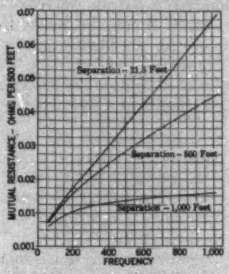


FIG. 8—CROSS KEYS TESTS

Variation in mutual resistance with frequency and separation

mutual resistance with increase in frequency in the range from 60 to 1000 cycles. These results have been replotted on Fig. 8, and it is apparent that for separations within the range of 20 to 500 ft. the mutual resistance increases rapidly in almost linear relation to the frequency. For the frequency range and circuit lengths involved in this series of tests, it would appear that a formula for the mutual resistance, based on a d-c. distribution in the earth, is inadequate.

The mutual-inductance curve of Fig. 9 has been com-

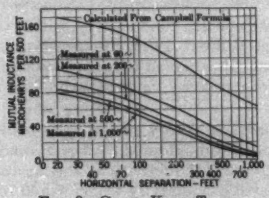


FIG. 9—CROSS KEYS TESTS

Campbell theory comparison of measured and calculated mutual inductances

puted according to the formulas given by Campbell, and for comparison purposes the mutual inductances derived from the mutual reactances shown on Fig. 3 are also plotted. It will be seen that the observed mutual inductances decrease as the frequency is increased, and that while the trend of the observed values is towards agreement with the calculated values as the frequency is decreased, the agreement is far from good at 60 cycles, the lowest frequency used in these tests.

In the immediate vicinity of the grounding electrode on the disturbing circuit, however, the experimental observations of mutual impedance gradient can be explained fairly well in terms of a d-c. distribution. The curves of Figs. 5 and 6 show that in the immediate neighborhood of the electrode, the gradient along any radius diverging from the electrode decreases very rapidly with increase in distance from the electrode, and is approximately in phase with the current. The gradient along the radius under the disturbing line approaches asymptotically a constant value, and

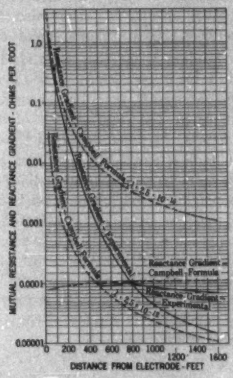


FIG. 10—CROSS KEYS TESTS

Mutual impedance gradient in vicinity of grounding electrode. Comparison with calculated values

beyond 300 ft. from the electrode the phase angle changes rapidly from a very small value to a value approximating 80 deg. The gradient along the other radii, however, appears to decrease indefinitely

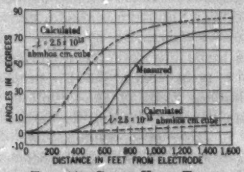


FIG. 11—CROSS KEYS TESTS

Comparison of measured and calculated (from Campbell's formula) angles of mutual impedance gradient

and the phase angles are smaller. Such effects are in qualitative accord with predictions based on a d-c. distribution, as will be seen by reference to Figs. 10 and 11.

On Fig. 10 are plotted the resistance and reactance components of the observed gradient under the disturbing line, with values computed using Campbell's

formulas. Two calculated curves for the resistance component are plotted, for conductivities of $2.5 \times 10^{-15}$ and $2.5 \times 10^{-13}$ (abmhos per cm. cube). It will be seen that the experimental values lie between these two curves, tending towards the former for short distances from the electrode and towards the latter for long distances. As in the measurements previously described, the calculated mutual reactance component is greater than the measured value, although in this case the discrepancy is substantially smaller. On Fig. 11 are shown the phase angles of the gradient as computed from the calculated values of resistance and reactance components given on Fig. 10. Here also the measured curve falls between the two calculated curves.

Since the gradient near the electrode is obviously affected mainly by the conductivity of the earth in the immediate neighborhood, and that at remote points is influenced more by the conductivity of the earth at substantial depths, the possibility that the earth in this region is not homogeneous, but stratified, is suggested. These curves seem to support the conclusion that the earth in this neighborhood has at least two strata, the upper one having a very low conductivity and the lower one a conductivity approximately a hundred times greater. Further experimental evidence tending to the same conclusion has been obtained, and will be described presently. For the present it may be pointed out that this conclusion is supported by the geological data pertaining to this region, for which an upper layer of sand and gravel from 130 to 170 ft. in depth is indicated, superimposed on a mixed structure of sand, clay, and shale, with a substantial amount of ground water.

*Methods Considering A-C. Distribution of Earth Current.* The problem of computing the mutual impedance of ground-return circuits, considering an a-c. distribution in the earth has been attacked by several writers.[3] In the interpretation of the experimental results, the papers of J. R. Carson[7] and F. Pollaczek[6] have been used, since a minimum of assumptions was made in the solutions advanced by these writers. The assumptions made are that the disturbing circuit is straight and of great length,[9] that the propagation constant, in absolute units, of the circuit is very small compared to unity, and also that the earth is a homogeneous body of fairly good conductivity. With these assumptions it is found possible to solve the fundamental field equations for the magnetic and electric fields in the vicinity of the disturbing conductor at points remote from the ends of the circuit and thence to get the mutual impedance. Physically, this method recognizes and takes into account the fact that in a conductor of large extent, such as the earth, the distribution of alternating current will be influenced by the changing magnetic field. Qualitatively, the effects are similar to those involved in the well-known skin effect, and may be thought of in terms of a distribution of eddy currents in the earth. It is obvious that the distribution of the eddy currents will depend on the earth conductivity and also on the frequency. The resultant fields, and hence the mutual impedances, will then be functions of earth conductivity and of frequency.

Presentation of the formulas and graphs giving the results of the analysis is outside the scope of the present paper, and reference should be made to the original papers for these. As an illustration of the results, however, the curves of Fig. 12 have been prepared, showing the calculated mutual resistance and reactance of ground-return circuits at a frequency of 60 cycles for

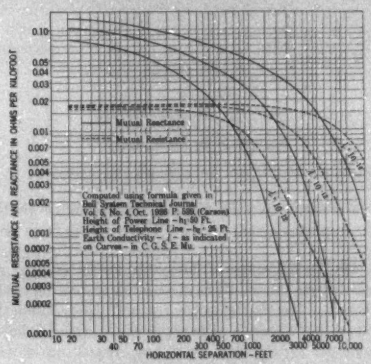


FIG. 12—RESISTANCE AND REACTANCE OF GROUND-RETURN CIRCUITS FREQUENCY 60 CYCLES

several values of earth conductivity, within the range of experimental values. Both the resistance and reactance components are seen to be pronouncedly affected by earth conductivity, particularly for the larger separations.

In applying this theory to the tests made at Cross Keys, the procedure adopted, in the absence of direct data on the earth conductivity at this location, was to choose an earth conductivity which would result in the best fit between the calculated and observed values, and to see whether a single value for earth conductivity would suffice to explain all the results. On Fig. 13 comparisons have been made between the experimentally determined mutual impedances for the 60-and 500-cycle frequencies; the curves were computed by use of the formulas given by Carson. It will be seen that in so far as the magnitude of the mutual impedance is concerned an excellent agreement can be made between the calculated and observed values. However, for the best agreement it is found necessary to assume a different earth conductivity

3. See bibliography references 3 to 9, inc.

at 500 cycles than at 60 cycles. Thus, while at 60 cycles the indicated earth conductivity is $4.2 \times 10^{-12}$ abmhos per cm. cube, at 500 cycles it is $2.76 \times 10^{-12}$. However, a computed curve for 500 cycles, using a conductivity of $4.2 \times 10^{-12}$ falls below the experimental curve by only 30 per cent. Table I gives the values of earth conductivity required to give the best fit to the curve of mutual impedance at each frequency. The range is not large, extending only from $4.2 \times 10^{-12}$ at 60 cycles to $2.0 \times 10^{-12}$ at 1000 cycles.

Turning to the components of the mutual impedance, however, the agreement is found to be not as good. Fig. 14 shows the measured values of mutual resistance and reactance at 60 cycles and at 500 cycles, also the computed values, the calculations at each frequency being made with the earth conductivity indicated in Table I. At 60 cycles the agreement is quite good, but at 500 cycles the departure between calculated and measured values is large. The measured mutual resistances are consistently lower than those calculated, while the measured mutual reactances are higher.

As indicated by the above comparisons, a theory of the kind under discussion leads to results which are in quite good quantitative agreement with the experimental results; it is of some interest to discover whether an extension of the theoretical ideas would lead to still closer agreement. It was stated previously that the measurements around the grounding electrode

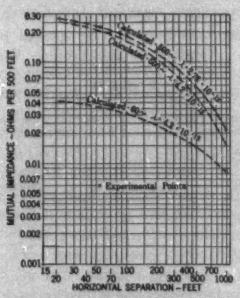


FIG. 13—CROSS KEYS TESTS—CARSON THEORY

Comparison between calculated and measured values of mutual impedance

could be accounted for on the hypothesis that the earth in this neighborhood is stratified, with a conductivity of around $2.5 \times 10^{-12}$ near the surface and $2.5 \times 10^{-13}$ in the lower depths. Qualitatively, it is to be expected that with such an earth structure the mutual resistance would be less, and the mutual reactance greater, than the corresponding values for an earth of uniform conductivity, since the eddy currents near the surface of the earth will be less, due to the lower earth conductivity.

Quantitatively, it would seem that a first approximation to the effect of a stratified earth in which the upper stratum has a much lower conductivity than that of the lower region could be obtained by assuming that the currents in the upper layer are negligible and hence that this layer can be abolished. The mutual impedances can then be worked out by the formulas applicable to a homogeneous earth, using the earth conductivity of the lower region and fictitious conductor heights, formed by adding the thickness of the upper stratum to the heights of the conductors above the actual earth's

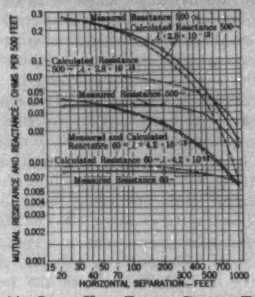


FIG. 14—CROSS KEYS TESTS—CARSON THEORY

Comparison between calculated and measured values of mutual resistance and reactance

surfaces. Preliminary calculations have been made using this scheme, and it was found that using a conductivity of $5.0 \times 10^{-12}$ for the lower stratum and a thickness of 130 feet for the upper stratum an excellent

TABLE I
CROSS-KEYS TESTS
Earth Conductivity Giving Best Agreement Between Calculated and Measured Values of Mutual Impedance

| Frequency cycles | Indicated earths conductivity from Carson's formulas abmhos per cm. cube |
|---|---|
| 60 | $4.2 \times 10^{-12}$ |
| 200 | $3.75 \times 10^{-12}$ |
| 500 | $2.76 \times 10^{-12}$ |
| 1000 | $2.0 \times 10^{-12}$ |

agreement could be found between calculated and observed values for all frequencies. The agreement extended not only to the magnitudes of the mutual impedances, but to the components as well.

Because of the simplifying assumption that the disturbing circuit is so long that the effects due to the ground connections at its ends can be neglected, the theory which we have been discussing is obviously inadequate to explain the phenomena in the neighborhood of the grounding electrode.

## PRACTICAL METHODS FOR PREDETERMINING COUPLING BETWEEN POWER AND TELEPHONE LINES

The ultimate purpose of the work of the committee is to develop simple methods to enable the calculation of

the mutual impedance between power and telephone circuits before they are built. It is evident from the foregoing discussion that the use of any formula for the mutual impedance of ground-return circuits requires a knowledge of the conductivity of the earth or of the depth of the equivalent ground-plane. In the relatively few places in which tests have been made, a range of earth conductivity from $10^{-12}$ to $10^{-14}$ abmhos per cm. cube has been observed, and reference to Fig. 12 indicates that within this range of earth conductivity a variation in mutual impedances of 20 to 1 or more may exist. Therefore, other experimental work has been done with the object of developing relatively simple testing schemes, the results of which could be used to predict the coupling coefficients in advance of the construction of the power or telephone line. An obvious method is to determine an experimental coupling curve by performing tests similar to those made at Cross Keys, using short-length disturbed circuits and either an existing power or telephone line, or a specially laid out conductor, as the disturbing line.

This experimental curve would then be used to compute the coupling between power and telephone lines. One advantage of using an experimentally determined coupling curve is that it obviates the necessity of knowing or assuming a structure and conductivity of the earth; the coupling curve can be used directly without reference to any theoretical formulas. To determine the practicability of such a scheme, 60-cycle tests have been made in two locations where existing exposures were present, for the purpose of determining

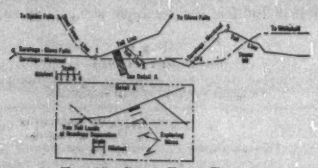

FIG. 15—GLENS FALLS TESTS

| | Circuit arrangements | |
|---|---|---|
| Tower 99 | 3-Phase conductors | Grounded |
| Circuit | Power | Telephone |
| Height | 50 ft. | 20 ft. |
| Frequency | 60 cycles | |

the accuracy with which experimental observations could be predicted.

*Tests at Glens Falls, N. Y.* Fig. 15 shows the arrangement of circuits involved in tests made at Glens Falls, N. Y. A section of the Saratoga-Glens Falls telephone line about six miles in length was energized with ground-return current. Measurements were made of the voltages induced in short ground-return circuits laid on the ground parallel to the straight section of the telephone line. The resistance and reactance components of the mutual impedance derived from these measurements are given on Fig. 16. As a matter of interest the mutual resistance and reactance computed by the use of the Carson formulas for an earth conductivity of $1.75 \times 10^{-13}$ are also given. This earth conductivity gives the best agreement between the calculated and observed magnitudes of the mutual impedances. The general agreement between the computed and observed quantities is much like that found from the Cross Keys tests.

Earth return current was then sent over the power line from Spier Falls to Tower 99, and induced voltages

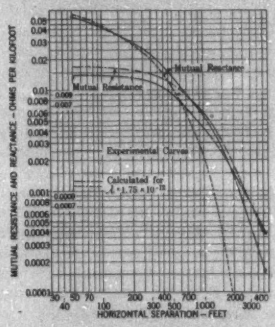


FIG. 16—GLENS FALLS TESTS

Experimental values of mutual resistance and reactance

measured in the entire exposed section of the Saratoga-Montreal telephone line, and in several parts of the exposure as indicated on the sketch. In Table II,

TABLE II

GLENS FALLS TESTS

Measured Mutual Impedances of Power and Telephone Circuits and Comparison with Values Calculated from Experimentally Determined Coupling Curves

| Section of telephone line | Measured mutual impedance—ohms | Calculated mutual impedance—ohms |
|---|---|---|
| 0–1 | 0.0586 /68.5° | 0.0614 /63.3° |
| 1–2 | 0.0294 /52.4° | 0.0564 /49.8° |
| 2–3 | 0.0476 /73.4° | 0.0382 /69.6° |
| 3–4 | 0.107 /56.4° | 0.113 /49.2° |
| 4–5 | 0.100 /44.4° | 0.0117 /35.8° |
| 0–5 | 0.347 /53.8° | 0.267 /55.3° |

the observed mutual impedances determined from this latter test are compared with values calculated by using the experimental coupling curve given on Fig. 16. The agreement between computed and observed values is, in general, only fair, although for two of the parts, the agreement is excellent. It is thought that the rather poor check for Sections 1-2 and 2-3 is due to the inductive effect of currents set up in the ground wire on another power line which extended through these sections. With regard to the extreme departure of the measured mutual impedance for Section 4-5 from that calculated it is impossible to decide the cause from the

experimental data available. A possible explanation is that it is due to a large difference in earth conductivity in this region from that in the region in which the coupling curve was determined. The large difference in this section is reflected in the rather poor check in the over-all coupling. (Section 0-5).

*Tests at Massillon, Ohio.* Tests made at Massillon, Ohio, were similar to those at Glens Falls, except that the arrangements were somewhat more elaborate.

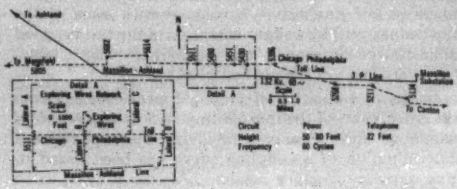


FIG. 17—MASSILLON TESTS—CIRCUIT ARRANGEMENTS

The layout of the circuits involved is shown in Fig. 17. The exposure is about 16 mi. long with separation between the power and telephone line ranging from a crossing to about 4200 ft., a large part of the exposure being at a separation of about 3000 ft. A set of "exploring wires," each 200 ft. in length, was laid on the ground parallel to the telephone line as shown in the detail of Fig. 17. These were arranged in four groups and were distributed over an area approximately 1½ by 2 mi. Coupling curves were determined from measurements of the voltage induced in the exploring wires for the condition of the telephone line energized with 6 amperes ground-return current, and also for the condition of the power line energized with 40 amperes ground-return current. The mutual impedances derived from the two sets of measurements are practically identical. Fig. 18 shows the resistive and reactive components of the coupling curve using the average of all measurements made on the exploring wires. A comparison of the measured curves with curves calculated by Carson's formulas for a value of earth conductivity of $3.6 \times 10^{-12}$ abmhos per cm. cube show the same type of agreement as that observed at Cross Keys and Glens Falls.

The principal reason for using such a large number of exploring wires on this particular test was to investigate the effect of local irregularities of the earth upon an experimental coupling curve and to determine the minimum number and length of exploring wires which it is necessary to use in order to be reasonably confident of the accuracy of the results. The data indicate that if only one of the seven groups of 200-ft. exploring wires had been used, the maximum deviation of any one point from the corresponding point on the average curve would have been less than 25 per cent and that the probable deviation would have been less than 10 per cent. This deviation could probably be reduced by using a somewhat longer exploring wire.

Measurements were also made of the voltage induced in sections of the telephone line when the power line was energized with ground-return current. A comparison of the measured values of the mutual impedance and those given from calculations using the coupling curves of Fig. 18 are given in Table III. With the exception of the section from pole 5134 to 5211, for which the calculations may be subject to some error due to proximity to the end of the disturbing circuit, and the section from pole 5614 to 5682, the agreement between measured and calculated values is satisfactory.

*D-C. Determination of Earth Conductivity.* In con-

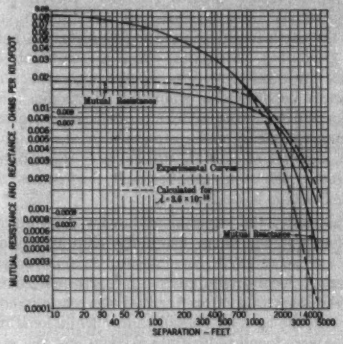


FIG. 18—MASSILLON TESTS

Experimental values of mutual resistance and reactance

sidering the experimental results described above, particularly the reasonably good agreement between the experimental coupling curves and those calculated by means of the Carson formulas with suitably chosen

TABLE III
MASSILLON TESTS

Measured Mutual Impedances of Power and Telephone Circuits and Comparison with Values Calculated from Experimentally Determined Coupling Curves

| Exposure | | Measured mutual impedance-ohms | Calculated mutual impedance—ohms |
|---|---|---|---|
| From pole | To pole | | |
| 5134 | 5211 | 0.0308 /45.9° | 0.0415 /35.5° |
| 5211 | 5268 | 0.0532 /44.7° | 0.0442 /34.2° |
| 5268 | 5386 | 0.282 /63.7° | 0.280 /64° |
| 5386 | 5511 | 0.0707 /30.3° | 0.0630 /28.2° |
| 5511 | 5614 | 0.0386 /29.7° | 0.0427 /28.5° |
| 5614 | 5682 | 0.0164 /18.4° | 0.0117 /14.8° |
| 5682 | 5805 | 0.141 /62.4° | 0.149 /59.2° |
| 5134 | 5805 | 0.609 /53.7° | 0.612 /52.5° |

earth conductivity, it seemed desirable to investigate whether an experimental value of earth conductivity alone would be sufficient information for the determination of coupling curves with enough accuracy for many

purposes. With this in mind, an investigation has been undertaken of more direct methods for determining the conductivity of the earth or more generally of methods for determining the structure of the earth in a particular location (whether homogeneous or stratified and, if the latter, the thickness of the strata) and the earth conductivity. The work is at present only in an early stage, but a brief statement of the method followed and of the results so far obtained may be of interest.

The procedure followed amounts to an investigation of the mutual resistance of a number of suitably located ground-return circuits, with direct current. It will be recalled that in an earlier part of the paper it was stated that for a homogeneous earth the mutual resistance of two ground-return circuits, for direct current, can be easily derived, and expressed in a formula involving only the earth conductivity and the distances between the grounding electrodes. For a stratified earth, similar formulas have been worked out involving the distances between the grounding electrodes and the conductivities, and the thicknesses of the several strata. By means of measurements of the mutual resistance for direct currents of circuits with suitably located ground electrodes, the conductivities and thicknesses of the strata can then be determined.

Practically, the experimental work presents many problems, among them being the elimination of the effects of stray earth currents and evaluation of the effects of local irregularities in earth conductivity. A preliminary trial of the method was made in connection with the tests at Massillon, and while local irregularities were found to be quite marked, yet the average earth conductivity in the region covered by the tests was about $1.5 \times 10^{-13}$ abmhos per cm. cube, which is not greatly different from that indicated by the coupling tests. A quite extended series of tests at Cross Keys, using an improved technique, yielded results in excellent agreement with the hypothesis that at this location the earth is stratified, having an upper layer about 150 feet thick with a conductivity about $3.4 \times 10^{-15}$ and a conductivity in the lower stratum about $2.6 \times 10^{-13}$.

## Conclusion

In conclusion, it is well to recall the end towards which the work described in this paper has been directed. It was desired, first, to obtain a sufficiently detailed experimental study of the mutual impedances of ground-return circuits to enable the formation of an adequate picture of the physical phenomena involved; also to test out the theoretical formulas available. Second, the aim was to investigate practical means for enabling the calculation of the ground-return mutual impedances of power and telephone lines.

With regard to the first item, it was found that an analysis in terms of an "equivalent ground-plane" was inadequate to represent completely the observed phenomena. However, when information is available as to the proper value of ground-plane depth, this method can be used to advantage in many cases where approximate results only are desired.

A theory based on the assumption of a d-c. distribution in the earth gave a somewhat better explanation, particularly in connection with the mutual impedances of circuits in which the points of ground connection were in close proximity, but left much to be desired in the way of quantitative agreement with the experimental results. The results of a theory which considers the effect of eddy currents in the earth are shown to be in fair qualitative agreement with some of the test values, and by a slight extension of the theory, good quantitative agreement can be found. This theory, however, does not explain end effects.

In the investigation of practical means for enabling the calculation of the mutual impedances of power and telephone lines a scheme involving the experimental determination of a coupling curve has been found to give quite satisfactory results. Further work is to be done on this problem, and similar tests must be made in several other locations before the method can be considered completely satisfactory. Other methods are also being investigated.

## Acknowledgment

The authors wish to express their appreciation of the assistance of Messrs. F. J. Grueter and B. C. Griffith in the field testing, analysis of the data and preparation of this paper, also to many others who have aided in this work. Thanks are due to the operating power and telephone companies who lent the facilities for some of the work described, and to members of their organizations who assisted in the tests.

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The following list is far from complete, but covers the more important papers which were consulted in the course of the work:

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9. "Gegenseitige Induktion Zwischen Wechselstromleitungen von Endliche Lange, F. Pollaczek, *Ann. der Physik*, Vol. 87, Dec. 1928, pp. 965-999. This paper treats of the mutual impedances of circuits of finite length. However, the assumptions regarding conditions at the ground connection seem to depart considerably from the practical conditions of the experiments reported in the present paper. For this reason, and the fact that numerical evaluations by these formulas are very laborious, no calculations by this method have as yet been made for comparison with the experimental results.

## Discussion

**E. P. Peck:** In this paper, the authors have drawn some conclusions regarding the structure and conductivity of the earth at the test location near Cross Keys, N. J. One of the other Project Committees of the Joint Subcommittee on Development and Research had previously made similar tests at this same location, from which the effective conductivity was determined by the same method as that used by the authors of this paper. In addition, because of the wide range of frequency used in

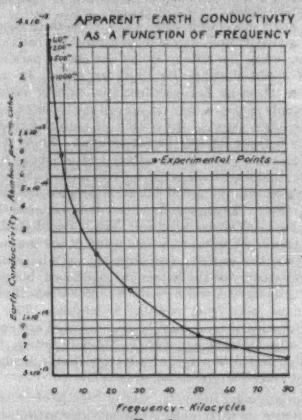



FIG. 1

these tests, it was possible to check an hypothesis as to the structure of the earth by a method entirely different from those described in the paper. The conclusions from the two different methods of attack are quite similar and it may be of interest to consider these other tests.

The tests described here were carried on, in connection with studies of inductive coordination at carrier frequencies. The mutual impedances were determined for the same circuits described in the paper, for a frequency range from 60 to 80,000 cycles. In these measurements, however, no attempt was made to determine the phase angle between the induced voltage and the inducing current.

By substituting the measured values of mutal impedance in Carson's formula, an effective value of earth conductivity was obtained for each frequency. A curve showing the variation of the earth conductivity with frequency is given. It will be seen that at 60 cycles, a value of earth conductivity of $3.3 \times 10^{-12}$ is indicated and that if the curve is extrapolated a limiting value of earth conductivity at the higher frequencies is approximately $5 \times 10^{-13}$.

In the case of a circuit with ground return energized with alternating current, the distribution of the earth current will be such that the impedance of the circuit will be a minimum. When the frequency of the current is low, the resistance of the earth return will be the controlling factor and the current will spread over a large cross section of the earth. At the higher frequencies, the inductance becomes the controlling factor and the earth return current will tend toward concentration in a much smaller cross-sectional area of the earth near the metallic conductor.

If the structure of the earth is such that there is an upper layer of poor conductivity and a lower layer of good conductivity, the apparent conductivity of the earth as determined from measurements of mutual impedance, will decrease with an increase of frequency until all of the current is in the upper layer and the apparent earth conductivity becomes a constant value. Using this method of analysis, the data yields the following conclusions: value of earth conductivity of the lower layer approximately $3.3 \times 10^{-12}$ abmhos per cm. cube; value of earth conductivity of the upper layer approximately $5 \times 10^{-13}$ abmhos. These values are in very good agreement with the results described in the paper where the earth conductivity determined directly from d-c. measurements indicated a conductivity of the lower layer of $2.6 \times 10^{-12}$ and the upper layer of $3.4 \times 10^{-13}$.

A comparison of the apparent earth conductivity from the two tests is given in the table below:

APPARENT EARTH CONDUCTIVITY

| Frequency | Table I of paper | Tests described in this discussion |
|---|---|---|
| 60 | $4.2 \times 10^{-12}$ | $3.3 \times 10^{-12}$ |
| 200 | $3.75 \times 10^{-12}$ | $2.95 \times 10^{-12}$ |
| 500 | $2.76 \times 10^{-12}$ | $2.6 \times 10^{-12}$ |
| 1000 | $2.0 \times 10^{-12}$ | $2.0 \times 10^{-12}$ |

**E. B. King:** From the standpoint of the practical operating problem, it may be of interest to point out the extent to which mutual impedance tests between power and communication circuits have been conducted in the past year, together with a brief discussion of some of the methods used in making these tests.

Incomplete records show that over thirty sets of cooperative tests have been made in various parts of Canada and the United States during the past twelve months.

These tests indicate a wide range of equivalent earth conductivities from about $2 \times 10^{-12}$ to approximately $10^{-16}$ c. g. s. electromagnetic units. A summary of the results indicates that there were four cases with earth conductivities between $10^{-11}$ and $10^{-12}$, fourteen cases between $10^{-12}$ and $10^{-13}$, ten cases between $10^{-13}$ and $10^{-14}$ and four cases between $10^{-14}$ and $10^{-15}$. In several of these exposures the separation was one-half mile or more. At a separation of 3000 ft. the ratio of the mutual impedance between the power and communication circuits would be approximately 20 to 1 for a range of earth conductivity between $10^{-12}$ and $10^{-13}$, in which limits about 75 per cent. of the exposures fell. For these same limits at a separation of 1000 ft. the ratio would be about 5 to 1, while for roadway separations, the ratio is less than 2 to 1. This wide range of earth conductivities and the resulting effect on the mutual impedance indicate the necessity for making mutual impedance tests, especially in cases of wider separations, where it is desired to obtain a reasonably accurate picture of the probable voltages that may be induced on the communication circuits. The cooperative tests that have been made fall under the following two general classifications:

1. Tests with the power line energized at low single phase voltage and grounded beyond the limits of each end of the exposure.

2. Tests with the power line energized at normal operating voltages, and the voltage induced on the communication circuits measured by means of automatic recording oscillographs at times of faults placed between one or more phase conductors and ground.

Most of the tests made come under the first classification.

In the tests described in the paper by Messrs. Bowen and Gilkeson an alternating current potentiometer was used to determine the magnitude and phase relation of the mutual impedance. However, such an instrument is not ordinarily available to operating companies wishing to conduct cooperative tests. Where the induced voltages are about 15 volts or more, standard a-c. voltmeters, ammeters and wattmeters can ordinarily be used with sufficient accuracy. For lower induced voltages down to about one-half volt, satisfactory results can usually be obtained by means of thermocouple voltmeters, amplifier voltmeters, and low power factor wattmeters.

**D. A. Pierce:** The tests described by Messrs. Bowen and Gilkeson are very necessary and apparently give satisfactory results. However, with tests of this character as with tests of most any other nature, a large part of the story in obtaining the final result is in an interpretation of the test results. Messrs. Bowen and Gilkeson have presented a most satisfactory discussion of ways and means for obtaining certain test results but they have not considered it within the scope of their paper to attempt an interpretation of the results obtained.

The work which they have conducted is primarily in connection with the study by the Joint Subcommittee on Development and Research of the coordination of power and communication lines. The power companies have made considerable progress in recent years in improving the operating characteristics of their lines. However, we have not as yet progressed to a point where there are not occasional breakdowns of insulators between conductor and earth. This breakdown of insulation results in a flow of current out over the conductors, with a return through the earth. This current in turn will produce a voltage in any nearby communication circuits, with its magnitude depending upon the magnitude of the coupling factor between the circuits and the current in the earth. By the use of the method of "Symmetrical Components," which has been developed by C. L. Fortescue and others, the fault current can be calculated and the ground current determined for any given condition with a reasonable degree of accuracy. This paper points out means for obtaining the coupling between the two circuits. These two factors permit us to calculate the induced voltage in the telephone line for an assumed given condition. Unfortunately, this does not complete the story in a coordination problem. We must also take into account the probability of the assumed condition of current—the number of times that the given condition will occur in a given length of time. In other words, a situation which would induce a given voltage "a" in a telephone line once in five years is entirely different from a situation which would induce the same voltage "a" into the telephone line once a week or even once a month.

Other factors, such as the effect of a given voltage in a telephone circuit, the distribution of this voltage between various parts of the circuit, and means for mitigating the voltage must also be considered before a complete answer can be given.

The Joint Subcommittee on Development and Research is working on all of these factors and hopes that within a reasonable time satisfactory answers can be obtained. However, much remains to be done before complete answers to all of these questions are known to the American industry and in the meantime we are simply going on trying to determine a reasonable solution based upon the facts we have in each case.

**L. P. Ferris:** Geological conditions undoubtedly influence the "equivalent earth conductivity" in different locations which we obtain when we compare experimental results with theoretical computations based upon the usual assumption of a homogeneous earth. It will be interesting as studies of this nature progress to endeavor to correlate the results with geological conditions.

I should like to bring to your attention a point which should be of interest to those applying the methods proposed in the paper to the practical predetermination of induced voltage. In mountainous districts it is not uncommon to find the strata of the earth greatly inclined with respect to their original horizontal position. This is evidenced by the outcroppings of the rock at the surface, some of these outcroppings showing the strata to be almost perpendicular. In such a region I believe the direction of the primary circuit with respect to the direction of the stratification planes has an important influence on the resulting distribution of the current in the earth, and hence, upon the mutual impedance between grounded circuits. It seems evident that if the primary circuit is parallel to the stratification planes, the distribution of earth current in the different strata, once we are beyond the region of end effects, will tend to remain constant from one location to another without the necessity of the current passing from one stratum to another. Under this condition, also, the current would tend to concentrate in the strata of higher conductivity. In contrast to this condition, if the primary circuit runs at right angles to the stratification planes, the earth current throughout the length of the line will have to pass from one stratum to another, giving a different distribution of earth current than in the first case. Under these conditions, we should certainly expect the coupling to be different, and, I believe, generally greater than in the case where the circuits all run parallel to the strata.

In the study of a specific case, which led to these conclusions, six short secondary lines were laid out parallel to a railway circuit in a region where the railway circuit was closely parallel to the planes of upturned strata, for about ten miles. In this same locality, a telephone line paralleled the railway circuit. By measurements in the railway circuit and in the short secondary circuits, a curve showing the relation of mutual impedance to separation between circuits was determined. From this curve and an accurate survey of the railway and telephone lines, the over-all mutual impedance in the ten-mile section was estimated and compared with the actual mutual impedance determined by measurements. The agreement in this case was good, the estimated value being about 4 per cent. high. Based on this same coupling curve, estimates were also made of the mutual impedance in two other sections of exposure 3½ and 8 miles in length, in the same vicinity as the section just mentioned, but generally at right angles thereto, which gave a condition where the primary current must pass from stratum to stratum. The over-all coupling for each of these sections was measured and compared with the estimated values. For the 3½-mile section, the estimated value proved 46 per cent too low and for the 8-mile section 21 per cent lower than the measured value.

I would conclude, therefore, that in regions of considerable stratification of the earth which is much inclined to the horizontal, the results of coupling tests where the current paths are in one direction with respect to the prevailing planes of the strata, should not be expected to apply accurately to an exposure, even in that immediate vicinity, in which the path of the inducing current would necessarily be at a markedly different angle with respect to the stratification planes. This, of course, is of more importance at larger separations where a difference in effective earth conductivity has more effect upon the coefficient of induction than at small separations. I hope that it may be possible in the future for an experimental investigation to be made, in which the system of primary and secondary circuits employed to determine a coupling curve, may be rotated from a position parallel to the outcropppings of strata to one at right angles thereto. I believe the results to be obtained will be both interesting and important.

**L. C. Peterson:** The paper deals with a subject which is of great interest to both power and telephone engineers. The phenomena discussed, however, apply only to steady state conditions. Under certain circumstances the transient induced voltages may also be of importance. It may, therefore, perhaps be of interest to mention some work which has been done on this problem. In a forthcoming issue of the *Bell System Technical Journal* this work will be discussed more fully.

Consider a system of two wires, 1 and 2 (wire 1 being infinite in length and hence end effects are neglected), parallel with each other and located on the surface of the earth but insulated from it except at the ends. The distance between the wires is $x$ cm. Let the voltage on wire 2 due to a unit current step (that is, a current equal to zero before $t = 0$ and unity thereafter) on wire 1 be denoted by $Z_{12}(t)$; then, the voltage on wire 2 due to a current $I(t)$ in wire 1 is given by the following formula:

$$V_{12}(t) = \frac{d}{dt}\int_0 Z_{12}(\tau)\, I(t-\tau)\, d\tau \qquad (1)$$

We shall apply this formula to the calculation of the transient induced voltage due to the sudden flow of a current $I(t) = \sin \omega t$. As $I(0) = 0$, formula (1) reduces to

$$V_{12}(t) = \int_0^t Z_{12}(\tau)\, \frac{d}{dt} I(t-\tau)\, d\tau \qquad (2)$$

The fundamental information required is thus a knowledge of $Z_{12}(t)$. In the case under consideration where both wires are located on the surface of the earth it can be shown that $Z_{12}(t)$ is given by

$$Z_{12}(t) = \frac{1}{\pi \lambda x^2}\left(1 - e^{-\frac{\pi \lambda x^2}{t}}\right) \qquad (3)$$

where $\lambda$ is the ground conductivity. It may be noted that in obtaining this formula use has been made of Carson's fundamental formulas which may be found in reference (4) of the paper by Messrs. Gilkeson and Bowen. From (2) and (3) and by assuming $I(t) = \sin \omega t$ we get

$$V_{12}(t) = \frac{\sin \omega t}{\pi \lambda x^2} - \frac{\omega}{2\pi \lambda x^2}\left[e^{j\omega t}\int_0^t e^{-\frac{\pi \lambda x^2}{t} - j\omega t}\, d\tau + e^{-j\omega t}\int_0^t e^{-\frac{\pi \lambda x^2}{t} + j\omega t}\, d\tau\right] \qquad (4)$$

The solutions of the integrals appearing in (4) are not known in closed form. The following series expansions for small and large values of time may be derived however:

$$V_{12}(t) = \frac{\sin \omega t}{\pi \lambda x^2} - \frac{\omega}{\pi \lambda x^2}\, e^{-\frac{\pi \lambda x^2}{t}}\left(t^2 \frac{\cos \omega t}{\pi \lambda x^2} + t^3\left(\frac{\omega \sin \omega t}{\pi \lambda x^2} - \frac{2!\cos \omega t}{(\pi \lambda x^2)^2}\right) + t^4\left(\frac{3!\cos \omega t}{(\pi \lambda x^2)^2} - \frac{3\,\omega \sin \omega t}{(\pi \lambda x^2)^2} - \frac{\omega^2 \cos \omega t}{\pi \lambda x^2}\right) + \ldots\right) \qquad (5)$$

and

$$V_{12}(t) = -\frac{1}{\omega}\left(\frac{1}{t^2} - \frac{\pi \lambda x}{t^3} + \frac{1}{t^4}\left(\frac{(\pi \lambda x^2)^2}{2!} - \frac{3!}{\omega^2}\right) + \ldots\right) + S \qquad (6)$$

where $S$ denotes the steady state voltage.

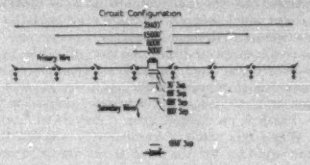
For such values of time where neither of these series expansions would give very accurate results some means of mechanical integration has to be employed.

The complete expression for the disturbing current contains in addition to the term $\sin \omega t$ also the term $e^{-\beta t}$ where $\beta$ is the damping constant of the circuit. For small values of time the voltage due to the current $e^{-\beta t}$ may be found by a process analogous to that used in obtaining equation (5), while for larger values of time mechanical integration must be resorted to.

For more complicated time functions of the disturbing current, the analytical evaluation of the integrals becomes quite difficult and mechanical integration must be used.

**K. L. Maurer:** A very interesting feature of this paper is the description of methods of obtaining experimental information upon which can be based estimates of mutual impedances of ground return circuits in advance of their construction. It is usually a relatively simple matter to measure the self and mutual constants of circuits which either directly or indirectly involve the earth, after the circuits have been established. However, it often is important to have information on such constants in advance of construction as they may have a material bearing on features of design. The importance of this in relation to the problem of inductive coordination of power and communication systems is obvious.

A knowledge of the self and mutual constants, on a ground return basis, of elements of electrical networks is also often of importance in connection with other problems in the fields of



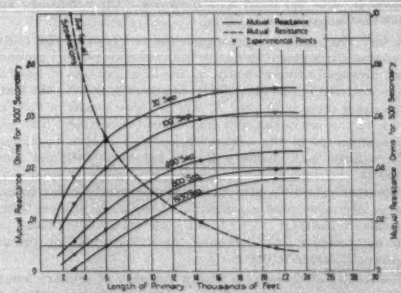




FIG. 2—VARIATION OF MUTUAL IMPEDANCE BETWEEN SHORT PARALLEL STRAIGHT WIRES GROUNDED AT THEIR ENDS AS THE LENGTH OF ONE WIRE IS VARIED

communication and power transmission. For example, in the case of a fault on a transmission line, from line to ground, the self-impedance of the faulted phase and the division of return current between ground wire and earth involve grounded circuit theory. Another good example is the propulsion systems of electrified railroads using the running rails to return all or a part of the current. Determination of self and mutual impedances of various elements of the propulsion network and the amount of current escaping from track to earth require a knowledge of the ground return constants of these circuit elements.

A series of field tests was completed several months ago in the eastern part of Pennsylvania in connection with advance estimates of induced voltages from a railroad electrification. The testing arrangements were generally similar to those used at Cross Keys, as described in the paper. The primary circuit consisted of a straight wire laid on the ground and connected to

ground rods at its terminals. This wire was unreeled from a specially equipped motor truck which also contained a variable frequency generator used for energizing the primary. For the secondary, or disturbed circuits, wires were also laid on the ground parallel to the primary at various separations from it and grounded at the terminals. The secondaries were unreeled from a second truck which was equipped with apparatus for determining the mutual impedance. Testing frequencies between 25 and 75 cycles were used.

One object of the tests was to cover a large number of locations in as short a time as possible, and the equipment was designed and the test procedure arranged to promote this end. For practical reasons it was desired to limit the primary length to 5000 or 6000 ft. The secondaries were arranged symmetrically about the center of the primary and their length was generally limited to 500 ft. to avoid effects due to proximity of the primary and secondary ground connections. Separations from 30 to 2000 ft. were used.

It was discovered in the early stages of the tests that for this circuit arrangement, the real component of the observed mutual impedance was much larger than could reasonably be accounted for by the infinite length circuit theory of Carson[1] and Pollaczek.[2] From this it was suspected that the spacing of the primary and secondary electrodes was not sufficiently wide to avoid end effects. A value of ground conductivity was obtained from the real component by the use of the Campbell[3] expression for mutual resistance which is predicated upon a d-c. distribution of earth current. When this value of conductivity was substituted into the Carson equation for the mutual reactance, a much larger value was obtained than had been measured. This observation led to the conclusion that for this locality, the primary length of 6000 ft. was too short to approximate the conditions upon which the Carson theory is based.

A test was made to investigate the behavior of the mutual impedance for a given frequency between two parallel grounded wires, arranged symmetrically, as the length of one of the wires was increased from about 3000 ft. to about 21,000 ft., the length of the other remaining fixed at 500 ft. The results of this test, shown on the accompanying curves are interesting. The reactive component of the mutual impedance is seen to increase quite rapidly with primary length between 3000 and about 10,000 ft., beyond which the increase is more gradual. The real component of the mutual impedance, on the other hand, is seen to decrease quite rapidly with increasing primary length up to about 15,000 ft. The trend of these curves indicates that both components would become about constant at primary lengths of 25,000 to 30,000 ft.

The results of these tests with a plurality of primary lengths were useful in interpreting the results of the tests in which the 6000-ft. primary was used.

**J. Riordan:** The experimental observations given in this paper by Messrs. Bowen and Gilkeson are for a steady state condition with periodic current. It may be of interest to describe briefly some work done in finding formulas for the transient impedances of ground return circuits, which is based upon a formula for steady state mutual impedance between ground return wires of finite length recently given by R. M. Foster.[4] Mr. Foster's formula for the mutual impedance between differential elements of two wires is in a remarkably simple form. While the integrations necessary to obtain a formula for straight wires of finite length cannot be effected in closed form in terms of known functions, the integrations can be performed for a unit step current. My result is as follows:

The voltage in wire 2 of two straight parallel wires separated by distance $x$, lying on the surface of the ground and insulated from it except at the ends, with unit step current (zero $t < 0$, unity $0 < t$) in wire 1, is given by the following formula:

$$Z_{12}(t) = \frac{1}{2\pi\lambda}\left[\phi(z_2+a)-\phi(z_1+a)-\phi(z_2-a)+\phi(z_1-a)\right] \quad (1)$$

Here the rectangular coordinates of the terminals of wire 1 are $(o, o, -a)$ and $(o, o, +a)$ and of wire 2 are $(x, o, z_1)$ and $(x, o, z_2)$; $\lambda$ is the ground conductivity in electromagnetic c. g. s. units. The function appearing is:

$$\phi(u) = \frac{-1}{\sqrt{x^2+u^2}} + \frac{\sqrt{x^2+u^2}}{x^2}\,\mathrm{erf}\left(\sqrt{\frac{\pi\lambda}{t}}\sqrt{x^2+u^2}\right) - \frac{u}{x^2}\exp\left(-\frac{\pi\lambda x^2}{t}\right)\mathrm{erf}\left(u\frac{\sqrt{\pi\lambda}}{t}\right)$$

$$\text{where } \mathrm{erf}(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-u^2}\,du$$

The time is in seconds and distances are in centimeters; the dimensions of the result are abvolts per unit abampere, that is, abohms.

When wire 1 is made infinite this formula reduces to the corresponding formula (per unit length of wire 2) given in L. C. Peterson's discussion of this paper, namely:

$$\frac{Z_{12}(t)}{z_2-z_1} = \frac{1}{\pi\lambda x^2}\left[1-\exp\left(\frac{-\pi\lambda x^2}{t}\right)\right] \quad (1a)$$

When the current in wire 1 is a function of the time such as is ordinarily found, $1-e^{-\gamma t}$, $e^{-\gamma t}\sin wt$, $\sin wt$, or combinations thereof, the resulting voltage is not expressed in terms of known functions. My results for these cases are not given here because the formulas are complicated. In practical computation when curves of $\phi(u)$ given above are available, it is probably more expedient for these time functions of current to use Carson's extension formula, one form of which is:

$$V(t) = \frac{d}{dt}\int_0^t I(t-T)\,Z_{12}(T)\,dT^{5}$$

and perform the integration numerically or mechanically.

**A. E. Bowen and C. L. Gilkeson:** The excellent agreement between the results reported in the paper and those reported by Mr. Peck is very gratifying, and lends further support to the theory advanced in the paper as to the stratified nature of the earth at the Cross Keys location.

The discussions by Messrs. King and Pierce are a valuable addition to the paper for they show the relationship of this work to the general problem of inductive coordination.

The discussions by Messrs. Ferris and Maurer have brought out the importance of several precautions which should be taken in using the exploring wire method of predetermining the mutual impedance of power and telephone circuits. One of these possible sources of errors, as brought out by Mr. Ferris, is the possibility of the earth conductivity changing appreciably within the length of the line. Because of this possibility, where the exposure is long, or where there is some indication that the earth structure may change within the exposure, exploring wire measurements should be made at two or more points within the exposure. If such a precaution is not followed the results of the tests may apply to only one section of the exposure and may result in a very misleading idea of the total coupling between the two circuits.

1. Reference 7 of paper by Messrs. Bowen and Gilkeson.
2. Reference 6 of paper by Messrs. Bowen and Gilkeson.
3. Reference 2 of paper by Messrs. Bowen and Gilkeson.
4. Bulletin of the American Mathematical Society, May, 1930, pp. 367-368 (Abstract).
5. *Electric Circuit Theory and the Operational Calculus*, J. R. Carson, McGraw-Hill Co., 1926, p. 16.

Another possible source of error may be due to local irregularities where the exploring wires are installed. A limited amount of experience has indicated that if a coupling curve (such as that shown in Fig. 16) is determined from measurements in exploring wires at several separations using an exploring wire length of at least 500 ft. these errors are partially averaged out and the remaining error should be quite small.

The discussion by Mr. Maurer on the effects caused by proximity of the ground on the disturbing and disturbed circuits is of great interest, and the experimental results given in his curves are a valuable contribution. The method of attack is different from that chosen by the authors, but the results seem at least qualitatively in accord with those given in the paper. The experimental investigation of the problem seems not yet far enough advanced so that the relative importance of the factors influencing this effect can be evaluated. It seems evident, however, that the region in which end effects will be felt will vary widely in different locations, being greatly influenced by the ground conductivity. The structure of the earth and the frequency of the current will also affect the extent of this region.

The calculated curves of Fig. 10 in the paper illustrate roughly the effect of earth conductivity upon the extent of this area. The effect of the frequency of the current in the disturbing circuit should be such that as it is increased the region influenced by "end effect" is somewhat reduced. Further tests are in progress to amplify our information on these points.

In the area influenced by end effects three phenomena are present which do not appear in other parts of the exposure. Two of these are illustrated in Fig. 5 of the paper, which shows that within this region the gradient of mutual impedance parallel to the disturbing circuit is not a constant and that the gradient perpendicular to the circuit is far from being negligibly small. Fig. 6 shows that near the point of grounding the phase angle of mutual impedance is very small, gradually increasing to a constant value at the point where end effect fades out. Since the region affected depends so largely upon earth conductivity, no rule can be given as to the minimum length of the disturbing circuit which may be used with exploring wires. For this reason steps should be taken in any particular case to assure that the primary line is made so long that the voltages induced in the exploring wires are free from end effects.

Since the paper was written a more complete study of the end effect phenomena has been made at Cross Keys. This includes the determination of the magnitude and direction of the gradient of mutual impedance within a radius of 2000 ft. of one of the electrodes. These measurements have added much to our knowledge of the phenomena but have not changed any of the results given in the paper.

The discussions of Messrs. Peterson and Riordan concerning voltages induced by transient currents are of considerable interest. There is but a small amount of experimental information available on this phase of the problem and much work remains to be done. It is noted that in both developments theoretical formulas for the steady-state mutual impedances are used, and in this respect, the work given in this paper should be useful.

# Effects of the Magnetic Field
## on Lichtenberg Figures

BY C. EDWARD MAGNUSSON[1]

Fellow, A. I. E. E.

***Synopsis.***—*This paper deals with new forms of Lichtenberg figures produced under the combined stress of dielectric and magnetic fields. The effects produced by the magnetic field may be used for determining whether electrons, positive ions, or protons, are basically the active elements in the formation of the positive as well as the negative figures. The photographs also show that the presence of the magnetic field greatly extends the range of air pressures within which figures of definite form can be obtained; that figures taken at low air pressures possess structures strikingly different from those hitherto known; and that these figures may prove a key to the mechanism of the electric spark.*

* * * * *

MANY extensive investigations have been made to ascertain the nature of Lichtenberg figures and lately, on their use for recording certain characteristics of electric surges and impulses, for measuring short time intervals, etc.; but no attempt seems to have been made to determine what effects, if any, would be produced on the figures if formed under the stress of the magnetic field. That a reaction should be expected is evident, if the figures are formed by rapidly moving electrons, ions or protons, as has been postulated in the several theories advanced to explain the phenomena.

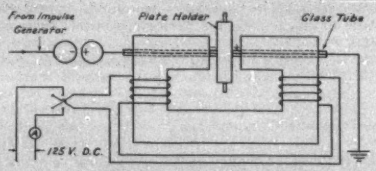



FIG. 1—CIRCUIT DIAGRAM

Photographic plates: Lumiere, Sigma, 3¼ in. x 4¼ in. (8.3 x 11.8 cm.)
Source of voltage: "Static" from a belt.
Spark-Gap: Copper spheres, 10 in. (25.4 cm.) in diam.
Electromagnet: movable cylindrical pole cores, 2.8 in. (7.1 cm.) in diam. Circular pole faces, 2.8 in. (7.1 cm.) in diam., in parallel planes; spacing of pole faces, (space occupied by plate holder) for the figures reproduced in this paper: 1.18 in. (3 cm.)

The experimental results are in fact striking and provide the means for determining whether electrons, ions, or protons, are basically the active elements in the formation of the positive as well as the negative figures. The photographs show also that the presence of the magnetic field greatly extends the range of air pressures within which figures of definite form can be obtained; that at low air pressures the structures of the figures are radically different from those hitherto known; and that these figures may prove a key to the mechanism of the electric spark.

This paper deals with the results obtained during the first stage of an investigation on the effects produced by the magnetic field on Lichtenberg figures in progress at the University of Washington. The 280 photographs already taken form a very interesting exhibit; but unfortunately many features of the photographic records cannot be satisfactorily reproduced in halftone cuts.

A diagram of the electric circuit and the arrangement of the apparatus used in the experiments is shown in Fig. 1. The following data will serve in place of a detailed description of the equipment:[2]

A cross-section of the plate holder loaded with two plates, as used in the first part of the work, is shown in Fig. 2.

A pair of photographic plates were placed with the emulsion side outwards; that is in contact with the + and − electrodes. A thin brass plate, 3¼ in. by 4¼ in., was placed between the two photographic plates. For air pressure greater than 25 cm. Hg., the brass plate was not used, as better results were obtained without it; but in order to obtain well-defined figures at lower air pressures, it was found necessary to have the brass plate in contact with the two photographic plates, as shown in Fig. 2. By trial, it was found that the positive and negative figures could be taken simultaneously and just as good photographs obtained as when a separate exposure was made for either the positive or the negative figure. By using two plates as shown in Fig. 2, the number of exposures was cut in two, and, what is of greater importance, both the positive and the

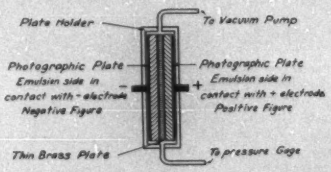



FIG. 2—CROSS-SECTION OF LOADED PLATE HOLDER

1. Professor of Electrical Engineering and Director Engineering Experiment Station, University of Washington.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

2. Lichtenberg Figures, A. I. E. E. JL., Vol. XLVII, 1928, p. 830.

negative figure were obtained for the identical spark or impulse.

For all the figures illustrating this paper, the direction of the magnetic lines of force was perpendicular to the plane of the photographic plate; the direction of the field could be reversed by means of a double-throw field switch. On the legend below each figure, the direction of the magnetic field with respect to the printed page is indicated by the letters $N$ or $S$. The letter $S$ indicates that the south pole was in front, and

FIG. 3

Pressure 76.1 cm.; Gap 4.0 cm.; Field $N$, 12,300 cm$^2$. Electrode +; Paired with Fig. 4; Neg. No. 193.

the north pole back, of the printed page; that is, the direction of the magnetic lines of force is towards the reader. The notation $N$ indicates the reverse,—the north pole is in front and the south pole back of the printed page, or the direction of the magnetic lines of force is away from the reader.

Under each figure, the legend gives the quantitative

FIG. 4

Pressure 76.1 cm.; Gap 4.0 cm.; Field $S$, 12,300 cm$^2$. Electrode −; Paired with Fig. 3.; Neg. No. 194.

data for the conditions under which the exposure was made. The air pressure is given in cm. Hg.; the spark-gap spacing in cm.; the direction of the magnetic field, $N$ or $S$; the field strength in lines of force per cm.$^2$; the polarity of the electrode in contact with the emulsion side of the plate as + or − ; and, finally, the number of the corresponding figure in the pair, produced by the same impulse.

Figs. 3 and 4 were taken under normal atmospheric pressure conditions. On careful scrutiny, a distinct bending of the rays or streamers in the negative figure may be noted, but little if any effect can be observed on the positive figure. However, exposures made under less than atmospheric pressure, as illustrated by Figs. 5 to 10 inclusive, show very marked bending and changes in structure of the otherwise radial streamers.

*The Negative Figure.* For the range of air pressures and impressed voltages represented in Figs. 3 to 10, inclusive, the main effect produced by the magnetic field on the negative figures is the bending of the rays; *clockwise*, if the magnetic lines of force are in the $N$

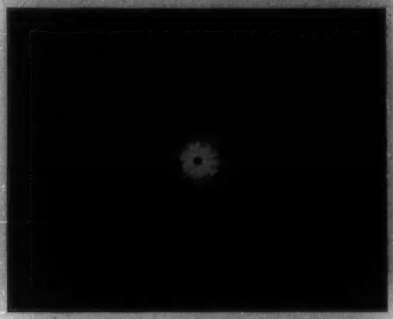


FIG. 5

Pressure 30.0 cm.; Gap 4.0 cm.; Field $N$, 13,000 cm$^2$. Electrode +; Paired with Fig. 6.; Neg. No. 135.

FIG. 6

Pressure 30.0 cm.; Gap 4.0 cm.; Field $S$, 13,000 cm$^2$. Electrode −; Paired with Fig. 5; Neg. No. 136.

direction, as in Fig. 10, and *counterclockwise*, if the field is in the $S$ direction, as in Figs. 6 and 8.

The observed reaction on the negative figure is in full accord with theory. There seems to be little or no difference of opinion as to the mechanism of the formation of the negative figure. The theories are based on the postulate that, under the impulse voltage-gradient, streams or rays or waves of electrons are projected radially from the negative electrode at high velocity

over the emulsion surface of the photographic plate. The effect of the magnetic field in bending the otherwise radially projected rays or streamers is in accord with this assumption. Thus in Fig. 10 the direction of the magnetic lines of force is $N$; that is, from the reader through the printed page. A stream of electrons projected radially from the negative electrode over the

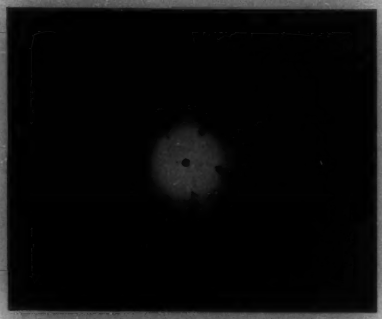


FIG. 7

Pressure 15.0 cm.; Gap 2.5 cm.; Field $N$, 12,300 cm$^3$.
Electrode +; Paired with Fig. 8; Neg. No. 171.

photographic plate, and therefore at right angles to the magnetic field, should be deflected in a clockwise direction; precisely as shown in the figure. In Figs. 6 and 8 the magnetic field is in the $S$ direction, the reverse of

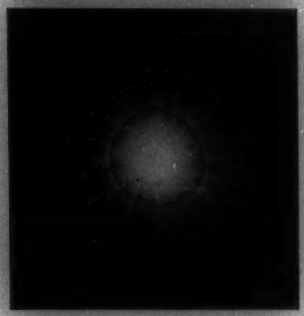


FIG. 8

Pressure 15.0 cm.; Gap 2.5 cm.; Field $S$, 12,300 cm$^3$.
Electrode −; Paired with Fig. 7; Neg. No. 172.

that in Fig. 10; therefore, the radially projected electrons should be deflected in the counterclockwise direction, which the figures show to be the case. The effects of the magnetic field confirm the assumption that electrons, projected at a high velocity from the negative electrode, are the active elements in the formation of the negative figure.

*The Positive Figure.* For the positive figure the situation is somewhat more complex, and several theories have been advanced to explain its formation.

Pzribram[3] contends that positive ions, projected radially from the positive electrode are essential fac-

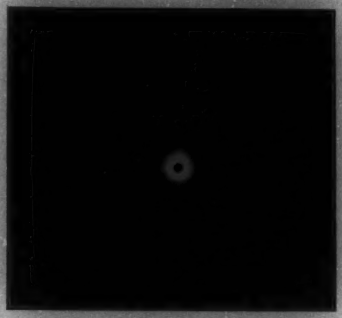


FIG. 9

Pressure 12.0 cm.; Gap 1.2 cm.; Field $S$, 12,400 cm$^3$.
Electrode +; Paired with Fig. 10; Neg. No. 185.

tors in the mechanism forming the positive figures. He expresses the basic postulates of the theory of formation for both positive and negative figures in the "Fundamentalgegensatz: negatives Elektron—positives Ion."

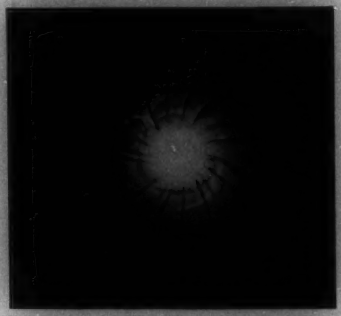


FIG. 10

Pressure 12.0 cm.; Gap 1.2 cm.; Field $N$, 12,400 cm$^3$.
Electrode −; Paired with Fig. 9; Neg. No. 186.

In order to reconcile the theory with experimental facts, Pedersen postulates protons, positive hydrogen nuclei, as the active elements in place of the more general positive ion. In an important monograph on "The Positive Figure" Pedersen[4] gives a comprehensive

3. K. Pzribram, *Handbuch der Physik*, Vol. XIV, 1927, p. 404.
4. P. O. Pedersen, Lichtenberg Figures III, 1929, p. 105, *Kgl. Danske Vid. Selskab, Math.-Fys. Meddelelser*, VIII, 10.

review of the subject and concludes as follows: "that formation of positive spreaders is due to protons which the strong field at the tip of the spreaders drive outwards with great velocity, by which means electrons are set free in sufficient number to initiate a sudden and strong ionization by collision which again sets free electrons in sufficient numbers necessary to carry away the charge towards the electrode is found to explain throughout in a satisfactory manner the many peculiar features presented by the positive spreaders."

Yoshida[5] offers an entirely different solution: He

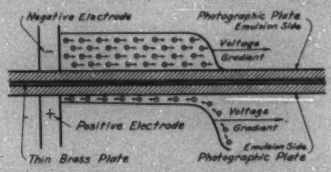



FIG. 11—VOLTAGE GRADIENTS AND ELECTRON STREAMS AT POSITIVE AND NEGATIVE ELECTRODES

holds that the mechanism for the formation of the positive figure consists of electrons attracted by and moving towards the positive electrode. That is, the electrons in motion are the active elements in the formation of both the positive and the negative figures;

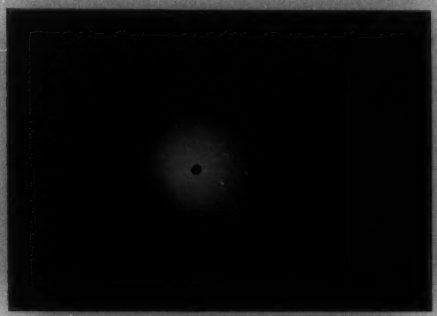


FIG. 12

Pressure 5.0 cm.; Gap 0.6 cm.; Field $N$, 12,000 cm$^3$.
Electrode +; Paired with Fig. 13; Neg. No. 213.

motion in direction towards the positive electrode for the positive figure, and away from the negative electrode for the negative figure.

The experimental evidence hitherto available has been inadequate to either fully establish or refute the proposed theories, but it appears that the reaction of the magnetic field will provide the required criterion. In this connection, let the discussion of Figs. 7 and 9 be confined to the space within a radial range of about one inch (2.5 cm.) from the electrode; that is, the reverse bend of the tips of the streamers may be due to other factors which have not as yet been fully determined.

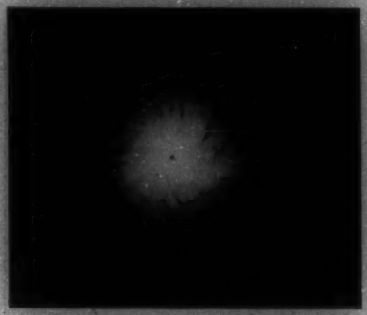


FIG. 13

Pressure 5.0 cm.; Gap 0.6 cm.; Field $S$, 12,000 cm$^3$.
Electrode −; Paired with Fig. 12; Neg. No. 214.

Let the argument be applied first to the postulates of positive ions or of protons projected outwards from the positive electrode. Consider the direction of motion that positive ions or protons would have at some point,—as $a$ in Fig. 7,—under the combined stress of the voltage gradient and the magnetic field. The

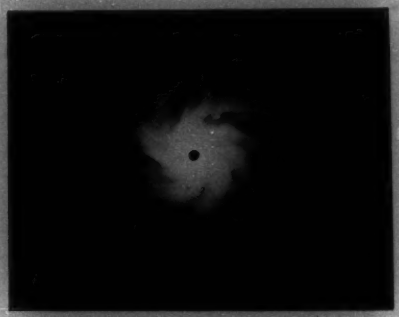


FIG. 14

Pressure 2.0 cm.; Gap 0.5 cm.; Field $N$, 12,300 cm$^3$.
Electrode +; Paired with Fig. 15; Neg. No. 326.

magnetic field is in the $N$ direction. The force of the voltage gradient projects the positive charge radially away from the electrode and simultaneously, the reaction of the magnetic field produces a force on the positive ions or protons at right angles to their motion and in the *counterclockwise direction*. The photographic

5. U. Yoshida, *Mem. Col. Sci.*, Kyoto Univ., Vol. 2, 1917, p. 105.

record in Fig. 7 shows the streamers deflected in the *clockwise direction*, and therefore the theory based on the postulates of positive ions or protons as the essential elements in the formation of the positive figure does not conform to the experimental evidence.

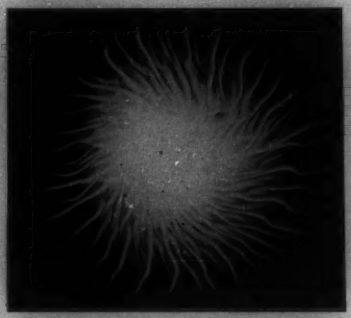


FIG. 15

Pressure 2.0 cm.; Gap 0.5 cm.; Field $S$, 12,300 cm$^2$.
Electrode $-$; Paired with Fig. 14; Neg. No. 325.

Let the same argument be applied to the assumption that electrons falling towards the positive electrode are the active elements in the formation of the positive figures. Consider the direction of motion that an electron at the point $a$ in Fig. 7 would have under the combined stress of the dielectric and magnetic fields;

FIG. 16

Pressure 0.75 cm.; Gap 0.5 cm.; Field $N$, 12,600 cm$^2$.
Electrode $-$; Paired with Fig. ..; Neg. No. 381.

the voltage gradient would cause the electron to fall radially towards the positive electrode, while the reaction of the magnetic field would be at right angles to the direction of motion of the electron and, as in the previous case, in the *counterclockwise* direction. The resulting curved path, (if the positive electrode is used as the point of reference), would be deflected in the *clockwise* direction; that is, in accord with the form of the streamers in Fig. 7.

Similar observations may be made for Fig. 9. In this case the magnetic field is in the $S$ direction. The

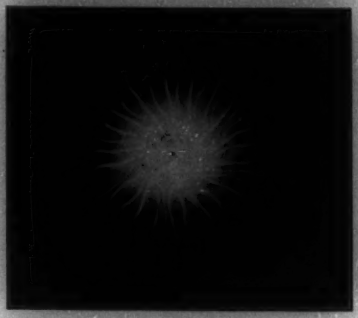


FIG. 17

Pressure 0.25 cm.; Gap 0.5 cm.; Field $S$, 12,500 cm$^2$.
Electrode $-$; Paired with Fig. ..; Neg. No. 395.

reaction of the magnetic field on positive ion or proton at any point as $a$, Fig. 9, projected by the voltage gradient radially outwards from the positive electrode, would be a force at right angles to the direction of motion that would cause a deflection in the *clockwise*

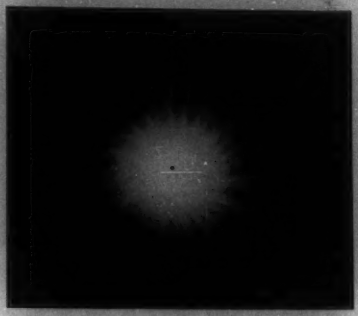


FIG. 18

Pressure 0.09 cm.; Gap 0.5 cm.; Field $S$, 12,500 cm$^2$.
Electrode $-$; Paired with Fig. ..; Neg. No. 397.

*direction*. This is, however, in the reverse direction to that shown by the streamers in Fig. 9.

On the other hand, consider an electron at the point $a$ in Fig. 9, under the stress of the voltage gradient, falling radially towards the positive electrode. The reaction of the magnetic field would be at right angles

to the direction of motion and in the clockwise direction. Using the positive electrode as the center of reference, the resulting path of the electron would be deflected in the *counterclockwise* direction. The theory based on the postulate of electrons falling towards the positive electrode as the active elements in the formation of the

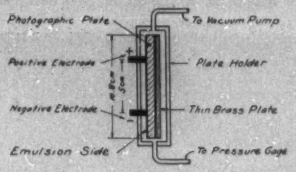



FIG. 19—LOADED PLATE HOLDER

positive figure is supported by the photographic records in Figs. 7 and 9.

To illustrate the explanation offered for the formation of both the negative and the positive figures, a diagrammatic representation of the voltage gradient waves and the direction of motion of the electrons with respect to both the positive and the negative electrodes is shown in Fig. 11. The diagram shows in cross-section of the holder with the two photographic plates, the brass plate and the positive and negative electrodes as when

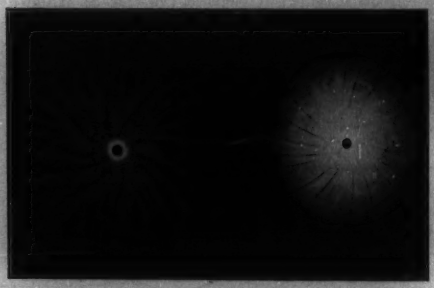


FIG. 20

Pressure 15.0 cm.; Gap 1.0 cm.; Field $N$, 12,500 cm$^2$.
Electrode −, +; Paired with Fig. . . ; Neg. No. 394.

exposures were made for Figs. 3 to 10 and 12 to 18, inclusive.

The steep ionizing voltage gradient waves spread outwards from the two electrodes. From the negative electrode, a wave or stream of electrons is projected radially over the emulsion surface of the upper photographic plate. The negative figure is formed as the stream of electrons pass over the plate and as an after effect, the air near the surface of the plate becomes highly ionized.

An ionizing voltage gradient wave likewise travels outwards from the positive electrode over the emulsion surface of the lower photographic plate. The direction of motion of the electrons is, however, towards the electrode,—that is, opposite to the motion of the voltage gradient wave. It is also assumed that the positive streamers, or grooves, are paths of very low resistance and that therefore the voltage gradient will be of ionizing intensity for greater distances from the electrode than in the corresponding negative figure.

*New Types or Forms of Lichtenberg Figures.* In the presence of the magnetic field the range of air pressure within which Lichtenberg figures of definite form and structure can be obtained is greatly extended.

The lower limit of air pressure in which Lichtenberg figures, hitherto taken without the presence of the magnetic field have even a semblance of definite form and structure, is approximately 5 cm. Hg. At lower air pressures the figures lack definition and have the appearance of a nebulous haze or fog. Under the

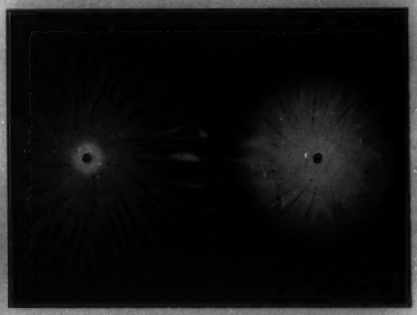


FIG. 21

Pressure 15.0 cm.; Gap 1.1 cm.; Field $N$, 12,500 cm$^2$.
Electrode −, +; Paired with Fig. . . ; Neg. No. 393.

stress of the magnetic field the results are strikingly different; as evidenced by the photographs shown in Figs. 12 to 18, inclusive, figures of definite form and sharply defined structural details can be obtained at much lower air pressure. Special attention is called to Figs. 15 to 18 as being radically different in structure from the negative figures obtained at air pressures greater than 10 cm. Hg. The positive figures are weaker and not so well defined, but possess structural forms at much lower air pressures when under the stress of the magnetic field.

*Both Electrodes on One Plate.* For Figs. 20 to 24 inclusive, both electrodes were in contact with the emulsion side of a single plate. The arrangement of the electrodes, photographic plate, and brass plate, is shown in Fig. 19. By this method, both the positive and the negative figures produced by a single impulse are obtained on the same photographic plate. This arrangement has been used in attempts to determine

the nature of the figures themselves and in the study of related phenomena, such as sparkover[6] and breakdown of dielectrics, etc.; but when exposure is made under the stress of the magnetic field, the resulting figures acquire different forms that throw new light on the processes involved.

In Figs. 20 to 24 are shown a series of exposures

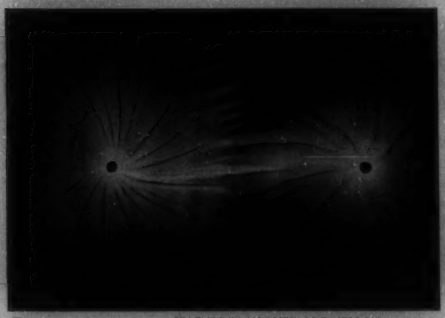


FIG. 22

Pressure 15.0 cm.; Gap 3.8 cm.; Field $S$, 12,300 cm$^2$.
Electrode −, +; Paired with Fig. . . .; Neg. No. 388.

showing positive and negative figures for progressively higher impressed voltages and correspondingly greater after effects. In order to correlate the more prominent features of the above figures let it be assumed:

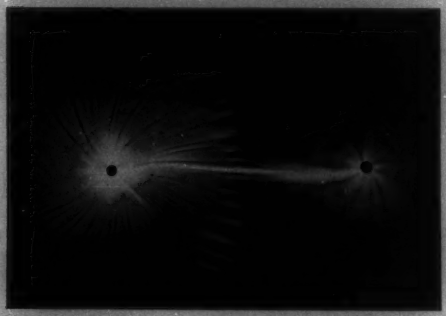


FIG. 23

Pressure 15.0 cm.; Gap 4.0 cm.; Field $N$, 12,500 cm$^2$.
Electrode −, +; Paired with Fig. . . .; Neg. No. 384.

(a) That the positive streamers or grooves are paths of high conductivity.

(b) That the space near to the negative figure, and especially near its periphery, is in a highly ionized state after the figure is formed.

(c) That the difference of potential between the two electrodes persists for some time after the Lichtenberg figures proper, have been formed.

The bending of the streamers in the positive and negative figures is in the same direction, using the

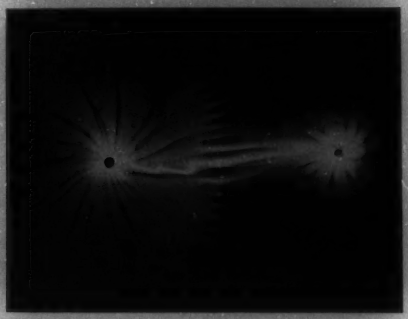


FIG. 24

Pressure 15.0 cm.; Gap 4.0 cm.; Field $S$, 12,500 cm$^2$.
Electrode −, +; Paired with Fig. . . .; Neg. No. 385.

electrodes as centers of reference. In Figs. 20, 21, and 23, the magnetic field was in the $N$ direction and produced clockwise deflections in both the negative and the positive figures. For Figs. 22 and 24 the direction of the magnetic field was in the $S$ direction and as a consequence, the streamers for both the positive and the negative figures show counterclockwise deflections.

In Fig. 20 the impressed voltage was barely sufficient

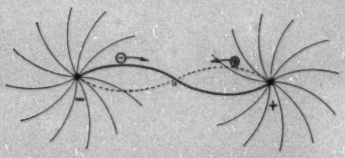



FIG. 25—DEFLECTIONS OF POSITIVE AND NEGATIVE STREAMER

to form a single connecting bridge or link between the two figures. In Fig. 21, with slightly higher voltage impressed, three paths bridge the gap between the two figures. Due to higher impressed voltages larger number of paths between the two figures is found in Figs. 22, 23, and 24. Each tuft or brush of light formed near the periphery of the negative figure is directed towards, and connected to, a prong or tip of a streamer in the positive figure. It should be noted that the brushes or paths bridging the space between the original

6. Erwin Marx, "Untersuchungen Uber den Elektrischen Durschlag und Uberschlag in Unhomogenen Felde," *Archiv für Elektroteknik*, Vol. 20, 1928, p. 605.

Lichtenberg figures are apparently formed after the negative figure proper has been completed. This is shown most clearly in Fig. 21, but can readily be observed in Figs. 22, 23, and 24.

The tufts or brushes formed at the tips of the streamers in the positive figure, Figs. 21, 22, and 23, increase in size as the impressed voltage is increased. If sufficiently high voltage persists between the electrodes after the initial figures have been formed the gap between the electrodes is bridged by a sparkover as shown in Figs. 23 and 24.

The path of the sparkover, Figs. 23 and 24, between the two electrodes has sharp zigzag, lightning-like turns, superimposed on a basic double inflection, which in the main conforms to the deflections of the initially formed positive and negative figures. This indicates that the elements flowing in the sparkover channel are negatively charged; that is, the channel is formed by electrons attracted to the positive electrode and repelled from the negative electrode.

In Fig. 25 under the same conditions as in Fig. 23, the deflections of the positive and negative streamers are indicated by the curved lines extending from the electrodes as centers. It is evident that under the combined stress of the dielectric and magnetic fields, the path of the electrons coming from the negative electrode that pass through the point $a$ and flow into the positive electrode follow the solid line curve as drawn in Fig. 25,—that is, in a path having a double deflection similar in form to the sparkover path in Fig. 23. On the other hand, positive ions or protons projected from the positive electrode under the same combined stress of the dielectric and magnetic fields, that pass through the point $a$ and flow into the negative electrode, as in Fig. 23, must take a path as indicated by the broken line in Fig. 25; that is, a path having a double bend in the reverse direction to that of the sparkover in Fig. 23. If the same argument be applied to Fig. 24, a like conclusion will be reached, only it should be noted that since the magnetic field is in the opposite direction, the deflections would be in the reverse order. It appears, therefore, that electrons and not positive ions or protons were primarily the active elements in forming the sparkover channels in Figs. 23 and 24.

The bending of the streamers, due to the reaction of the magnetic field, increases with decreasing air pressure; but the rate of increase is greater for the positive figures than for the corresponding negative figures.

Several factors, such as the velocity of formation of the positive and negative streamers, the intensity and duration of the voltage impulse, the form of the voltage gradient waves, the strength and direction of the magnetic field, spacing of the field poles, the dimensions of plate holder, etc., enter into the problem of securing adequate experimental evidence for a quantitative analysis of the phenomena. The investigation will be continued as soon as the larger apparatus of more suitable design, now under construction, become available.

## Discussion

**H. A. Erikson:** The paper prepared by Dr. C. E. Magnusson embodies results which show, it seems to me, in a conclusive manner that the electric transfer involved in the negative and positive discharges is negative in character. The compound character of the discharge line connecting the two pole centers and its directions of curvature are, it seems, conclusive on this point. This is a distinct accomplishment and is a step in advance.

Besides this, the results obtained present a number of features which, it is to be hoped, further research will clarify. For example, in the positive discharges at the lower pressures, why do the branches from the main trunk only pass from the convex side in the presence of the magnetic field? Also, why does the curvature reverse at the end of the positive streamer? Then there is a question as to how the photographic action is brought about. Is it due to the radiation produced as a consequence of the ionic recombination in the air close to the film?

It seems to me that Simpson's explanation of the lightning discharges* is extremely suggestive in connection with the results given in the paper. It would seem that the streamers in the positive discharge are due to what may be termed Simpson rockets, whereby at the head end, due to the intense field, ionization by collision takes place progressively from point to point and the resulting free electrons are discharged from the tail end. The positive ions so formed remain virtually stationary and through recombination give rise to the radiation to which the photographic action is due. The situation at the negative pole on this view is such that only the electron tail effect is in evidence.

**C. M. Foust:** Professor C. E. Magnusson's magnetic experiments with Lichtenberg figures are certain to result in a greatly improved understanding of the electrical mechanism whereby these figures are formed, and this improved understanding may have far reaching consequences for the following reasons:

1. Because Lichtenberg figures are one phase of our familiar corona phenomena and more extensive knowledge of the mechanism of corona will be helpful in many engineering problems.
2. Because Lichtenberg figures are made by surge voltages and surges are of vital importance in electrical design.
3. Because Lichtenberg figures are closely related to the surge voltage performance of insulation, and improved knowledge concerning the figures should promote better understanding of the surge breakdown of insulation.
4. Because a Lichtenberg figure is decidedly a gas phenomenon and electricity in gases is a subject of great interest to engineers.

The difficulties to be encountered in conducting experiments of this type are not obvious and Professor Magnusson has not called attention to them. The close association required between the high voltage necessary to produce the figures (several kilovolts) and the intense magnetic field required to deflect them makes the problem of insulating electrodes difficult. In addition partial vacuum must also be obtained and this, of course, introduces other problems.

The recent extensive use of Lichtenberg figures for measurement of surges on power systems has of course introduced questions regarding calibration, effect of wave shape, and arrangements of size and shape of electrodes. In Pedersen's comprehensive study as well as in the works of others it has been brought out that, while the size of the positive figure is practically independent of wave form, the negative figure varies in size with both the shape of the front and tail of the applied voltage wave. Also in view of general understanding that the velocity of formation of the positive streamer is considerably greater than that of the negative it would appear that the voltage distribution

*The Twentieth Kelvin Lecture, JOURNAL OF THE A. I. E. E., Vol. 67, p. 82. (Nov., 1922).

between the positive and negative electrodes with the series arrangement shown in Figs. 2 and 19 would be determined by the shape of the applied voltage wave. The author's comments regarding these considerations and the wave shape used in his studies would be of interest.

Professor Magnusson's experiments and analysis suggest that the active elements in the formation of the positive Lichtenberg figures are electrons which move toward the electrode. As he points out this is contrary to Pedersen's conclusion which stated that the streamers were formed by protons moving away from the electrode. Certain characteristics of the figures shown suggest that both may be correct. Assume that immediately upon application of voltage, protons move away from the electrode at high but diminishing velocity and that they leave in their pathway a great number of free electrons which move toward the positively charged electrode. The electrons moving inward will be deflected from their radial pathway as shown in Fig. 25. Also the outward moving protons will be deflected at the streamer tips in the opposite direction as is observed in Figs. 7 to 9 and to some extent in all positive figures shown.

In Figs. 20 and 21 in this paper and many figures shown by Pedersen a decided bright glow is observed at the junction of positive and negative streamers. The assumption of charges of opposite polarity at streamer tips would appear to account for this much more satisfactorily than an assumption of like charges.

Professor Magnusson is to be congratulated on the painstaking perseverance with which he has pursued this investigation and future results from him will be of great interest.

**George E. Quinan:** While other experimenters have, I believe, produced the Lichtenberg figures under the influence of the magnetic field, the present paper is the first to point out the support given by this experiment to the hypothesis of Yoshida that the positive figures are produced by electrons being drawn into the positive electrode and not by moving positive ions.

This at once accounts for the characteristic positive streamers in that ionized channels of low resistance would be formed progressively outward following the receding front of the potential gradient, as illustrated in Fig. 11. It also accounts for the greater diameter of the positive figures since the low resistance paths afforded incoming electrons, permit ionization to proceed to a greater radial distance from the electrode.

Under the type of voltage gradient suggested in Fig. 11, the branches of the positive streamers are readily accounted for through the tendency of negative electrons to move into the positive ionized streamer channels in their immediate vicinity. Also, these branches under the influence of the magnetic field should join their stems with the same direction of curvature with reference to their junctures to the stems that the stems themselves have with reference to the positive electrodes. This would result in the branches coming into the stems from the convex side only, and this is what actually occurs. Fig. 9 is a good illustration of this.

The size of the Lichtenberg figures varies with the voltage and inversely with the atmospheric pressure. This has lent support in the case of the negative figures to the hypothesis that they are formed as a result of electrons being shot radially from the negative electrodes. Added support is now given this idea by the observed direction of bending in the magnetic field and by the fact that the degree of bending increases as the voltage decreases.

While these considerations lend support to the notion that electrons in motion are in some way responsible for the formation of the figures, it is by no means clear to the writer as to how certain important features of the figures can be thus accounted for. The sharply defined radial lines of the negative figures along which the photographic film has escaped the effects of the bombardment are not what one would expect from a discharge of mutually repellent particles. Neither are they easily reconciled with the notion advanced by some observers that the effect on the film is produced by a discharge from the film itself into the ionized space adjacent to its surface.

Quite as characteristic of these figures as their form is the difference between the positive and negative in brightness. The negative is characteristically bright, the positive dark. This suggests a radical difference in method of formation hardly explained by assuming a mere reversal in the direction of movement of the electrons.

Another difficulty arises from the fact that the negative figures frequently, as in Fig. 8, show concentric bands of different brightness with the outer bands brighter than those nearer the source of the assumed electronic shower. The negative figure in Fig. 8 has superimposed upon it as a result of oscillation, first a positive figure, then a negative figure of approximately the same diameter as the positive, next (presumably) a positive figure, which, however, is not distinguishable, and lastly another negative figure. The first negative figure is brightest, the second less bright, and the last one darkest of the three. This hardly seems consistent with the notion of three successive discharges of electrons from the central electrode.

The writer unfortunately has nothing constructive to offer in lieu of the suggestions advanced in Dr. Magnusson's paper and merely wishes to suggest that in continuing the experiments with the Lichtenberg figures the possibility of finding a more satistory fundamental hypothesis be not overlooked.

# A Survey of Room Noise in Telephone Locations

BY W. J. WILLIAMS[1] and RALPH G. McCURDY[2]

Member A. I. E. E. Member A. I. E. E.

*Synopsis.—This paper describes a survey made to determine the range of magnitudes of room noise present in telephone locations. Measurements were made in a total of 250 locations in New York City and environs, distributed among businesses and residences in accordance with telephone traffic distribution. In each location, measurements were made by a marginal audibility method using the human ear as a part of the measuring device, and by a visual indicating meter. A brief description is included of the apparatus employed with each of these methods. Results are presented for measurements made in various classes of rooms, under winter and summer conditions.*

* * * * *

AMONG the projects of the Joint Subcommittee on Development and Research of the N. E. L. A. and Bell System is one (No. 4) which is studying the effects of noise[3] on telephone transmission and methods for its measurement. It was appreciated that, in addition to noises of electrical origin caused by exposures to power circuits or by sources incidental to the operation of the telephone system, there are also noises in the rooms in which telephones are used which have an important effect on telephone service. In studying the effects of noises, it is, of course, necessary to consider both noises of electrical origin and room noises. It was desired that, in laboratory tests of the effects of line noises on speech transmission, typical amounts of room noise should be provided at the test location. The survey described herein was made to obtain room noise data for these laboratory tests.

The methods described should be of general interest in connection with other noise problems. Increasing attention is being given, both in America and in Europe, to the general problem of noise as an undesirable attribute of modern civilization. Some efforts are being made to investigate sources of city noise. Modifications have been made in the design of machines and appliances, such as typewriters, motor cars, electric refrigerators, rotating electrical machinery, and domestic oil burners, so as to reduce the noise involved in their operation. Attention is being given to the quieting of rooms by means of acoustic treatment. Studies are being made of the effects of noise on living beings, including effects on the efficiency of workers.[4] In all of this work, quantitative measurement is important.

For the specific problem in hand, it was desired to obtain information on the magnitudes of room noise, as well as some general indication of the frequency composition of typical room noises.

While it is recognized that ordinary room noise is a highly variable quantity changing from instant to instant in loudness and frequency composition, it is felt that sufficient measurements were made to specify the makeup of a typical room noise for use in the laboratory tests, and in addition to obtain an indication of the effect of various factors, described below, upon the noise. Since it was desired to make the measurements as representative as possible of typical telephoning conditions, they were made at times of day and in types of locations determined by a study of telephone message traffic. Since the results would be affected by the choice of locations, they are presumably less typical for non-telephone than for telephone purposes.

The residences included in the survey ranged from apartments in large city buildings to small homes in outlying towns. In the business locations were included offices, stores, factories and workshops, and public buildings, such as hotels and clubs.[5] Establishments of various characters were included in each classification; they ranged in size from small stores to great manufacturing plants.

In making all measurements, an attempt was made to simulate the normal conditions which would obtain when a telephone call was placed. If noises existed in the room, which would be discontinued when the telephone was being used, such noises were stopped while the measurements were being made. On the other hand, care was taken to see that none of the normal noises of a particular location was discontinued because of the fact that measurements were being taken.

It was recognized that there would be a difference between the room noise experienced on local and on long-distance calls. The survey was made on the basis of telephone traffic as a whole, which consists predominantly of local calls.

The survey consisted of two series of tests, one made during the months of January, February, March, and April, and the other made during the months of July and August. The former series was the more compre-

1. Technical Advisor, National Electric Light Ass'n., New York, N. Y.

2. Development and Research Dept., American Tel. & Tel. Co., New York, N. Y.

3. In this joint work, noise is taken to mean any extraneous sound which would tend to interfere with telephone conversation.

Room noise is used to include any extraneous sounds at the place where the measurement is made, except those proceeding from the telephone receiver. It thus includes, in addition to noises such as the rattling of papers or the roar of street traffic, any other sounds extraneous to the telephone conversation, for example, those of other conversations or of music produced nearby.

4. D. A. Laird, "The Effects of Noise," *Jl. Acoustical Soc. Amer.*, Jan. 1930, p. 256.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 25-27, 1930.*

5. In public buildings, only a very small proportion of the telephone locations tested were in booths or at coin-box telephones.

hensive, including 205 measurements; the results given herein are based on this series of tests except where specifically noted otherwise. The second series of tests was made for the purpose of determining the difference between the room noise encountered under winter conditions and that encountered under summer conditions. Consequently, a selected group of the locations, which had been measured in the winter, were measured again under summer conditions.

It must be appreciated, in generalizing from the data given, that tests were made in only a limited number of locations.

Two methods were employed in making the measurements described in this paper, one electrical and the other aural. The electrical method employed a condenser-transmitter pick-up, amplifiers and detector. A weighting network was incorporated in the amplifier to simulate the sensitivity characteristic of the ear. The aural method, known as the "masking method," involved the measurement of the masking effect of the noise on various warbler tones recorded on a phonograph record. Both of these methods will be described in greater detail below.

## General Results

Some of the interesting results which were obtained from this survey may be summarized as follows:

On the average, room noise in residences was about 20 db. less in magnitude than that in business locations.

The spread in the magnitudes of business room noises was about 40 db., as compared to 20 db. for residence room noises. These spreads include 90 per cent of the measurements, excluding the lowest and highest 5 per cent. The standard deviation of the measurements was about 12 db. for business noise and 6 db. for residence noise.

Room noises average 4 or 5 db. higher in summer than in winter.

In general, the magnitude of residence noise was affected to only a minor extent by the size of the town or city in which it was measured.

On the average, the frequency composition of residence noise was about the same as that of business noise. The masking effect of the noise on a tone covering the range 750-1500 cycles was greater than that on ranges above and below this. The magnitudes of components in the lower part of the range covered (about 250-5000 cycles) appeared to be somewhat larger than those in the higher part of this range.

## Methods of Measurement

The two methods which were employed in the survey are as follows:

*Aural Method—Masking of Warbler Tone.*[6] In this method a tone of varying pitch (warble) is produced and sent into a receiver. The receiver cap is provided with slots shaped so that the observer's ear canal is always open to the air of the room regardless of how firmly the receiver is pressed against the ear. The tone is generated by means of a phonograph record and a magnetic phonograph record pick-up, and is a variable-frequency tone, the pitch of which varies between certain limits several times per second. An attenuator is placed between the magnetic pick-up and the receiver. The observer sets the attenuator at a point where he can barely recognize the sound of the warble in the presence of the room noise. He also obtains the setting at which he can barely hear the warble in a perfectly quiet room. The difference between these two settings is a measure of the masking effect of the noise in this room upon the warbler tone, for this particular observer.

An idea of the frequency composition of a given room noise may be obtained by using several different warbler tones, each covering a different portion of the voice-frequency range. This is based on the fact that, in general, a tone of a given frequency masks to a greater extent tones that are near it in frequency than tones that are far removed from it in frequency.

The phonograph records used in the present room noise survey were three-band records, *i. e.*, three warbler tones were cut on each record, each tone

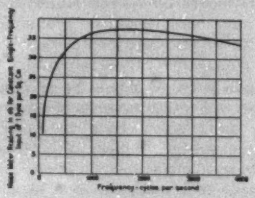



Fig. 1—Response Characteristic of Room Noise Meter

occupying about one-third of the available space. The frequencies included in the various bands were as follows: high band, 1500-5600 cycles per second; middle band, 750-1500 cycles per second; low band, 250-750 cycles per second. In each band the frequency varied continuously from the lower to the upper limit and back to the lower limit, the period of such a complete "warble" being about one-sixth of a second.

*Electrical Method—Room Noise Meter.* There is, of course, a number of different electrical methods which might be employed for measuring room noise, ranging from a single over-all measurement to a complete wave shape or frequency analysis. The complete analysis or the measurement of energy present in a considerable number of narrow frequency bands is subject to the disadvantages, for such a survey as this, of slowness of measurement and bulkiness of testing equipment.

The method which was adopted was one based on the use of a frequency weighting simulating the sensitivity of the ear. This frequency characteristic is shown on Fig. 1. It is an equal loudness weighting; that is, the room noise meter was so constructed that different

6. R. H. Galt, *Jl. Acoustical Soc. Amer.*, October 1929, p. 147.

single-frequency noises of equal loudness would give approximately the same meter readings. The shape of an equal-loudness curve is somewhat flatter for high levels of loudness than for low ones. The weighting curve chosen for the meter was for a loudness corresponding to that of a 1000-cycle tone 30 or 40 db. above the threshold of audibility. This general level is not far from the middle of the range of levels of room noise components. The loudness data used were those given

Fig. 2—Schematic Diagram of Room Noise Meter

by Kingsbury,[7] based on experimental data on single-frequency tones.

The sensitivity of the meter is such that a 1000-cycle tone about 28 db. above threshold would give a reading of 0 db. on the meter scale.

The room noise meter employed is shown together with its auxiliary equipment in Fig. 3. It consists of a condenser transmitter for converting acoustical energy into electrical energy, six stages of amplification for raising the level of the noise currents sufficiently to operate a thermocouple meter indicating device, and a weighting network, as described above, as well as certain apparatus not employed in obtaining the results reported here. The general layout of the circuit is indicated in the schematic diagram of Fig. 2. A portable battery supply and means for calibrating form the necessary auxiliary equipment. An adjustable attenuator controlled by a key and a dial is provided between stages of the amplifier so that the noise energy being measured may be brought within the range of the meter over a range of levels of 80 db. (corresponding to a power range of 100,000,000 to 1).

*Operation of the Room Noise Meter.* The noise meter is first calibrated, as described below, so that its sensitivity is set at a predetermined value. The condenser transmitter is then placed at the spot where it is desired to measure noise, and the gain of the amplifier is adjusted by means of the key and dial until the needle of the microammeter in the output circuit fluctuates about a given point. The settings of the key and dial then give a measure of the noise. In addition to the average readings obtained in this manner, readings of the fluctuations in the noise can be similarly obtained. As an aid in the reading, the microammeter scale is calibrated in decibels.

The calibration of the meter in the field consists of a check on the over-all sensitivity of the instrument. The filament currents and plate voltages are adjusted to the correct values. Then a fixed percentage of the electrical output of a standard buzzer, the current from which is measured by a thermocouple, is fed into a special receiver which is placed in a prescribed way on the condenser transmitter. The gain of the amplifier is then adjusted until the output microammeter needle reaches a predetermined point. The sensitivity of the meter will then be as shown on Fig. 1.

An over-all calibration of the meter, as a function of frequency, is given on this figure. To obtain this, separate determinations were made of the volts generated by the condenser transmitter per unit of pressure, and the meter reading per volt generated by the transmitter, as a function of frequency; and the results were combined to give the values shown. Harmonics in the testing waves were reduced to such a point that they did not affect the results. After a substantial part of the survey had been completed, a check was made of the electrical portion of the calibration, and the changes found were quite negligible.

*Accuracy of the Meter.* The precision of the apparatus is substantially greater than the precision with which ordinary varying noises can be measured. The readings obtained for steady inputs are proportional to the input, with an error of less than ½ db., over the entire range of noise amplitudes found in the survey. The apparatus is shielded electrically. In only one case did electrical fields produce any observed errors in the readings; this was when an attempt was made to measure the room noise near a rotary converter in a power station. The vacuum tubes are mounted in such a way that the effects of ordinary mechanical vibration on the readings are negligible.

*Comparison of the Two Methods.* In general, the meter method gives results in physical terms while the

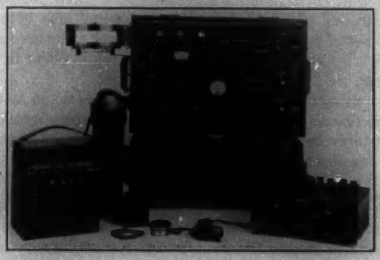


Fig. 3—Room Noise Meter and Auxiliary Equipment

masking method gives them in terms of effects on the ear; consequently, the choice of the method to be employed in any particular case depends somewhat on the use to which data will be put. It is true that the meter includes a network to simulate the sensitivity of the ear for various frequencies; it does not, however, simulate other properties of the ear, such as the departures from linearity in response by which subjective tones are produced by the ear mechanism, and the

7. *Physical Review*, Vol. 19, April 1927, pp. 588-600.

complicated way in which one sound masks another.[8]

The meter method, unlike the masking method, avoids any errors due to variations in human ears. This advantage is offset to some extent by the fluctuations of the meter needle, which makes it difficult to obtain the mean reading if the noise is unsteady as is the case with most room noises.

In the case of noises of a distinctly intermittent,

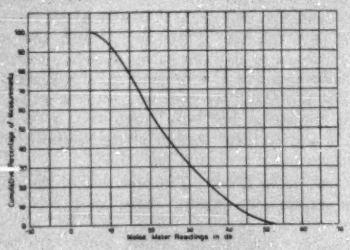



Fig. 4—Results of Noise Meter Measurements of Noise in Business Locations

staccato character, the warbler tone can be heard and recognized in the brief intervals when the noise is a minimum. A preliminary investigation showed that, for a noise of this sort, the relation between readings obtained by the masking method and by the meter method was different from the relation obtained for a steady noise, the warbler readings being relatively lower in the case of intermittent noise.

Both methods were used in the survey, because it was felt that each gave information which could not be as accurately obtained from the other, and also because the use of two methods enabled each one to be used as a check upon apparatus defects which might occur in the other.

In using the masking method, data were taken by two experienced observers and corresponding measurements averaged. All meter measurements were made by one observer.

## Results of Survey

*Noise in Business Locations.* One hundred and nine business locations were visited. The magnitudes of the noises measured varied from that found in a doctor's quiet office to the din of a large manufacturing plant. Distribution curves for the noises measured are shown in Fig. 4 for the meter method and Fig. 5 for the masking method. For any point on one of these curves the corresponding per cent of all of the measurements made had values equal to or greater than the indicated abscissa value.

It may be seen that with the exception of the "high" curve of Fig. 5 the curves for meter and masking methods are fairly similar in shape. The "middle" curve has been selected to represent the masking method.

If there are excluded as extremes those noises which were so low that 95 per cent of all the noises measured equaled or exceeded them, and those which were so high that only 5 per cent of the measurements equaled or exceeded them, the spread of noise magnitudes is seen to be about 40 db. The standard deviation of the measurements is about 12 db.

As shown on Figs. 4 and 5 the median business room noise would produce a reading of 23 db. on the meter scale and a masking of 27 db. on the high-frequency warbler tone, 39 db. on the middle-frequency tone, and 31 db. on the low-frequency tone. The average business room noise was about 2 db. higher than the median.

Some conception of the amounts of noise represented by these figures may perhaps be gained from the following. The extremely loud noise measured in a local station of the New York subway while an express train was passing produced a meter reading of 70 db., while the lowest noises measured in the survey, in quiet residences, gave readings near 0 db.

Data on noise at the business locations tested have been grouped so as to show the average differences in the room noise values obtained for different types of business and for different sizes of towns. It will be appreciated that only a very small number of measurements were included in each sub-classification, and that consequently it is not safe to generalize from these sub-groupings as to room noise conditions in general.

Averages of the room noise measurements for the

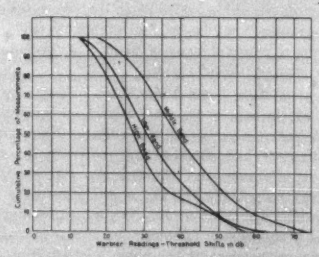



Fig. 5—Results of Measurements of Noise in Business Locations by Masking Method

different types of business locations are shown in the following table:[9]

8. R. L. Wegel and C. E. Lane, "Auditory Masking and Dynamics of the Inner Ear," *Physical Rev.*, Feb. 1924.

9. It will be noted that in the results given, the difference between the masking of the middle-frequency tone and the meter reading is relatively constant. It was found that for any considerable sub-group of the measurements, this difference was not far from 15 db. This figure, of course, would not in general hold for a single noise selected at random. There was a general tendency for the difference to be somewhat larger for larger values of noise.

| Type of business location | Masking of middle-frequency tone | Meter reading | Number of measurements |
|---|---|---|---|
| Offices | 42 db. | 24 db. | 34 |
| Stores | 34 | 18 | 34 |
| Factories | 57 | 40 | 18 |
| Public buildings | 35 | 21 | 23 |
| Average of all businesses (weighted according to number of measurements made) | 40 | 25 | 109 |

The above figures show a significant difference between the noise measured in factories and that measured in other types of location. The other differences shown were found not to be significant when examined in the light of the spread in values for individual locations in each class.

Averages of the business room noise measurements obtained in various sizes of towns are shown in the table below.

| Size of town | Masking of middle frequency tone | Meter reading | Number of measurements |
|---|---|---|---|
| Class A (over 400,000 pop.) | 45 db. | 26 db. | 39 |
| Class B (100,000 to 400,000 pop.) | 37 " | 22 " | 18 |
| Class C (10,000 to 100,000 pop.) | 42 " | 27 " | 41 |
| Class D (less than 10,000 pop.) | 27 " | 11 " | 11 |

These figures indicate that (with the exception of Class C towns) the business noise measured in large cities was greater than that in smaller towns. This is believed to hold true despite a fairly large spread in individual measurements within a given class. The exception in the case of Class C towns is explained by the fact that a fairly large percentage of the measurements in this class were made in large factories.

Room noise in business locations was observed to be quite complex in frequency composition. The masking effect of the noise on the middle band was greater than that on the high and low bands. In order to give an approximate interpretation of this in terms of pressures in various frequency regions, account must be taken of the relative magnitudes of threshold pressures in the three warbler frequency bands, since the masking effects were obtained by subtracting threshold settings of the attenuator from the settings made in the presence of the noise. For the middle and upper bands, threshold pressures are about the same; hence, the lower values of masking for the high range indicate that components in this range are in general relatively weak. As previously determined,[10] threshold pressures at frequencies in the low band are several decibels higher than those in the other bands. Combining the values of masking for the low and middle bands with the corresponding threshold pressures, it is seen that the physical magnitudes of components in the low- and middle-frequency ranges are in general not far different. The above analysis is, of course, very rough, as the whole range from 250 to 5600 cycles is divided into only three bands.

*Room Noise in Residence Locations.* Measurements were made in 96 residence locations.

Figs. 6 and 7 show distribution curves for these measurements. Compared with the corresponding measurements made in business locations it is apparent that the room noises encountered in residences were not only much

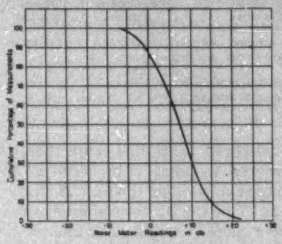


Fig. 6—Results of Noise Meter Measurements of Noise in Residence Locations

smaller in magnitude but also varied less in magnitude than business room noises. The average of the residence room noises is about 18 db. less than the average of the business room noises, while the spread in residence room noise (using the 95 per cent and 5 per cent points on the curves as limits) is 20 db., compared to 40 db. for business noise; the standard deviation of the residence measurements is 6 db., compared to 12 db. for

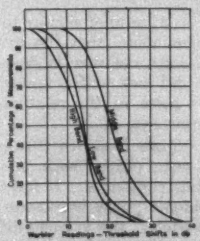


Fig. 7—Results of Measurements of Noise in Residence Locations by Masking Methods

the business measurements. Unlike the curves for business noise, the curves for residence noise are very symmetrical, showing similar distributions above and below the average values.

As shown on Figs. 6 and 7, the median residence room noise would produce a reading of 7 db. on the meter, and a masking of 12 db. on the high-frequency warbler tone, 20 db. on the middle-frequency tone, and 13 db. on the low-frequency tone. The average was about the same as the median.

10. H. Fletcher, "Useful Numerical Constants of Speech and Hearing," *Bell System Tech. Jl.*, July 1925.

The average of the room noises measured in single-family houses was practically the same as the average of the noises measured in apartments.

Averages of the residence room noise measurements obtained in towns of various sizes are shown in the following table:

| Size of town | Masking of middle-frequency tone | Meter reading | Number of measurements |
|---|---|---|---|
| Class A (over 400,000 pop.) | 20 db. | 7 db. | 33 |
| Class B (100,000 to 400,000 pop.) | 20 " | 8 " | 14 |
| Class C (10,000 to 100,000 pop.) | 23 " | 6 " | 37 |
| Class D (less than 10,000 pop.) | 17 " | 7 " | 12 |

It will be observed from this table that the residence noises measured in large cities were no greater than those measured in smaller towns. A study of the data showed that 27 of the 33 measurements made in Class A towns were made in residences which would be classed as apartment houses. It is possible that the noise usually associated with big cities is confined chiefly to non-residential locations, and that apartments on side streets are no noisier than residences in smaller towns. It should be recalled, however, that the number of measurements in each class of town was very small. In any case the data tend to show that the difference between residence noise in the large city and that in the smaller town probably is not extremely large. The measurements for Class A cities were made chiefly in Manhattan and Brooklyn with a small number in Newark.

It was found, in a manner similar to that discussed above for business noise, that the average residence room noise was quite complex in frequency makeup, and apparently did not differ materially from the average business noise in the relative amplitudes of low and high frequencies.

*Comparison of Room Noise in Winter and Summer.* Forty locations were visited both in summer and in winter and the data compared. It was found that both business and residence noises were somewhat greater in summer than in winter, the average difference being 4 or 5 db. The spread in values obtained under summer conditions was less than that found for the winter conditions. This was because the noises which showed the least magnitude, when measured in winter, were found to be higher under summer conditions, while the highest noises measured failed to show an appreciable change with season. These highest noises were largely caused by indoor machinery, and would not be appreciably modified by outside sources.

The average frequency composition of the noises measured under both summer and winter conditions seemed to remain about the same as far as could be determined.

## Selection of Typical Room Noise and Its Reproduction

The data obtained have been used in determing the characteristics of a typical room noise to be recorded on a phonograph record and reproduced for use in laboratory tests.

Since the data revealed no difference between the average frequency composition of great and small noises, it has been possible to choose a single recorded noise and to vary merely the amplitude of the reproduced noise, keeping its frequency makeup constant.

The recording and reproduction of such a noise have presented problems, particularly from the point of view of naturalness. It has been found difficult to reproduce a noise by simple means in such a way as to give the illusion that the noise is real, not artificial. The requirements for reproducing a noise which will be typical in its effect on the intelligibility of speech transmitted over telephone circuit are, however, considerably less severe than those for obtaining naturalness. Three main factors seem to be involved in the problem. In the first place, room noises often contain high-frequency components, undoubtedly including some extremely high frequencies. These components, while they are generally of low energy content, seem to contribute substantially to the naturalness of the sounds. The effect of these components on the intelligibility of speech transmitted over a telephone circuit would, however, be much less than their contribution to the

LIST OF TOWNS WHERE ROOM NOISE SURVEY MEASUREMENTS WERE MADE

| Size of town | Name of town | Number of measurements: Business | Number of measurements: Residential |
|---|---|---|---|
| Class A (over 400,000 pop.) | Brooklyn, N. Y. | 7 | 18 |
| | Manhattan, N. Y. | 32 | 13 |
| | Newark, N. J. | 0 | 2 |
| | Total | 39 | 33 |
| Class B (100,000 to 400,000 pop.) | Jamaica, N. Y. | 11 | 11 |
| | Yonkers, N. Y. | 7 | 3 |
| | Total | 18 | 14 |
| Class C (10,000 to 100,000 pop.) | Bloomfield, N. J. | 0 | 2 |
| | East Orange, N. J. | 7 | 9 |
| | Flushing, N. Y. | 0 | 5 |
| | Harrison, N. J. | 3 | 0 |
| | Kearny, N. J. | 6 | 0 |
| | Maplewood, N. J. | 6 | 10 |
| | Milburn, N. J. | 4 | 1 |
| | Mt. Vernon, N. Y. | 6 | 4 |
| | New Rochelle, N.Y. | 0 | 2 |
| | Orange, N. J. | 4 | 0 |
| | Summit, N. J. | 2 | 2 |
| | West Orange, N. J. | 3 | 2 |
| | Total | 41 | 37 |
| Class D (less than 100,000 pop.) | Hollis, N. Y. | 6 | 7 |
| | Madison, N. J. | 0 | 3 |
| | Pelham, N. Y. | 3 | 1 |
| | Richmond Hill, N. Y. | 2 | 1 |
| | Total | 11 | 12 |
| | Grand total | 109 | 96 |

naturalness of the noise, since the transmitted speech is generally limited to a band of not more than 3000 cycles. The frequency band transmitted by the recording and reproducing system was nearly twice this amount, being limited both by the mechanical characteristics of the apparatus and by the unavoidable noise generated in this apparatus, the amount of this noise increasing as the band width increases. Second, room noises emanate from a considerable number of sources located in different positions, so that in order to reproduce them with complete fidelity each source must be reproduced separately in its own position. On account of binaural effects in hearing, the proper locating of sources seems to have a considerable effect on naturalness. The most practical method of securing an approximation to this effect in the reproduced noise is to dispose a number of loudspeakers in different places in the room, chosen by test so that false directional effects are avoided. Third, the effects of reverberation must be considered. A noise picked up in a highly reverberant room, and reproduced in another highly reverberant room, would have in it two sets of reverberations. The best method of taking care of this seems to be to make artificial adjustments in the reverberation in the two rooms. Finally, there is a residual effect due to the fact that a person experiencing an actual noise is aided in his recognition of the noise by visual and other factors enabling him to refer it easily to its source; these are, of course, not present when the sound is reproduced.

## Conclusions and Acknowledgment

While a certain amount of work on room noise conditions in telephone locations had been previously carried out, this survey represents a considerable advance in knowledge of room noise magnitudes. It provides data for work on the effects of noise on telephone transmission, as well as furnishing certain information of wider interest. The methods of measurement employed, when further developed in the light of the experience gained in this work, should prove valuable in other room noise investigations.

The authors wish to acknowledge the work of Messrs. J. W. Whittington and R. E. Philipson of the National Electric Light Association and Messrs. J. M. Barstow and R. S. Tucker of the American Telephone and Telegraph Company, in designing and building the room noise meter and in carrying out the survey.

# The 220,000-Volt System
## of the Hydro-Electric Power Commission of Ontario

BY E. T. J. BRANDON*

Fellow, A. I. E. E.

***Synopsis.***—*Power requirements of the Commission's 25-cycle Niagara System are outlined. Preliminary studies in connection with the choice of transmission voltage, location of terminal transformer station, etc. are discussed, together with the technical studies involved in the design of a system for transmitting 260,000 hp., 230 mi. at 220,000 volts, and transforming same at the receiving end, for interconnection with the existing 110,000-volt system.*

*The Toronto-Leaside 220,000-volt transformer station is described, including the 220,000-volt switching arrangement, 45,000-kv-a. three-winding transformer banks, 110,000- and 13,200-volt switching arrangements, 25,000-kv-a. vertical-shaft out-door synchronous condensers, relaying, communication, and control.*

*The 220,000-volt transmission system is also described, including the use of aero-photography in surveying the route and locating the towers, design of supporting structures, details of conductor supports, insulation, ground wire practise, etc.*

*The paper concludes with a résumé of operating experience on the 220,000-volt system to date, and an outline of the future development of the system as at present anticipated.*

* * * * *

### Introduction

THE Niagara System of the Hydro-Electric Power Commission of Ontario is the major system of the Commission, covering an area of some 12,000 sq. mi. in the south westerly portion of the Province, adjacent to the shores of Lakes Ontario and Erie. This area, roughly rectangular in shape, extends from the municipalities situated on the Detroit and St. Clair Rivers on the west, to the metropolitan area of Toronto on the east, a distance of some 230 mi.

With the exception of several large electrochemical and metallurgical customers located in the immediate vicinity of the Niagara River, the power demand on this system comes from some 371 municipalities, ranging in size from the City of Toronto to the small villages and rural districts.

Previous to October 1928, this "Municipal" load was supplied entirely from the Commission's generating stations located on the Niagara River, over a network of approximately 1200 circuit miles of 110,000-volt transmission lines. There were nineteen 110,000-volt transformer stations varying in capacity from 90,000 kv-a. to 3750 kv-a.

Commencing in October 1928, due to the fact that generation on the Niagara River had reached the limit dictated by the International Treaty regarding water diversion, power to supply the increasing demand was purchased under contract. A block of 260,000 hp. was purchased from the Gatineau Power Company, supplied from its generating plants located on the Gatineau River in the Province of Quebec, some 230 mi. to the east of Toronto, and transmitted over the Commission's transmission lines from the interprovincial boundary, for interconnection with the Niagara System.

It is the object of this paper to present some of the problems brought up by this interconnection, particularly as they affected the fundamental plan for the supply of power to metropolitan area of the City of Toronto.

### History of System Growth

The growth of the annual peak load on the Municipal System from December 1922, one year after the placing into operation of the Commission's Queenston-Chippawa generating station at Niagara Falls, to December 1929, is shown in Fig. 1. It will be noticed that at the end of this period the annual increment was of the order of 50,000 kw. This figure becomes 75,000 kw. if the increment on the remainder of the Niagara System is included.

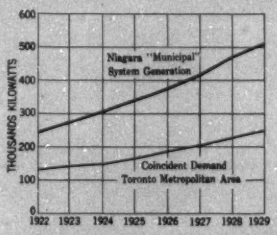



Fig. 1—Growth of Annual Peak Loads

The growth of the annual peak load in the metropolitan area of the City of Toronto is also included in Fig. 1. It will be noticed that the Toronto load represents nearly one-half of the Municipal load, having an annual increment at the end of the period of the order of 25,000 kw.

Referring to Fig. 2, the original station of the Commission in Toronto is that marked as Strachan Transformer Station. A double-circuit transmission line was brought into the city, paralleling the shore of Lake Ontario, and the station was located approximately two miles from the business center of the city. The growth of the city at that time was largely to the west and

*Chief Electrical Engineer, Hydro-Electric Power Commission of Ontario, Toronto, Ont., Canada.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*



30-97

north west, being somewhat limited to the east by the barrier of the Don River Valley.

In 1918, a second smaller station (York Transformer Station) was constructed west of the city, primarily to serve the suburban industrial load in that area.

In 1921, with the taking over of a competing power company, a private right-of-way to the north was acquired, and adjacent to it, two new transformer stations were constructed and placed in operation in 1924. These stations are marked as Wiltshire Transformer Station and Bridgman Transformer Station.

At this time, the distribution of load was such that these three city stations were spaced almost equally around the center of gravity of the load and at three-mile centers,—an almost ideal arrangement. Power was supplied over four 110,000-volt circuits, with a double-circuit infeed at 90,000 volts from the acquired power company's station forming a peak supply. In December, 1926, the installed capacities were—Strachan 90,000 kv-a.; York 15,000 kv-a.; Wiltshire

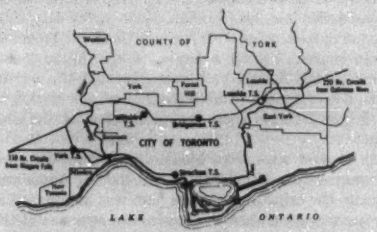



FIG. 2—TORONTO AND VICINITY, SHOWING HIGH-VOLTAGE TRANSMISSION LINES AND STATIONS. DECEMBER 1929

45,000 kv-a.; and Bridgman (including the 90,000-volt capacity) 78,000 kv-a.

In the meantime, the barrier of the Don River Valley had been broken down with adequate viaducts, and a rapid residential growth to the east had taken place. By 1926, the load demand of the area had increased to the point where the necessity of a fifth 110,000-volt transformer station, located to serve that area, was indicated.

It was at this time that the contract with the Gatineau Power Company was entered into, and Toronto, being at the easterly limit of the then existing System, and representing approximately one-half the System load, was chosen as the point at which the necessary interconnection would be made. The problem of additional transformer stations became merged, therefore, with the problem of devising a plan whereby this new source would be incorporated with the existing system.

At this point it should be mentioned that the Hydro-Electric Power Commission does not distribute power throughout the city. The Commission is responsible for transmitting power to the city and providing for its transformation to distribution voltage,—in this case 13,200 volts. At this point, the power is delivered to the local Commission, (in this instance, the Toronto Hydro-Electric System), for distribution to the ultimate consumer. This paper, therefore, deals only with the main transformer stations, and not with the 13,200-volt, (or lower) distribution system.

### LOAD ANALYSIS AND LOCATION OF STATION

Coincident with the carrying on of negotiations for the supply of power from the Gatineau Power Company, economic studies were carried out to decide on the transmission voltage to be adopted. Calculations were carried out at 110,000 volts, at 220,000 volts, and at two intermediate voltages. As the power was to be purchased at the transmission voltage, studies included estimates of the cost of transmission, transformation at the receiving end where required, and tying in with the existing system, and also included a range of sizes of transmission conductors, so as to arrive at the most economical conductor for each voltage.

In addition to the purely economic comparison, consideration was also given to such factors as service security, the multi-circuit system economically possible at 110,000 volts ordinarily providing a greater degree of service security than a two-circuit 220,000-volt system; the relative immunity of the different types of construction to flashover, it being expected at that time that lines of higher voltage might be more susceptible to such occurrences; the control of charging kv-a. on the 230-mi. circuits, though the frequency, being 25 cycles, rendered this less of a problem than on other systems operating at 50 or 60 cycles.

As a result of these studies, a nominal transmission voltage of 220,000 volts was adopted, a transmission system of two circuits of 795,000-cir. mil. A. C. S. R. being decided upon as the most economical arrangement.

The decision to adopt 220,000-volt transmission gave a preliminary conception of a system layout. It was thought at this time that transformer stations operating at this voltage should be kept well outside urban areas, as the insulation problem was not yet regarded as solved. Dirt and smoke incidental to urban areas were therefore to be avoided.

The first arrangement located the 220,000-volt station north and east of the city limits, and it was proposed to step-down at this point to 110,000 volts, transmitting the power into the city at this voltage. One of the stations to be supplied in this manner was to be the fifth station previously mentioned as being desirable east of the Don River Valley. The necessary synchronous condensers were to be operated from the delta-connected tertiary windings.

A more detailed analysis of the load division in the metropolitan area of the city than had been made heretofore was undertaken, with a view to establishing

economic station locations, and at the same time, to form the basis of stability studies which it was intended to undertake later.

Fig. 3 shows the distribution of load in the metropolitan area of the city in thousands of kv-a. per sq. mi. as determined in December 1926. The figures represent the arithmetic sum of the peaks of the various classes of load in the separate square miles, but it has been calculated that the same figure also represents the coincident peak demand in horsepower, and may be used as such when obtaining station capacity.

The maximum demand per sq. mi. was in the down-town business area, approximately 15,500 kw. coincident. Residential districts had demands varying between 2600 and 3300 kw. per sq. mi. There were 11 sq. mi. having commercial power loads alone in excess of 2500 kw. The average for the 76 sq. mi. covered was 2450 kw. per sq. mi. coincident.

From these figures of actual distribution, an attempt was made to estimate the load in the respective square miles for the years 1930, 1933, and 1936. The peculiar

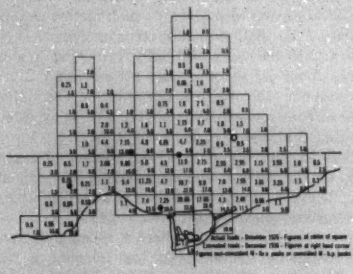


Fig. 3—Toronto and Vicinity—Load Distribution per Square Mile

condition of each unit was considered,—whether business, manufacturing, or residential, whether rapidly growing or near apparent saturation, whether affected by natural barriers, etc.—and an attempt was made to estimate the growth accordingly. The distribution arrived at for 1936 is also shown in Fig. 3.

The maximum down-town square mile was increased to 25,000 kw., while the average for 98 sq. mi. was increased to 4800 kw., both coincident.

A resurvey of the distribution has recently been completed, and shows that the figures for December 1929 are in very close agreement with those estimated. Since the original survey was completed, the data have been so useful that arrangements have now been made to bring the record up-to-date annually.

Alternative sites for transformer stations were selected, and economic dividing lines between these sites and existing stations were drawn, the object being to plan a 110,000-volt distribution system in which each station would be so located as to be as near its load center as possible.

These studies brought out the possibility of locating the new 220,000-volt station so as to supply 13,200-volt power directly, utilizing the delta tertiary windings which were to be included in any event. The increase in the cost of the transformers would be relatively small, which would allow practically the whole of the cost of the second transformation, from 110,000 volts, to be utilized to extend the limits of 13,200-volt distribution from the station, thereby fully loading the station at this voltage within a few years. If the 110,000-volt stations were correctly located at three-mile centers, supplying power to a distance of 1½ mi., then such a station could distribute power to a distance of 3½ mi.; in other words, it could cover 25 sq. mi. as against 4.5 sq. mi., allowing for the fact that underground distribution feeders follow right-angled city streets.

In Fig. 2 it will be noticed that the valley of the Don River cuts through the city from the north east. This barrier had been broken down to the east, but to the north east up to 1926 very little development had taken place. For this reason, it was found possible to extend the 220,000-volt system through this territory from the original tentative location of the station into an urban location such as would allow of the above plan.

As several sites were available of sufficient size to accommodate a 180,000-kv-a. 220,000-volt transformer station, the original tentative plan was abandoned and the investigation narrowed down to a selection of these possible locations. The following features were weighed in connection with each—(a) the distance from the center of gravity of its distributed load, allowing for the gradual trend of that center of gravity with the estimated load growth; (b) the ease with which such power could be distributed from the station; (c) the ease of connection to the existing 110,000-volt system, so that all power in excess of that required at 13,200 volts could be transmitted to other existing stations; (d) the ease of access at 220,000 volts; (e) the possibility of expansion in the transformer capacity of the station, above the immediate requirements; and (f) in view of the necessarily bulky equipment to be transported to it the accessibility of the station.

The studies were completed with the selection of the present site. It may be said that this site is nearly as close to what is rapidly becoming the retail business center of the city as the original station built in 1911 was to the then retail center. It is practically one mile from the center of gravity of its 13,200-volt distribution area, but the estimated trend of this center is towards the station.

The 220,000-volt lines enter the station on a 200-ft. wide right-of-way, special bridge type structures enabling four 220,000-volt circuits to be accommodated. The 110,000-volt connection to the existing system is

accomplished by means of a 110,000-volt d-c. line, provided with two circuits of 605,000-cir. mil. aluminum and supported on special narrow-base towers erected on the railway right-of-way, immediately adjacent to which the station is located. The 13,200-volt connections to the distributing stations of the Toronto Hydro-Electric System are all underground, the possibilities of extending to the required capacity being excellent. The site has an area of something more than 12.0 acres, and the present arrangement will allow of an installation of 360,000 kv-a. transformer capacity.

## System Studies

As required for harmonic circulation and for the operation of the condensers, the preliminary design of transformers included tertiary windings of approximately 60 per cent capacity, but as it was later decided that the station would ultimately deliver all of its power to the 13,200-volt distribution system, these windings were increased to 100 per cent capacity.

This arrangement of windings,—*i. e.*, three windings, 220,000-, 110,000-, and 13,200-volt, each of full capacity—practically decided the size of the transformers to be the largest that could be transported in a built-up condition between the manufacturers' plants and the transformer station, it appearing undesirable to undertake the construction of these units in the field. Four banks of three 15,000-kv-a., single-phase, oil-insulated, water-cooled units were decided upon.

The terms of the contract permitted a certain range of voltage control at the generating station, a portion of which it was considered desirable to reserve for emergency operating conditions. The condenser capacity required to maintain satisfactory receiving-end voltage regulation, while keeping within the above limitation, was calculated as 100,000 kv-a., the transmitted power being of the order of 200,000 kw. These condensers, 25,000 kv-a. per transformer bank, operate on the respective load busses to maintain the distribution voltage within the required limits.

In the preliminary arrangement, with the 220,000-volt station stepping down only to 110,000 volts, it was assumed that the condensers could operate to maintain the 110,000-volt bus voltage for parallel operation with the existing system, the regulation on the condenser bus being then relatively unimportant. With the condensers now operating on the load bus, on which the regulation is definitely limited, it was considered desirable in order to control the exchange of wattless current between the interconnected systems to introduce under-load tap-changing on the 110,000-volt windings.

The selection of the range of voltage taps required on the windings of the transformers, together with the problem of the division of load between the three windings, was the object of considerable study. During the early years of operation of the station, the load distributed at 13,200 volts would be increasing from an estimated minimum of 40,000 kw. to full-load on the transformers, while the load transmitted to other stations at 110,000 volts, to maintain the full contract demand, would be correspondingly decreasing. Further than that, it was appreciated that the distribution of load between the two secondaries would be subject to wide daily variations due to the necessity of maintaining an average week-day load factor of approximately 87 per cent on the 220,000-volt system, in order to take delivery of the energy allowed in the contract; whereas the load-factor of the 13,200-volt demand was more nearly 65 per cent.

These studies indicated the necessity of maintaining parallel between all banks on all three windings, and for this the adopted station diagram provides, though it was found desirable to insert reactors in the 13,200-volt connections.

The transformer taps adopted were: on the 220,000-volt windings, one 5 per cent tap above and below a normal of 118,000 (204,400) volts; on the 110,000-volt windings, three 2½ per cent taps above and below a normal of 65,000 (112,600) volts; on the 13,200-volt windings, no load taps, though taps are provided for the operation of the under-load tap changers.

Calculations of short-circuit currents on the interconnected system showed that if all banks were connected in parallel, values of the order of 1,250,000 kv-a. would be reached on 13,200-volt equipment, rising to nearly 1,750,000 kv-a., if the station were developed to its ultimate capacity. It was decided to set a limit of 1,000,000 kv-a. ultimate, with feeder reactors to protect the outgoing feeders. For this reason, the "star-bus" arrangement was adopted, with 5 per cent reactors between the individual transformer and feeder groups and this bus.

Values of the order of 1,250,000 kv-a. and 1,750,000 kv-a. on the 220,000-volt equipment, and 1,250,000 and 1,600,000 kv-a. on the 110,000-volt equipment, were calculated. It was decided that the future arrangement of the 110,000-volt system would be such that the short-circuit capacity in Toronto would be limited to 1,500,000 kv-a., and breakers of this capacity were installed. With these restrictions on the lower voltages, 220,000-volt breakers of 2,500,000 kv-a. rupturing capacity, practically the lowest rating, were considered as ample, and these were adopted.

During the time the design of this system was being carried out the problem of stability was receiving considerable attention. Various methods of calculation were being advanced, though methods to determine the behavior of systems under various fault conditions had not yet been presented in detail. However, it was felt that the design of this system should promote, as far as possible, the ability of the various generating equipments to remain in synchronism during system disturbances. To this end, the highest speed of clearance obtainable in 220-kv. circuit breakers at that time was specified, and the relay system designed so that under

practically any condition the relays would operate to clear faults instantaneously.

Quick response excitation systems were installed on the generators of the Gatineau Power Company, and on the synchronous condensers at Leaside. In the former case, motor-generator exciter sets driven from service generators direct connected to the main units were used, separately excited from pilot-exciters. They were equipped with voltage regulators of the exciter rheostatic type, operated from positive-phase sequence net-works. In the latter case, direct-connected main exciters were used, separately excited from pilot exciters also direct-connected, and with quick-acting regulators and positive-phase sequence networks. The speed of the condensers being 500 rev. per min., the desired speed of excitation response was obtained with these direct-connected units.

No changes were made in the excitation system at the Commission's Queenston Generating Station, this being

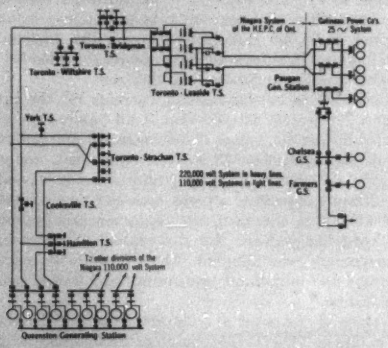



FIG. 4—DIAGRAM OF CONNECTIONS BETWEEN GATINEAU POWER COMPANY'S GENERATING STATIONS AND COMMISSION'S QUEENSTON GENERATING STATION

direct-connected exciters running at 187.5 rev per min., with standard vibrating type voltage regulators.

Operation of the interconnection (Fig. 4) required the provision of facilities for synchronizing, (or re-synchronizing in event of the systems splitting apart), sectionalizing to allow of necessary maintenance work, as well as the establishment of a routine of operating procedure.

The provision of facilities for synchronizing depends upon whether it is decided to adopt a rigid tie between systems, or whether, in event of serious trouble on either, the systems shall be allowed to part. This decision has not yet been made, as up to the present there has been only one 220,000-volt circuit in operation.

Should the 220-kv. supply be interrupted at the Leaside Transformer Station, synchronizing may be accomplished across the 110-kv. circuit breakers. Gatineau potential is obtained from the 13.2-kv. windings of the transformers, and Niagara potential is brought from the Bridgman Transformer Station, three miles distant.

For troubles not cleared rapidly on the 110,000-volt system, the systems operate at present as with a loose tie, splitting apart usually at the Bridgman Transformer Station. This is very close to the preferred arrangement, as it leaves both systems approximately self-supporting. To provide for this contingency, synchronizing facilities are also provided at this point.

To promote system stability and allow for transmission line maintenance work an automatic interswitching station about the midpoint of the line was originally contemplated. Construction of this station, however, has been deferred and will be considered after two-circuit operation and tests have determined its necessity. In the meantime to facilitate maintenance the installation of disconnecting switches at this midpoint is now being undertaken.

Dispatching on the Niagara System has in the past been divided between the dispatching of load at the generating stations on the Niagara River, centered at Niagara Falls, and the dispatching for the remainder of the system, centered at the Dundas Transformer Station. Separate control of generation has been necessary to obtain the most efficient use of the allowable water diversion at Niagara Falls, involving the optimum energy output among generating plants varying in efficiency from 30 hp. per cu. ft. per sec. to 10 hp. per cu. ft. sec.

Upon the establishment of the interconnection, the metropolitan area of Toronto, including the respective infeeds, was set up as a separate subsystem. Control of this subsystem, in so far as line and voltage conditions are concerned, was transferred to the operators at the Leaside Transformer Station.

As the problem of obtaining the full benefits of the contract amount of power and energy is so closely connected with the problem of generation in the Commission's plants, control of the power demand from the Gatineau Power Company remains with the load supervisors at Niagara Falls, who under normal conditions instruct the Leaside operators.

Between Leaside and Niagara Falls direct telephone communication is available over private wires of the Commission. Between Leaside and the Gatineau Power Company direct communication by teletypewriter and by private-wire telephone is available.

## FEATURES OF THE TORONTO-LEASIDE 220,000-VOLT TRANSFORMER STATION

The general system and economic studies described had located the transformer station in Toronto, and had dictated certain of the major features to be incorporated in the actual station design.

The station site had been purchased, and studies were first made with the object of determining the trans-

former capacity that could ultimately be accommodated. These studies also included variations of the station diagram. The general requirements of the ultimate arrangement sought were, (a) that the maximum capacity of the site should be realized, keeping in view that the diagram and layout should allow of progressive additions to the station, with the minimum of revision to then existing equipment; (b) that the minimum of 220,000-volt switching be specified, on account of its expensive nature; (c) that the 110,000-volt switching arrangement should allow of future segregation, on account of short-circuit duties; and (d) that the 13,200-volt arrangement should be a unit for each bank, with reactor connections to a "star" bus, also on account of short-circuit duties.

The ultimate station arrangement decided upon is shown in Fig. 5. Eight banks of transformers, or a total of 360,000 kv-a., are provided for, with four 220,000-volt lines. For the 220,000-volt switching, a "ring" diagram has been decided upon, this being the most economical arrangement; for the 110,000-volt switching, a simplified double-bus arrangement has been adopted which will be operated as a "ring" during the early years; for the 13,200-volt switching, individual "rings" are used for each bank, the transformer connection, the feeders, the condenser connec-

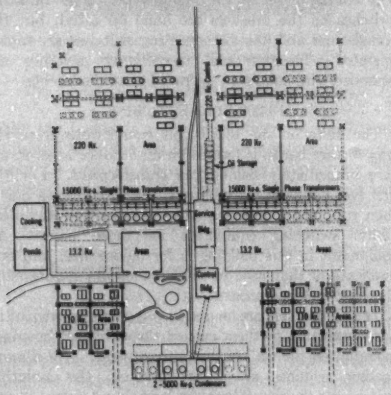



FIG. 5—PROPOSED ULTIMATE ARRANGEMENT TORONTO-LEASIDE TRANSFORMER STATION

tion, and a connection to the reactor bus being the units around the ring.

The portion shown in heavy lines in Fig. 5 is the initial installation required for the Gatineau contract power; this installation will be completed by the fall of the present year. The station diagram for this initial installation is shown in Fig. 6.

The advantages of the "ring" diagram may be seen from a study of the 220,000-volt switching. There are six equipments to be provided for—two lines and four transformer banks—and only six 220,000-volt oil circuit breakers, yet each equipment is protected by two breakers. The ring is normally operated with all switches closed, but any breaker may be taken out for emergency maintenance, or "exercising," without any attendant rearrangement switching, and without greatly endangering the security of the station. Further, there are no extensive bus sections, a failure on which might result in a major interruption. The diagram may not

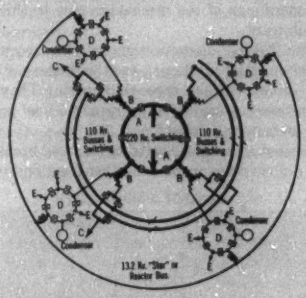



FIG. 6—SCHEMATIC CIRCLE DIAGRAM—MAIN SWITCHING. TORONTO-LEASIDE TRANSFORMER STATION

A. 220-Kv. incoming lines
B. Three-winding transformers 220/110/13.2 kv.—45,000 kv-a. each winding
C. 110-Kv. outgoing feeders
D. 13.2-Kv. ring bus
E. 13.2-Kv. outgoing feeders

of course be too greatly expanded, as an excess of units in the ring tends to weaken the arrangement. It is considered that six units is near the maximum, and for the extension to the station, a second ring will be used, probably with a single or double tie between rings.

Because it is desirable to operate the ring normally closed, motor-operated, isolating disconnecting switches are installed on each piece of equipment, so that if any equipment is to be removed from service for some time, its isolating switch may be opened and the ring again re-established.

## 220,000-VOLT SWITCHING

The 220,000-volt area is entirely outdoors, typical fabricated steel structures being used. (Fig. 7.) A minimum clearance of 12 ft. between phase wires has been specified, although clearances up to 20 ft. between relatively long strain-equipped leads are provided. Minimum ground clearance has been specified at 7 ft. 6 in. Both these figures are based on grading rings being provided; as these rings have not yet been installed, actual clearances are somewhat higher.

The oil circuit breakers have a current rating of 800 amperes, and a rated rupturing capacity of 2,500,000 kv-a. They are equipped with oil-filled bushings rated as being suitable for operation at 127 kv. to

ground; *i. e.*, 220-kv. solidly grounded, or 187-kv. isolated, neutral system, although provision has been made for bushings of a size suitable for a 220-kv. isolated neutral system.

Low-freezing oil is used in these breakers, although two 1000-watt immersion heaters have also been installed in each tank to prevent the oil from thickening at below zero temperatures. Also, in the mechanism housing, the breaker operating mechanism being of the centrifugal type, a 500-watt heater has been installed to eliminate dampness as well as to prevent slowing up of the operations of the mechanism due to thickening of the lubricant.

All the 220-kv. disconnecting switches are upright, mounted on pillar insulators, each with three stacks of six 17½-in. by 14½-in. three-skirt units. They are of the high-pressure contact type, rated at 1000 amperes, and are all motor operated.

When used as isolating switches on an oil breaker, the two sets of switches operate together from one control,

Fig. 7—220,000-Volt Switching for First Unit, Toronto-Leaside Transformer Station

electrical interlocks being provided to prevent their being operated under load. On the line disconnecting switches, hand-operated ground switches have been provided on the line side, means also being provided for single-pole operation when required for testing. Non-corrosive bolts are used on all bolted connections exposed to the weather which are likely to require to be unbolted in case of replacements.

The 220-kv. leads are constructed at three elevations. The lowest conductors are 20 ft. above ground and are of 2-in. copper tubing, supported on post insulators, with a maximum spacing of 24 ft. between supports. Provision is made for contraction and expansion of this tubing. The upper two tiers are spaced so as to give 20 ft. minimum clearance between tiers. They are both suspension-equipped—twenty 5-in. standard units, strained from the steel structures and designed for a maximum pull of 3000 lb. with ¾-in. ice loading and 8-lb. wind. Hollow-conductor copper cable with I-section core is used for these leads, having a conductivity equivalent to 750,000-cir. mil copper and an outside diameter of 1.26 in., sufficient to prevent corona formation in all weathers. In clamping this cable, it was found necessary, in order not to crush it, to use clamps which would exert a uniform pressure around the circumference of the cable. As few joints as possible are made, and no soldered connections are used at all.

### 110,000-Volt Switching

Similar construction is used for the 110-kv. switching, namely, outdoor equipment with copper tube busses supported on post insulators, and strain copper cable busses with suspension insulators. Post insulators have two units, each 20 in. high with four skirts, and the strain positions have 10 suspension units. The oil circuit breakers are rated at 135 kv. 600 amperes, with a rupturing capacity of 1,500,000 kv-a. and condenser bushings and solenoid operated mechanisms. Electric heaters are provided for heating the oil and mechanism housings of the breakers. Similar to the 220-kv. section, all connections on busses and to the equipment are clamped.

The disconnecting switches are of the swivel type, with three stacks of insulators, the center one rotating. The contacts are of the finger type. The isolating switches on the breakers are hand operated, but the transformer and line disconnecting switches are motor operated. The line and transformer switches are equipped with hand gang operated ground switches.

### 13,200-Volt Switching

The delta on the 13,200-volt connections from the transformer banks is formed on an outdoor steel structure immediately behind the transformers. For the first two banks of transformers, the three-phase bus is then run into a building which houses the complete 13-kv. switching equipment for these banks. All equipment in this building is for indoor use, and is a duplicate of that used in the Commission's Queenston Generating Station.

The oil breakers are housed in compartments with the bus connection to them carried through wall bushings mounted on the wall of the compartment. All disconnecting switches are gang operated, the isolating switches on the circuit breakers being hand operated and the feeder and transformer switches being motor operated by remote control from the control room. These disconnecting switches, as well as reactors and potential transformers, are also housed in separate compartments. The operating wheels for the hand operated switches are located outside the disconnecting switch-rooms in the passages. The busses, which consist of ¼ in. by 4 in. copper bar laid on the flat, are supported on extra heavy duty bus insulators.

The switching for the second two banks is radically different. From the delta bus, cable is run to separate

phase structures. The equipment is of outdoor isolated-phase metal-clad type.[1]

The breakers are solenoid operated with an electrical interlock only. The breaker-isolating disconnecting switches are formed by the raising and lowering of the breaker oil tanks and mechanism by motor operation, the breaker bushing being equipped with a contact

FIG. 8—INSTALLATION OF FIRST TWO 45,000-KV-A., 220,000-VOLT BANKS OF TRANSFORMERS

Tap-changing equipment immediately to the rear of transformers, and not visible in photograph. Toronto-Leaside Transformer Station

while the bushings connecting through to the bus are equipped with floating fingers. An automatic shutter closes the opening when the breaker is lowered. The feeder disconnecting switches are oil immersed and motor operated.

The complete equipment for each phase is housed in a steel covering, the bus being located in a compound-filled compartment just under its roof.

## MAIN TRANSFORMERS

Four banks of transformers, and one spare, have been installed, each bank consisting of three 15,000-kv-a., single-phase 25-cycle, 118,000/65,000/13,200-volt oil-insulated water-cooled three-winding outdoor transformers. (Fig. 8) The banks are connected in star on the high-voltage winding, with the neutral point solidly grounded. The intermediate voltage windings are connected in star,—at present with the neutral isolated, the system neutral however being grounded through a resistance at the Queenston Generating Station. This intermediate voltage winding is provided with full insulation. The low-voltage winding is connected in delta and grounded through a zigzag reactor.

Each of the three windings has a continuous rating of 15,000 kv-a. A hand wheel is provided on top of each transformer cover for operating the tap changer on the high-voltage winding, when the transformer is not energized. Tap-changing equipment for operation under load is used on the intermediate voltage, with a special series transformer to boost or buck the terminal voltage 7½ per cent in 2½ per cent steps. This special transformer is energized from the low-voltage winding of the main transformer. The tap changers may be operated by hand on each transformer, or three, comprising a bank, may be operated simultaneously by remote control from the control room. The transformers are shell type and the outlet bushings are condenser type.

The tanks are made in three sections, which, with the cover, were shipped to the station unassembled. The main core was completely assembled in the factory, as were the series and preventive transformers; then each one was shipped in oil in special shipping tanks. Complete assembly of the transformer was made in the service building.

## SYNCHRONOUS CONDENSERS

In the synchronous condenser installation at Leaside, a radical departure from standard designs has been made in that vertical-shaft outdoor units have been adopted. (Fig. 9.) They have a combined spherical thrust and guide bearing located below the rotor, with direct-connected main and pilot exciters located below the thrust bearing. There are four such units, each

FIG. 9—INSTALLATION OF FIRST TWO 25,000-KV-A., 500-REV. PER MIN. VERTICAL-SHAFT SYNCHRONOUS CONDENSERS. TORONTO-LEASIDE TRANSFORMER STATION

rated at 25,000 kv-a. 500 rev. per min.; one connected to each bank of transformers.[2]

From a survey of existing condenser installations and experience with large generating apparatus, it was decided that units of the size dictated by preliminary studies should be of the totally enclosed type, with some means provided for the cleaning of the cooling medium. With such a unit, little if any additional cost would make the cover weathertight, which contributed to the adoption of outdoor machines.

Comparative estimates were prepared of indoor and outdoor arrangements, with both horizontal and vertical

1. For references see Bibliography.

shaft units. These estimates pointed to an outdoor installation, with a slight advantage in favor of the vertical shaft unit. The vertical shaft arrangement was finally selected, it being decided that such units were relatively more accessible for maintenance work.

Preliminary designs were worked out in cooperation with the engineers of the manufacturers, with the object of arriving at an arrangement which would best lend itself to ease of maintenance, and require the smallest amount of exposure to weather during dismantling. The arrangement decided upon is shown in detail in Fig. 10. The combined thrust and guide bearing is seen below the rotor, with the exciters (main and pilot) below this bearing. All moving electrical connections, therefore, are located indoors within the foundation, under the view of the operator and readily accessible.

To dismantle the machine, the exciters are disconnected immediately below the bearing, and are moved from under the machine on a small truck provided for the purpose. Removal of a small cover allows the crane (80-ton capacity gantry) to take the weight of the rotor, certain blocking is removed, and the rotor with its bearing is dropped down into the foundation. Replacing the cover, the unit is again weathertight and the armature and field windings are completely accessible.

The main unit is located above the ground level and is completely surrounded by a ventilating housing, the roof of which is lagged to prevent condensation. Automatic dampers control the air circulation, the object being to minimize coil creepage by maintaining constant machine temperature. All air drawn from outside is screened before entering the housing.

For floating the rotor during starting each unit is equipped with a high-pressure oil pump. The lubricating system is of the unit type provided with duplicate motor-driven lubricating pumps to circulate the oil through a tubular water cooler to the thrust and upper guide bearing. A central air compressor is provided for braking purposes, the speed of the unit being first reduced to one-half by dynamic braking. Both starting and stopping operations are fully automatic with remote control.

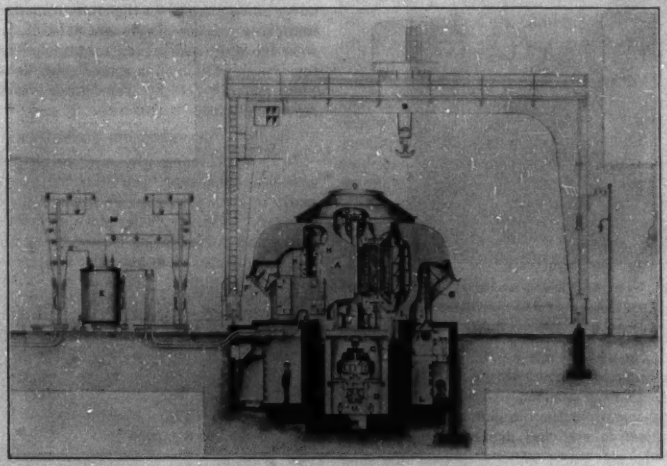


Fig. 10—25,000-Kv-a. Synchronous Condenser. Toronto-Leaside Transformer Station

A 25,000 Kv-a. condenser, 500-rev. per min., three-phase, 25-cycle, 13,200 volts
B 80-Ton gantry crane
C 150-Kw., 125-volt main exciter
D 30-Kw., 250-volt pilot exciter
E 9000 Kv-a. auto transformer
F Main incoming air damper
G Main outgoing air damper
H Recirculating air damper
I Damper for basement heating
J Spherical seat thrust bearing
K Upper guide bearing
L High-pressure oil pump for starting
M Starting structure and equipment
N Truck for handling exciters
O Threaded hole for rotor lifting eye
P Air filters
Q Current transformers

A central carbon-dioxide fire protection is provided, augmented by two copper water-rings near the armature end-connections.

In order to minimize vibration, care has been taken to isolate the machine foundations from adjacent structures. This is accomplished by using cork between the foundation and the roof of the condenser basement, and mastic between the base of the foundation and the basement floor. The soil on which the

foundation is located being of hard blue clay bordering on shale has not been disturbed.

### Lightning Protection

The problem of providing what would appear to be adequate lightning protection for the 220,000-volt station was given considerable study. When applied on 220,000-volt systems, the protective value of the available types of lightning arresters was very indefinite. The decision was made to initially omit arresters, but to coordinate as well as possible the transmission line and station insulation, at the same time using an increased number of ground wires on the adjacent portion of the line.[3]

For a distance of some two miles from the station, the number of suspension units (5-in. spacing) was reduced from 18 to 14, four ground wires were used instead of two, and the height of the supporting structures reduced some 13 ft. The increase in number of ground wires was expected to decrease the surge impedance of the phase wires, and therefore to cause a lowering of the voltage of surges entering this section.

The suspended bus in the station was protected by three ground wires, the height and separation of these ground wires being such that the bus would be protected from direct hits.

In the interval, the characteristics and protective value of arresters have been more clearly defined by extensive field and laboratory investigations, and a special design of 220,000-volt valve type arrester is now being installed. This special design has been chosen to protect the arrester against rise of dynamic voltage upon loss of load, at the same time affording maximum protection to the station apparatus.

Normally 18 units are in service, with four further units short-circuited by a disconnecting switch. This disconnecting switch, normally closed, is opened automatically by an over-voltage relay if the dynamic voltage exceeds a predetermined value. These arresters are being installed immediately adjacent to the transformers, one on each bank.

### Relaying

Of necessity the relay protective equipment at Leaside Station includes not only that required for the actual station protection, but also that required for the protection of the transmission system. This is more particularly true with the "ring" arrangement, as certain of the oil circuit-breakers have dual functions, being both line and transformer breakers at the same time. For these reasons, the combined relay scheme will be described here.[4]

The relay protection for this system is designed to meet, so far as possible, the following requirements: (a) the clearing of faults, instantly and selectively, leaving sound portions of the system in service; (b) in case of failure to clear instantaneously, to provide stand-by effect to separate the system into main sections and then to clear the section on which the fault persists; (c) to be fully effective (without readjustment) to both instantaneous and stand-by features, over a wide range of connected generator capacity including the condition where the fault current may be less than normal full-load value; (d) to be, in itself, safeguarded against tripping from accidental causes when no system fault exists; to be capable of easy checking, calibration, and testing; and to give as many data as possible as to the nature and location of the fault; and (e) to be capable of incorporation, without important changes, into a developing system, as well as capable of extension into existing systems.

Relaying which practically meets these requirements has been applied to the 220,000-volt lines, the Leaside Transformer Station, and is being extended to the lines and stations of the Gatineau-Niagara interconnection.

For relay purposes, the system may be considered as divided into elements, each bounded by automatic oil circuit breakers. These breakers carry the relaying current transformers, bushing type, and each such breaker is included within the respective element; *i. e.*, these "boundary" breakers are bracketted by two elements. The elements, in turn, are of two classes: those entirely within the station, (transformer banks and their wiring or bus-sections, known as "Zones"), and those which extend away from the station, (lines and feeders).

Each station zone is covered by simple current differential instantaneous protection, set below normal load current. To the condensers are added split-phase features on the stator windings.

To take care of incipient faults, and avoid tripping on magnetizing current when energizing, the transformer banks have an inverse time feature. The external wiring of the transformer zone is covered by instantaneous differential protection.

At each end where there is power infeed, long lines and feeders, at all voltages, are equipped with directional double-distance-range impedance relays, for phase-to-phase, and phase-to-ground faults. One set of distance relays with range definitely short of the remote end of the line, clears instantly for faults within 70 to 80 per cent of its end of the line. The second set, with range definitely beyond the remote end of the line, is timed under all conditions at about 0.6 sec., to be selective with faults on the bus and other lines.

The relays used consist of two solenoids on opposite ends of a balance arm, one actuated by phase-to-phase, or phase-to-ground, voltage and the other, by phase or residual current. The potential coil holds the contacts apart; the current coil tends to close them. The relay may be set for a ratio, volts divided by amperes, which allows the contacts to close instantly, and which, when applied to a line, corresponds to a length of the line. Any timing is obtained by a definite time auxiliary relay.

Other relays include directional, plunger type current, voltage, and auxiliary tripping relays of necessary

ranges, having very low energy consumption for use on 25-cycle bushing current transformers.

The distance relay is usually set well below full-load current, so that if it loses potential it will operate during normal operation. To avoid this, where relays are so set, a duplicate of the long range distance relay is used, energized from a duplicate source of potential.

For stand-by protection on phase faults, a set of distance relays of long range, usually duplicated as to potential because current settings are low, and timed beyond the instantaneous features—usually 1.2 to 1.4 sec.—are applied on each transformer bank. For grounds, residual current, or voltage, relays are used, timed in the same way.

For 220-kv. potentials, 13,200-volt potential transformers have been used on each bank, with transformer drop compensators to simulate the 220-kv. voltages. For use with line relays, these are selected by a switching arrangement of potentials.

The short 110,000-volt connection to the existing system is protected by current-differential pilot wire.

### Grounding

The attempt has been made at Leaside to establish one "ground" plane for the whole site, and thus avoid ground gradients due to fault currents in any one section of the station. Copperweld rods have been driven at the bottom of the transformer tunnel, cooling pond, and in all tower footings, and these are connected together with 2/0 copper wire. The 2/0 copper wire has also been laid along all building foundation footings just below the weeping tile, in all cases carefully covered with a few inches of earth to increase its contact area.

The site has been divided into various areas and the various ground networks segregated on a ground test-bus in the transformer tunnels. The combined network has resulted in a ground resistance of less than one-tenth of an ohm, which so far has remained consistently low.

The ground wire shielding over the 220-kv. line has been extended across the station at a height of 15 ft. above the highest bus, and is tied directly to that section of the general ground bus to which the 220-kv. transformer neutrals are connected. This shielding is extended across the 110-kv. switching area, and thence to the ground wire on the 110,000-volt line connection to the Niagara System.

### Batteries and Charging

Two storage batteries, one 250-volt and the other 48-volt, are installed to furnish a reliable source of power for the control of the station equipment, emergency lighting, and signals.

Duplicate charging sets are provided, each consisting of a three-unit motor-generator set, 550-volt, three-phase motor, and two diverter-pole d-c. generators,—one for 250-volt and the other for 48-volt, mounted on either end of the motor shaft. They are operated "floating" and have given very excellent service.

### Lighting

Power for lighting is obtained from two banks of three 50-kv-a. single-phase 550-volt and 199/115-volt delta-star dry type transformers. Emergency d-c. lighting is provided in the control building, and upon failure of the a-c. supply is automatically placed in service. Holoplane refractors have been used throughout, and in the wiring of all the outdoor standards, single-conductor lead-covered cable, with the lead forming the return circuit, has been used.

### Oil Handling System

Permanent oil piping is extended from a central oil-handling room to near each oil-circuit breaker and transformer, from which point, flexible hose connections are made as required. When removing oil from any equipment, it is pumped into any or all of six oil storage tanks having a total capacity of 30,000 gal. Two 40-gallon blotter type filters are used to treat the oil when replacing it. A by-pass has also been provided at the equipment, permitting the good oil piping to be flushed out before using.

### Water Supply

Two cooling ponds of reinforced concrete construction and having a total capacity of 225,000 gal. have been built immediately adjoining one another. They are equipped with spray nozzles and enclosed with wooden louvers.

Cooling water for the transformers and condenser bearings is circulated by means of two centrifugal pumps, each with a capacity of 1000 gallons per min. at 100 ft. head.

Water for domestic purposes, and for the cooling-pond make-up, is purchased from the town of Leaside.

### Communication

At Leaside, communication is provided with the load-dispatcher of the Gatineau Power Company at Val Tetreau, with the Commission's load-supervisor at Niagara Falls, and with other necessary stations on the 110,000-volt system and on the Toronto Hydro-Electric System.

Teletypewriter service over circuits of the Bell Telephone Company is used for practically all communication with the Gatineau Power Company. This service was chosen after consideration of carrier-current telephone, long and short wave radio, and direct private wire telephone over circuits constructed on the 220,000-volt right-of-way. To date the service has given excellent satisfaction, the printed message being a desirable feature.

The telephone circuit on the 220,000-volt right-of-way was first constructed through the inaccessible country in the east, but its performance was so good that it has since been extended to Leaside. Direct telephone service is now available to the Paugan Generating Station, but the service is used principally for com-

munication with patrol points and for load dispatching only in emergency.

Other communication is over the Commission's private wire system, or Bell telephone circuits within the city.

Within the confines of Leaside Station, and also to the head office of the Commission, communication is provided by means of a private automatic telephone exchange. Fixed instruments are installed in a number of convenient places, and jacks for portable phone connection are provided in many others.

### Control

Because of the complications introduced by the three-winding transformers, it was considered desirable, if not essential, to provide an arrangement of control which would lend itself to the incorporation of a dummy bus scheme. It was estimated that approximately 200

Fig. 11—Control Desk for First Unit—Toronto-Leaside Transformer Station

Four such desks will be required for ultimate station capacity

controllers would be needed for the ultimate station, and in order to confine these controllers within a reasonable space, miniature control has been adopted.

Standard telephone keys mounted on the top of desks about the size of ordinary office desks have been adopted. One of these desks is shown in Fig. 11, there being four required for the ultimate station. On the desk shown are assembled all the controllers and signal lamps required for:

One—220,000-volt line
Two—three-winding 45,000-kv-a. transformer banks
Two—110,000-volt lines
Six—13,200-volt feeders
Two—25,000-kv-a. condensers
Two—connections to the paralleling bus

Standard telephone equipment operated at 48 volts, has been used throughout, and use has also been made of the double-pole telephone key to isolate the operating coil circuits of the interposing relays when they are not in use. To facilitate tracing of circuits, color code is carried through the wiring, and terminal strips are located at all points where multiple-conductor cables end.

Individual keys are protected against accidental operation by a master key in the front of each desk, to be operated simultaneously. Interlocks have been provided on the 250-volt portion of the control to prevent operation of the disconnecting switches unless the oil circuit breakers in conjunction with them are open.

### Features of the 220,000-Volt Transmission System

In undertaking the construction of 220,000-volt transmission lines from the interprovincial boundary between the provinces of Ontario and Quebec to Toronto, it was early recognized that the problems that would arise would be many and varied. The Commission had not previously constructed any lines operating above 110,000 volts, nominal; nor were there any lines in Canada; and but few in the United States, operating at that time at 220,000 volts. The lines that were then in operation were located in territories much less subject to atmospheric disturbances than the territory through which these lines were to be constructed. As evidence of this fact, it was stated at that time that 220,000-volt circuits would seldom be involved in more than single-phase-to-ground flashovers due to lightning, whereas two flashovers involving more than one conductor have already been experienced. For at least one-half the distance, these lines were to be built through extremely rough country, accessible only over the poorest of roads, and generally only superficially surveyed.

### Route

The question of the route to be followed by these lines was very fully investigated, the alternatives considered lying between the shortest and most direct route, which involved more than 100 miles through the type of country described, (in places 25 miles from the nearest railway) and a route diverted well to the south, to take advantage of the well-developed country paralleling the shore of Lake Ontario. Economic considerations outweighed any advantage of the latter route, and the generally direct route has been followed (Fig. 12).

It was considered desirable to have these lines pass close to a future power development known as Chats Falls, on the Ottawa River, and this governed the choice of location of the river crossing. The route is therefore not direct from the generating source, but as nearly as possible direct from this latter point.

### Survey

Where absolutely dependable maps are available, a large proportion of the work of locating a line may be done in the office before any ground work is undertaken. For the majority of the territory to be traversed in this case, there were no such maps available, and it was

realized that to survey a route by means of field survey parties would be a long and tedious task. As the question of time was very important, (it being known that the first circuit would have to be completed within two years), the newer art of survey by aero-photography was adopted.[5]

This work was carried out by a commercial organization under contract, the company supplying the Commission, two sets of oblique photographs—(looking respectively north and south over the preliminary center-line), one set of vertical photographs looking down on the finally selected center line, and one complete mosaic for the whole line.

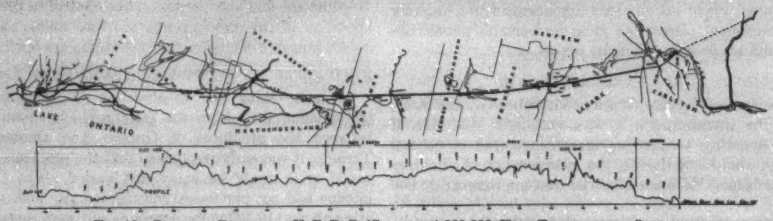



FIG. 12—PLAN AND PROFILE OF H. E. P. C. (GATINEAU) 220,000-VOLT TRANSMISSION SYSTEM

These photographs were made as follows: On the best maps available a preliminary route was drawn. The oblique photographs were taken flying over this route, and from the information thereby made available, the maps were corrected and all obstacles shown. The final route was then selected, and the vertical photographs taken flying over the new center line. As is customary, these verticals were taken with a 60 per cent overlap for the making of the most accurate mosaics and use with a stereoscope to show the contours.

On the mosaics, with the aid of the information available by the use of the individual prints under the stereoscope, the individual tower sites were located. The importance of the use of the stereoscope in this way can hardly be overestimated, as even the minor contours are revealed in remarkable detail. Field survey parties were then only required to run the center line as shown on the mosaic, stake the tower locations, and mark the limits of the right-of-way for clearing purposes.

## RIGHT-OF-WAY

The adoption of aerial surveying was found to be of considerable assistance when securing the rights for right-of-way. The easement method has been used throughout with the exception of a short section close to Toronto. The right-of-way agents were supplied with copies of the mosaic showing tower locations, and as the farmers along the route had not been disturbed by field survey parties working ahead of the agents, the first intimation that a number of them received of the lines crossing their property was the appearance of the agent to arrange for easements.

Easements were taken for a 40 year period, covering the right to erect and maintain towers and including the overhanging and stringing rights. Wherever clearing was necessary, these rights were purchased in addition, the farmer usually also being given the contract to carry out the clearing. Incidental damage to trees, crops, fences, etc., due to construction work, was settled for later.

In the case of crossing Crown lands, only notice of occupation given to the Government was necessary. On these lands, clearing was done by the Commission's Construction Department. In all clearing provision was made for haulage of material to the tower locations, by cutting a strip 12 ft. wide to the ground level.

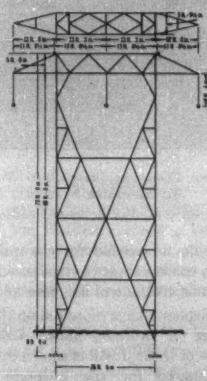


FIG. 13—OUTLINE STANDARD SINGLE-CIRCUIT SUSPENSION TOWER

The section in which the lines are located on purchased right-of-way extends for about 10 mi. east of Toronto. The purchased strip is 450 ft. wide, this being considered necessary to provide an adequate entrance for four 220,000-volt single-circuit tower lines, which will ultimately run into this station.

## DESIGN OF TOWERS

Before undertaking the design of structures, several lines already operating at 220,000 volts were inspected

and studied. Acknowledgment is made here of the courtesies extended the Commission's representatives at this time, all visited organizations willingly passing on to the Commission the benefit of their operating experience. Particular attention was paid to the question of tower clearances, it being considered

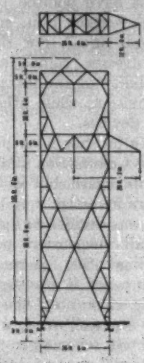


Fig. 14—Outline Standard Single Circuit Transposition Tower

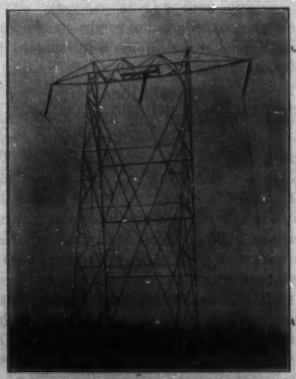


Fig. 15—Illustrating Use of Light Angle Tower with Ten Ft. Extension

Note extension of outside arm and provision for off-set of center conductor

desirable to be even more liberal in this respect than on any line at that time designed.

The standard suspension tower adopted is shown in Fig. 13. Conductor spacing is 25 ft. 3 in., which, with a 100-in. insulator string, insures a minimum clearance of 6 ft. to the tower steel assuming a maximum swing of 45 deg. Two ground wires are provided, located 14 ft. above and 12 ft. inside the outside power conductors, the minimum clearances at rest being 25 ft.

Towers are designed for a maximum conductor tension of 10,000 lb., and for a maximum ice and wind loading of ½-in. ice, 8-lb. wind, 30 deg. fahr., along the line, and ¾-in. ice, 11-lb. wind, 30 deg. fahr. across the line. Towers are constructed of carbon steel with silicon steel legs, the standard suspension tower, including footing, weighing some 10,400 lb.

In addition to the suspension tower, a light-angle tower, and what is known as a semi-anchor tower are provided. The outlines are approximately the same as for the suspension tower, the weights being 11,000 lb., and 15,900 lb., respectively. The light-angle tower is designed for long spans and for taking angles up to 4 deg.; the semi-anchor tower provides for dead-ending of conductors and for taking angles up to 20 deg. Both

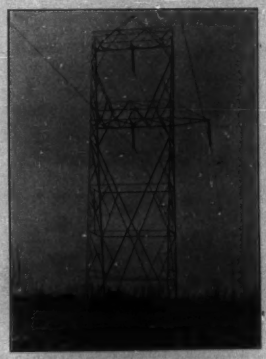


Fig. 16—Typical Installation of Transposition Towers—Same Tower Used Right and Left-Hand

these towers are provided with special off set heads for angles. In order to maintain the specified clearances, the arm on the outside of the angle is made longer, and by means of a drilled plate, provision is made to move the point of support of the center conductor to maintain its position in the center of the tower.

The standard transposition tower is shown in Fig. 14. Transpositions are of the rolling type, involving two towers of the type shown,—one right-hand and one left-hand. There are 33 transpositions per line in the 203 mi., which has been found sufficient to result in excellent service over the closely paralleling telephone circuit.

Ten-, twenty-, and thirty-foot extensions are provided for all towers, all of part silicon construction.

## Footings

All footings in earth are of the grillage type, consisting of channel sections with cross-ties. Footings vary in

weight from 1850 lb. for the suspension tower to 2360 lb. for the semi-anchor. They also vary as to the depth to which they are buried; for suspension and transposition towers, they are buried to a depth of 8 ft., for light-angles 8 ft. 6 in., and for semi-anchors, 9 ft. 6 in.

The stub-angle to which the tower leg is bolted is provided with a series of bolt-holes at 3-in. centers, making an adjustable telescopic joint by means of which minor variations in ground level at the four footings may be taken care of.

Rock footings consist of two channel members as in the case of the earth grillage, but without the cross ties. Each leg is anchored to the rock by means of two rock bolts fashioned in such a way that, when driven, a wedge expands the bottom of the bolt. The whole footing is then grouted in.

### Span

The standard span adopted for these lines is 1056 ft. Actual spans vary up to 2263 ft.; this being the only span, however, in excess of 2000 ft. There are approximately 1000 towers per line, or an average slightly under five to the mile.

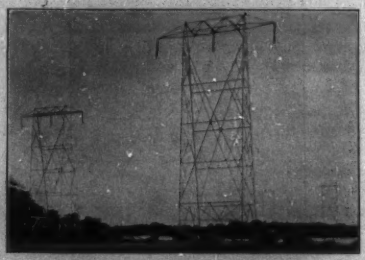


Fig. 17—General View Two Circuits Crossing Otonabee River

900 ft. span—20 ft. extensions on near towers to provide 60 ft. clearance to water level

A special attempt was made on these circuits to reduce the number of insulation points to a minimum. On the first circuit there are only 16 dead-end positions, —three at angles in excess of 18 deg., six at proposed interswitching points, four at long spans, two at railway crossings, and one at the terminal. At railway crossings, where it was formerly the practise to dead-end on each side of the crossing, two points of insulation are used on each side of the crossing, but all insulator strings are maintained in the suspension position, the crossing span usually being somewhat shorter than standard.

Tower extensions also have been used freely to lengthen a span—for example, across a minor depression, rather than use an intermediate tower. This has the result of somewhat increasing the average height of the conductor, but it does reduce the points of possible insulation failure. In the 203 mi. of the first circuit constructed, there is actually an average of only 1054 insulation points per conductor.

### Insulation

The subject of insulation for transmission lines of the various higher voltages has been, and still is, the subject of extensive field and laboratory investigations. These investigations have pointed to the desirability of some fourteen to sixteen 5-in. spacing suspension units for 220,000-volt lines. For the distribution of the electrostatic stresses some investigators have stressed the advisability of the installation of grading rings or similar provision, while others have doubted the efficacy of such devices.

Considerable attention has been paid to this point. The facilities of the Commission's laboratories do not permit of tests in this regard, but with the cooperation of the manufacturers investigations have been carried out. As a result it was decided to install eighteen 5-in. spacing units in all suspension positions, without grading rings or arcing horns. It was felt that as only 16 units could be installed if grading rings were used, in order to maintain clearances, the insurance of the additional two units was well worth while. It is hoped that with the protective scheme provided the speed of clearance of all faults will prevent damage to insulation due to cascading. So far this has been consistently true. If it is found desirable to add rings later, provision has been made in the conductor clamp for so doing.

In all strain positions, heavy-duty 5¾-in.-spacing units are installed instead of the 5-in.-spacing unit, the number of units being the same.

### Conductors

The power conductors are 795,000-cir. mil steel-reinforced aluminum cable, 27.2 per cent steel. Conductor is strung for a maximum tension of 10,000 lb., at which tension the maximum sag on a standard span is 36 ft. Minimum clearance to ground is established at 24 ft., except in suburban areas, road and rail crossings, etc., where 30 ft. clearance is maintained, while radial clearance to foreign structures and trees is 20 ft., and to the telephone circuit 35 ft.

Conductor joints are of the compression type, a steel sleeve being used on the core, and a long aluminum sleeve on the outside of the conductor.

Cable clamps are of a type designed to allow three-way movement of the conductor at the point of support, in order to mitigate vibration troubles. In addition, two types of vibration absorbers are used. The one provides an additional length of conductor clamped above the power conductor in the same clamp, and extending three ft. beyond the clamp on either side where it is again fastened to the power conductor. The other provides a layer of aluminum rods about 10 ft. long, secured in the main clamp and twisted about five times out over the power conductor, the ends being secured with an auxiliary clamp. The latter method is

apparently functioning better, although it is more expensive to install and probably represents a greater hazard, as strands improperly laid or secured may get loose.

The two ground wires are of the same construction as the steel core of the power conductor, being seven 0.1214-in. strands of galvanized crucible steel cable. The same compression joint as for the steel core is therefore used, heavily coated with bituminous paint. The cables are attached to the tower by means of a clamp similar to that used on the power conductors. This type of clamp has been considered essential, in order to avoid failures of the ground wires due to crystallization.

### Special Terminal Section

For approximately two miles in the vicinity of the terminal transformer station, the structures and line design have been modified to conform with the coordination of line and station insulation strength, as previously discussed. The structure height has been reduced some 13 ft., and the span has been reduced to about one-half. Four ground wires instead of two have been installed, and the number of suspension units reduced to 14. For about one mile from the station the ground wires are "conducting," composed of fifteen 0.12-in. aluminum strands and nineteen 0.096-in. steel strands. All other factors of design are unchanged.

Since the erection of the first circuit, a special "bridge-type" structure, having two tiers of conductors, has been designed for erection in the half-mile section immediately adjacent to the transformer station. At this point, real estate is expensive, and the right-of-way has been restricted to 200 ft. This "bridge structure" accommodates one 220,000-volt circuit in a width of 50 ft., or allows of four such circuits on this section of right-of-way. It is anticipated that this type of structure will be used in future in similar urban locations.

### Construction

Construction of the first of these 220,000-volt circuits was commenced in July 1927 and completed and placed in operation on October 1, 1928. Construction of the second circuit was commenced in May 1929, and approximately one-half was completed by October 1929. Since that time this half-circuit has been in service, connected in parallel with the first circuit, to obtain the benefit of the additional conductivity. The whole circuit is scheduled for completion in July 1930.

As the country is well-developed relatively flat farming country, construction of the westerly half of the system presented no great difficulties. Materials were delivered from the nearest rail point over good roads, in practically all cases by local trucking concerns working under contract. This method was adopted in place of having a considerable sum invested in construction machinery, and has been found to be very satisfactory.

For the easterly half of the system, all material was delivered during the winter. At this time, the deep snow tends to improve the road conditions, and delivery costs are very much lower. Most of the heavy clearing encountered in this section was also done in the winter time.

Line erection was carried out in three stages. Footings were dug and grillages placed by footing gangs, usually from 50 to 75 men. Templets were used in setting and leveling footings, the telescopic joint between the tower legs and the stub-angles assisting greatly in this regard. In the case of rock footings, the overburden and loose rock was first stripped away, so as to provide as level a surface as possible. The

Fig. 18—Illustrating Installation of Typical Rock Footing

Picture taken before final grouting-in of footing. Note adjustable telescopic-joint between stub-angle and tower leg

channel members, with the short stub-angles attached, were then placed and the templet erected. After all adjustment and leveling was complete, the bolt-holes were drilled and the legs anchored. With these footings, the telescopic joint eliminates any necessity of blasting to get all footings at the same elevation (Fig. 18).

Towers were erected by tower-erection gangs following the footing gangs, usually moving ahead into the various camps as the footing gang vacated them. Towers were assembled in panels on the ground, which were then lifted into place by means of a 30-ft. gin pole. When one section was completed, the gin pole was raised and held in place by tackle which allowed it to be moved from one side of the tower to the other at will. The last section to be lifted in place was the center portion of the head.

Great care was taken with the galvanizing, so that in order to eliminate drifting all towers were at

first "loose-bolted." No wrenches that had a cutting edge, such as the alligator wrench, were used. Time studies on standard towers showed that it took approximately 100 man-hours to complete the erection.

Stringing was carried out by stringing crews of from 60 to 70 men. Insulators were hung first, and wood or aluminum-sheave pulleys attached in the clamp position. Conductors were then paid out through the sheaves, particular attention being paid to the cable so as not to damage it in any way. Logs were usually placed in rocky ground to act as skids and so as to avoid contact with points of abrasion. The cable joints to complete approximately a five mile section were then made. This jointing was all done by special members of the stringing crews, trained for this operation.

Stringing to final tension was usually done with teams, although some has been done using a gasoline tractor. A considerable part of the country traversed did not allow of the use of the tractor, and the teams were found to be quite satisfactory. Sag sheets were provided, all sags being adjusted for stretch of the cable, as prestretching was not provided for.

Communication over the five-mile length of cable usually pulled to tension at one time was by means of telephone, the power conductors being used as the telephone wires. In this way, very good results were obtained, even when the conductors were lying on the ground.

Two trucks, and sometimes three, were attached to each gang, for material handling and transportation to and from the camps. These trucks were also hired by the day, including driver.

In general, the two circuits have been constructed with a spacing of 150 ft. between circuits. This spacing was decided upon after discussion of the possibility of single lightning disturbances affecting both circuits simultaneously. The desirability of having the two circuits on one right-of-way was stressed, for ease of patrol and to avoid duplication of the telephone service, and it was finally decided that this separation would appear to be sufficient to avoid the above contingency.

The progress of construction of the first circuit was very definitely scheduled, as a particular date on which power delivery would commence had to be met. Charts, showing the schedule for each operation, were drawn up, and the progress made during each week recorded. In this way, a continuous check of the progress was available, and the speed of progress could be regulated to insure safely meeting the date specified. The second circuit schedule has been much less exacting, the work being carried steadily forward with the personnel trained during the erection of the first circuit. Record of progress is still maintained, however, in order to provide a check on the various field organizations.

## Operation

The first unit of this 220,000-volt system, consisting of one transmission circuit and two banks of transformers at Leaside, was placed in service on October 1, 1928. The initial tests were carried out on September 23, 1928, at which time the entire transmission circuit and station bus work was energized to approximately 300,000 volts.

The western half of the second circuit was completed on October 1, 1929, since which time, in order to obtain the benefit of its conductivity, it has operated connected in parallel with the first circuit. The remainder of this circuit, and the installation of the third and fourth banks at Leaside, is scheduled for completion by October 1, 1930.

Between October 1, 1928 and April 1, 1930, ten line outages have occurred. These outages are classified as follows:

Three—due to insufficient clearance to trees, the clearing not having been completed when line was placed in service.

One —due to klydonograph connection breaking loose in a gale.

Four —during lightning storms, two being single-wire grounds, one a two-wire ground, and one a three-wire ground with very little ground fault current.

Two —not due to outside causes.

Except in one case, no permanent damage has resulted, the line returning to service immediately, the exception being when a conductor was actually broken by a tree felled by an inexperienced workman directly contrary to his foreman's orders. In the case of lightning flashovers, none of these have ever been definitely located.

Six flashovers occurred on the indoor 13,200-volt equipment during the early operating period, some of them involving two phases simultaneously. These flashovers were due to condensation of moisture in the newly completed building; this has since been eliminated, but the disturbance was so slight that the source of trouble was not located until the sixth flashover.

Except for some minor adjustments, the relay installation has given very satisfactory service. When trouble has occurred, the relay indicators have been found to give very valuable information as to the location and nature of the disturbance.

It has been found that the whole 230-mi. line can be energized or de-energized without disturbance to the remainder of the 110,000-volt system; in fact, no more precaution seems necessary than in switching a short section of 110,000-volt line.

Synchronizing the two systems at Leaside is extremely simple. On occasions when the systems have separated, they have been re-synchronized in two minutes.

From October 1, 1928 to September 15, 1929, a contract allotment of 80,000 hp. was carried over the single circuit, although momentary swings considerably in excess of 100,000 hp. were experienced. From September 15 to October 1, 1929, 130,000 hp. was carried over the single circuit without the aid of syn-

chronous condensers at Leaside. Since that time, a contract allotment of 150,000 hp. has been carried over the one and one-half circuit combination. For a short while, this load was also carried without the condensers, as unavoidable delays resulted in the condenser installation not being completed on schedule. At the present time, two of the 25,000-kv-a. units are in service.

Omitting the short period immediately following the placing into service of this system, a period of adjustment which all new systems suffer, the operation of the 220,000-volt system has been generally excellent, and may be very favorably compared with any section of the 110,000-volt system.

### Future Developments

At the time the contract was entered into with the Gatineau Power Company, the block of 260,000 hp. purchased was estimated as sufficient to provide for the Niagara System growth to 1931. Present indications are that this block will all be absorbed in 1930, and progress is being made on other developments to be completed in 1931.

The Ottawa River forms the interprovincial boundary between the provinces of Ontario and Quebec, and its power sites are therefore under the joint jurisdiction of the two provinces. Development of these sites is necessarily a joint undertaking between the owners of the waterpower rights in the respective provinces.

Development of the Chats Falls site is proceeding on this basis, the site being adjacent to the Ottawa River crossing of the present 220,000-volt lines. The Hydro-Electric Power Commission is the Ontario owner of the waterpower rights at this site, and a contract has been entered into with the Quebec owners, so that all the power available will be delivered to the Niagara System.

The total amount of power involved is some 200,000 hp., and it is expected that two more 220,000-volt circuits will be built to Toronto, construction of the first of these to commence late this year. The lines from the Gatineau Power Company will be interconnected at Chats Falls, making a four-line 220,000-volt system for some 460,000 hp.

The first of the Chats Falls power will be delivered in 1931, and additional transformer capacity will be added at the Leaside Transformer Station to provide for this. Transformation will be to 110,000 volts, so that the power may be transmitted over the existing facilities to the other Toronto Transformer Stations.

It is not at present expected that the full amount of power from Chats Falls will be taken into Leaside, completing it to its full capacity of 360,000 kv-a., but that rather a second 220,000-volt transformer station will be built in the Toronto area. The site for this station has not been selected, but studies are under way in this regard.

A contract has also been entered into with the Beauharnois Light, Heat, and Power Company, for the delivery of 250,000 hp., commencing in 1932, and providing for installments up to the full amount in 1936. This company will develop power in the Lake St. Francis-Lake St. Louis portion of the all-Canadian section of the St. Lawrence River. Delivery will also be to Toronto, over 220,000-volt circuits approximately 300 miles long. This power will be transformed in the second 220,000-volt transformer station mentioned above.

Within the next five or six years, there will be six 220,000-volt circuits entering the Toronto area, representing some 1400 circuit-miles of 220,000-volt lines, with two transformer stations totaling in capacity approximately 540,000 kv-a. For a few years, all of the Toronto area demand will be supplied from eastern sources, with a surplus to be transmitted west from Toronto over the existing 110,000-volt lines from Niagara Falls. This western feed of power will be only a temporary condition, as Toronto's own growth will soon absorb the surplus. It is this fact which dictates the location of the second station in Toronto, rather than farther west. The choice of this second station location is an interesting problem, as the location must be such as to meet the estimated load requirements of the Toronto area, and yet not necessitate too great an outlay to provide for this temporary condition.

### Acknowledgments

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## Discussion

**M. M. Samuels:** Mr. Brandon's paper would seem the beginning of a new era in plant description, it is by far the most complete and most systematic presentation of its kind that has ever come to my notice and I want to congratulate Mr. Brandon particularly on the manner of his presentation. It is more than a paper, it is both a textbook on modern high tension construction and a textbook on how to write up a description of a new plant. There is an abundance of new ideas, a great many radical and interesting departures from conventional

designs, many refreshingly courageous innovations and in each case there is not only a clear and concise description of the particular detail, but the reasons for it are also given, and the history of it is given together with descriptions of other methods which were considered and abandoned, together with the reasons why they were abandoned. Cost data would indeed be very interesting, but perhaps this is not within the range of an Institute paper, and furthermore cost data would reduce the attention which should be given to the overwhelming amount of design data. Too much discussion is being devoted nowadays to costs, even where the cost is of little consequence, and too little to design features. I suggest that the editing committee request future contributors that they use Mr. Brandon's paper as a guide for the set-up of descriptions of interesting new installations.

**E. T. J. Brandon:** It is indeed gratifying to receive such tribute as that rendered by Mr. Samuels in his discussion. One is frequently in doubt as to just how much detail should be included in such a paper, but it would appear that a happy solution has been obtained in this case.

Since the time of writing the paper the 220,000-volt system has operated without disturbance from any source. It must be admitted that the present lightning season has been somewhat below the average in number and severity of storms, but it is now possible to say that on August 24th, 1930, the system completed one whole year's operation without a single interruption due to external causes. This record reduces the average of interruptions on the 220,000-volt system, with practically two complete years of service, to 1.85 per 100 miles per year due to all causes, and 0.75 per 100 miles per year due to lightning flashovers alone.

# The Analytics of Transmission Calculations

## The Theoretical Foundation of the Quaternary Linear Real Transformation Connecting Input and Output Quantities in the General Electric Circuit Together with Its Application by Algebraic and Geometrical Methods

BY T. R. ROSEBRUGH*

Member, A. I. E. E.

*Synopsis.—This paper deals mainly with a more general and systematic method of handling certain classes of problems involving steady state transmission calculations in terms of real quantities than has hitherto been used.*

*Part I is introductory, however, and shows that the binary linear transformation which the writer showed in 1919 to exist for all ladder circuits in terms of complex quantities, and with determinant unity, occurs also in operational form for the general input—output network and likewise with determinant unity, thus including sine-wave as a particular case.*

*Part II views the general case of input-output circuits under sine wave conditions as a quaternary linear transformation in real quantities, likewise with determinant unity, but subject to a certain condition ("absolute covariant").*

*The subject matter involves on equal terms voltage-squared ($z$), current-squared ($w$), power ($x$), reactive voltamperes ($y$) for both input and output ends in the general circuit, and in the special case of a transmission line per se it also introduces mean values of these quantities throughout the length of the line, suggesting the engineering importance of some of them.*

*For this latter purpose the sixteen real coefficients of the transformation are given as functions of $s$ the length of the line leading to their mean values as tabulated.*

*Twenty identities involving values of the "a-set" of coefficients are given which are useful for checking numerical values and simplifying unnecessarily cumbrous results.*

*The relations between the "a-set" and the "b-set" coefficients are given. The diagram of the admittance-plane is used and it is pointed out that it is also a three-origin vector diagram, the exact interpretation being given. A table of statistical data about the points of a "kite framework" shows the proportionate values of each of the eight fundamental quantities at each of these points in extremely simple form. There are eight fundamental circles in the plane and 28 families of simple ratio-loci (circles) each family having its own radical axis. About half of these have obviously useful conceptions either in power or in communication engineering.*

*A wider point of view is now introduced in which linear functions of the eight fundamental quantities are dealt with. A classification is made of problems of complete and incomplete data. The former may or may not involve maximum conditions. Problems of maxima may be one-conditioned or two-conditioned.*

*The type-cases of each are studied and the other cases reduced to the type.*

*One-conditioned maxima are associated graphically with (Poncelet's) limit-points and analytically with a matrix which defines a line and three circles intersecting in these limit-points.*

*Two-conditioned maxima are represented graphically by the points of intersection of a circle cutting three others orthogonally, with one of the circles. Analytically the determinantal equation, rules for whose formation are given in each case, gives the radical center and the radius of the circle intersecting the other orthogonally.*

*Two simple examples are worked out algebraically and arithmetically.* *Acknowledgment is made of the assistance of Mr. V. G. Smith and Mr. G. DeB. Robinson.*

### Part I

THE present paper deals with the general case of an electric system with input and output terminals, having constant coefficients, when in the steady state. It has reference mainly to a system of calculation in terms of real quantities by means of a quaternary linear transformation conditioned by a quadratic covariant.

While several papers,[1,2,3,4,5] dealing with certain problems of this kind in terms of real quantities, have already appeared, this paper is intended, within limits which will appear later, as a systematic study of the whole subject with a view to the greatest possible generality of treatment.

2. The binary substitution or transformation in complex quantities

$$\left.\begin{aligned} E_1 &= a\,E_0 + b\,I_0 \\ I_1 &= c\,E_0 + d\,I_0 \end{aligned}\right\} \qquad (1)$$

whereby two input quantities $E_1$ and $I_1$ are obtainable from the two output quantities $E_0$ and $I_0$ is now fairly well known.

The author has shown[6] that this transformation together with its inverse namely

$$\left.\begin{aligned} E_0 &= d\,E_1 - b\,I_1 \\ I_0 &= -\,c\,E_1 + a\,I_1 \end{aligned}\right\} \qquad (2)$$

would lead to many practical conclusions with regard to the behavior of series and parallel combinations of transmission lines, transformers, tie lines, etc., as well

*Professor of Electrical Engineering, University of Toronto, Toronto, Ont., Can.

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30-117

as theoretically at least to solve some problems on the general network of which the units consist of such items. Some of these facts about circuits have now become widely known through the publications[7] of the Westinghouse Company.

3. It is fundamental in the establishment of these formulas that the determinant $a\,d - b\,c$ is unity. In the paper of 1919 referred to this is proved for quite general circuits but still not so general as the case of the general circuit of constant coefficients, and of any number of meshes and any couplings between meshes. It will therefore be shown in the next section how the proof may be extended to include such cases.

4. For a circuit of any number of meshes and having in general localized resistance inductance, and capacity, and coupled in any manner by such means and by mutual inductance and having only two meshes in which external e. m. f. is impressed called respectively the input and the output, the $n$ differential equations as is well known may be written

$$\sum_{s=1}^{n} f_{rs}\, q_s = e_r, \quad (r = 1, 2 \ldots n) \tag{3}$$

where $$f_{rs} = f_{sr} = a_{rs}\, p^2 + b_{rs}\, p + c_{rs} \tag{4}$$

These are in fact direct consequences of "Lagrange's Equations of Motion in Generalized Coordinates" and here two only of the set $e_r$ differ from zero, say $e_2$ and $e_1$ (input and output).

Now treating these equations as though they were algebraical instead of differential equations, and solving for $q_1$ and $q_2$

$$\begin{aligned} q_1 D &= e_1 F_{11} + e_2 F_{21} \\ q_2 D &= e_1 F_{12} + e_2 F_{22} \end{aligned} \tag{5}$$

in which the "$F$" quantities are the corresponding cofactors to the "$f$'s" and $D$ is the determinant of the "$f$'s." Put $-e_1 = e_1'$.

Then

$$\left.\begin{aligned} e_2 &= \frac{F_{11}}{F_{21}}\, e_1' + \frac{D}{F_{21}}\, q_1 &&= a'\, e_1' + b'\, q_1 \\ q_2 &= \left(\frac{F_{11}\, F_{22}}{F_{21}\, D} - \frac{F_{12}}{D}\right) e_1' + \frac{F_{22}}{F_{21}}\, q_1 &&= c'\, e_1' + d'\, q_1 \end{aligned}\right\} \tag{6}$$

Then $$\begin{vmatrix} a', b' \\ c', d' \end{vmatrix} = \frac{F_{12}}{F_{21}} = 1 \tag{7}$$

Now put $$i_1 = p\, q_1,\ i_2 = p\, q_2$$

then $$\left.\begin{aligned} e_2 &= a'\, e_1' + \frac{b'}{p}\, i_1 = a\, e_1' + b\, i_1 \\ i_2 &= p\, c'\, e_1' + d'\, i_1 = c\, e_1' + d\, i_1 \end{aligned}\right\} \tag{8}$$

Then $$\begin{vmatrix} a, b \\ c, d \end{vmatrix} = 1 \tag{9}$$

That is $a\,d - b\,c = 1$

Here $a$, $b$, $c$, and $d$ are rational functions of $p$ the time-differentiator. This relation true for all operational values of $p$ will then hold for the special equivalent $\omega j$. Thus the truth of this equation is established for the case of sine-wave.

## Part II

5(a). There are great advantages to be gained by proceeding in a uniform and symmetrical manner to develop the consequences of Equation (1) fully with regard to the values of four homogeneous real quantities at both ends of the circuit, namely voltage-squared, current-squared, power and reactive volt-amperes. Individual formulas have been used by previous writers but a consideration of the set of relations as a whole is the guiding idea in what follows.

Another advantage of the more general point of view here presented is that by the use of twenty algebraic identities thereby developed many expressions may be greatly simplified.

From the two Equations (1) expressing the binary linear transformation, may be deduced the quaternary linear transformation in real quantities which in combination with the equation of its covariant is to be the subject of Part II. The procedure is as follows:

From Equations (1) deduce Equations (10) by taking the conjugate of each quantity on the left hand side. Conjugates are here denoted by a circumflex.

Thus

$$\left.\begin{aligned} E_1 &= a\, E_0 + b\, I_0 \\ I_1 &= c\, E_0 + d\, I_0 \end{aligned}\right\} \text{(1) bis.} \quad \left.\begin{aligned} \hat{E}_1 &= \hat{a}\, \hat{E}_0 + \hat{b}\, \hat{I}_0 \\ \hat{I}_1 &= \hat{c}\, \hat{E}_0 + \hat{d}\, \hat{I}_0 \end{aligned}\right\} \tag{10}$$

Hence, expressing the four products obtained by taking each of the quantities on the left of one set multiplied into each of the like quantities of the other, four equations are obtained giving values in terms of similar quantities from the right hand side. The coefficients will be sixteen quantities similar to $a\,\hat{a}$.

On making the substitutions

$$E_0\, \hat{E}_0 = z,\ I_0\, \hat{I}_0 = w,\ I_0\, \hat{E}_0 = x + y\, j,\ \hat{I}_0\, E_0 = x - y\, j \tag{11}$$

$$E_1\, \hat{E}_1 = z',\ I_1\, \hat{I}_1 = w',\ I_1\, \hat{E}_1 = x' + y'\, j,\ \hat{I}_1\, E_1 = x' - y'\, j$$

the quaternary linear real transformation is obtained in the form

$$\begin{aligned} z' &= a_{11}\, z + a_{12}\, w + a_{13}\, x + a_{14}\, y \\ w' &= a_{21}\, z + a_{22}\, w + a_{23}\, x + a_{24}\, y \\ x' &= a_{31}\, z + a_{32}\, w + a_{33}\, x + a_{34}\, y \\ y' &= a_{41}\, z + a_{42}\, w + a_{43}\, x + a_{44}\, y \end{aligned} \tag{12}$$

7. "Electrical Characteristics of Transmission Circuits," by Westinghouse Engineers—William Nesbit, 1926.

The sixteen coefficients may be expressed as follows (if $a = a_0 + a_1 j$, $b = b_0 + b_1 j$, $c = c_0 + c_1 j$, $d = d_0 + d_1 j$)

$$
\begin{array}{l|l|l|l}
a_{11} = a_0^2 + a_1^2 & a_{12} = b_0^2 + b_1^2 & a_{13} = 2\,(a_0\,b_0 + a_1\,b_1) & a_{14} = 2\,(b_0\,a_1 - a_0\,b_1) \\
a_{21} = c_0^2 + c_1^2 & a_{22} = d_0^2 + d_1^2 & a_{23} = 2\,(c_0\,d_0 + c_1\,d_1) & a_{24} = 2\,(d_0\,c_1 - c_0\,d_1) \\
a_{31} = c_0\,a_0 + c_1\,a_1 & a_{32} = d_0\,b_0 + d_1\,b_1 & a_{33} = 1 + 2\,(a_1\,d_1 + b_0\,c_0) & a_{34} = 2\,(d_0\,a_1 - b_1\,c_0) \\
a_{41} = a_0\,c_1 - c_0\,a_1 & a_{42} = b_0\,d_1 - d_0\,b_1 & a_{43} = 2\,(a_0\,d_1 - b_1\,c_0) & a_{44} = 1 + 2\,(a_1\,d_1 - b_1\,c_1)
\end{array}
\qquad (13)
$$

Again starting from the inverse binary transformation (2) the inverse quaternary transformation is found which may be denoted by

$$
\begin{aligned}
z &= b_{11}\,z' + b_{12}\,w' + b_{13}\,x' + b_{14}\,y' \\
w &= b_{21}\,z' + b_{22}\,w' + b_{23}\,x' + b_{24}\,y' \\
x &= b_{31}\,z' + b_{32}\,w' + b_{33}\,x' + b_{34}\,y' \\
y &= b_{41}\,z' + b_{42}\,w' + b_{43}\,x' + b_{44}\,y'
\end{aligned}
\qquad (14)
$$

The values of the $b$-set when found are seen to be connected with the $a$-set by the following very simple relations:

$$
\begin{array}{l|l|l|l}
b_{11} = a_{22}, & b_{12} = a_{12}, & b_{13} = -2\,a_{32}, & b_{14} = -2\,a_{42} \\
b_{21} = a_{21}, & b_{22} = a_{11}, & b_{23} = -2\,a_{31}, & b_{24} = -2\,a_{41} \\
b_{31} = -\dfrac{1}{2}\,a_{23}, & b_{32} = -\dfrac{1}{2}\,a_{13}, & b_{33} = a_{33}, & b_{34} = a_{43} \\
b_{41} = -\dfrac{1}{2}\,a_{24}, & b_{42} = -\dfrac{1}{2}\,a_{14}, & b_{43} = a_{34}, & b_{44} = a_{44}
\end{array}
\qquad (15)
$$

These relations are for the most general input-output circuit and naturally lead to simpler ones where the circuit is symmetrical as in the case of the transmission line per se or the transmission line with similar transformers at both ends.

This may easily be shown to be identical with the cases where $a = d$.

In this case of input-output symmetry then the following additional relations hold:

$$
\begin{aligned}
&a_{11} = a_{22},\ a_{13} = 2\,a_{32},\ a_{14} = 2\,a_{42} \\
&a_{23} = 2\,a_{31},\ a_{24} = 2\,a_{41},\ a_{34} = a_{43}
\end{aligned}
\qquad (16)
$$

So that in this case the upper left and lower right quarters of the tables of the $a$-set and the $b$-set contain identical coefficients. The other eight pairs of $a$ and $b$ coefficients differ only in sign. This difference in sign is due to the convention with regard to current which is reckoned by an input rule of sense, at one end, and output at the other. The input rule of sense at both ends in the symmetrical circuit would identify completely the two sets of coefficients.

5(b). As an example the following are the values of the sixteen $a$-coefficients for the Paugan Falls-Leaside (Toronto) 25-cycle transmission line of the Hydro-Electric Power Commission of Ontario, the length of which is 229 miles, where the units are:—100,000 volts, 100 amperes, 10,000 kv-a.

| | | | |
|---|---|---|---|
| $a_{11}$ | $a_{12}$ | $a_{13}$ | $a_{14}$ |
| 0.961,71 | 0.006,438,0 | 0.053,583 | −0.147,97 |
| $a_{21}$ | $a_{22}$ | $a_{23}$ | $a_{24}$ |
| 0.257,22 | 0.961,71 | 0.004,677,8 | 0.994,70 |
| $a_{31}$ | $a_{32}$ | $a_{33}$ | $a_{34}$ |
| 0.002,338,9 | 0.026,791 | 1.000,031,82 | 0.013,673 |
| $a_{41}$ | $a_{42}$ | $a_{43}$ | $a_{44}$ |
| 0.497,35 | −0.073,984 | 0.013,673 | 0.923,38 |

These have been checked by a set of 10 identities.

6. Determinants. According to a theorem in determinants imputed to Kronecker by E. Pascal[8] the determinant of sixteen coefficients of type $a\,\tilde{a}$ must be unity since it would be the product of the squares of the determinants of (1) and (10).

The determinant of the sixteen real coefficients $a_{11}$ to $a_{44}$ may then be shown to be unity also.

7. A covariant under the transformation.

There are fundamental facts with regard to the translation from complex form to real quantities expressible as follows:

$$
\begin{aligned}
w\,z &= I_0\,\hat{I}_0\,.\,E_0\,\hat{E}_0 = I_0\,\hat{E}_0\,.\,\hat{I}_0\,E_0 \\
&= (x + y\,j)\,(x - y\,j) = x^2 + y^2 \qquad (17) \\
w'\,z' &= I_1\,\hat{I}_1\,.\,E_1\,\hat{E}_1 = I_1\,\hat{E}_1\,.\,\hat{I}_1\,E_1 \\
&= (x' + y'\,j)\,(x' - y'\,j) = x'^2 + y'^2
\end{aligned}
$$

that is

$$w\,z - x^2 - y^2 = 0 \qquad (18)$$

$$w'\,z' - x'^2 - y'^2 = 0 \qquad (19)$$

This suggests and it is in fact true that $w\,z - x^2 - y^2$ is an absolute covariant under the transformation (12). In ordinary language the situation is that the four Equations (12) when applied to any set of $z\,w\,x\,y$ will produce another possible (consistent) set of values for the $b$-end.

8. Consequences in twenty identities. Useful for checks of values of co-efficients and for simplifying formulas.

Since $a$, $b$, $c$, and $d$ are complex quantities they are defined by eight real numbers, which, however, since $a\,d - b\,c = 1$ must be equivalent to six independent real parameters on which the sixteen coefficients of the $a$-set depend.

There must therefore be ten independent relations between these sixteen coefficients. These ten identities are then to be found by noting the conditions which are consequences of the covariance of $w\,z - x^2 - y^2$.

8. E. Pascal, "I Determinanti," Milan 1897. But it is not to be found in Kronecker's "Werke."

By substituting for $w' z' - x^{2\prime} - y^{2\prime}$ in terms of $w, z, x$ and $y$ by (12) and identifying the result with $w z - x^2 - y^2$ the following ten identities are obtained:

$$a_{21}^2 + a_{41}^2 - a_{11} a_{21} = 0 \tag{20}$$
$$a_{22}^2 + a_{42}^2 - a_{12} a_{22} = 0 \tag{21}$$
$$a_{23}^2 + a_{43}^2 - a_{13} a_{23} = 1 \tag{22}$$
$$a_{24}^2 + a_{44}^2 - a_{14} a_{24} = 1 \tag{23}$$
$$a_{11} a_{12} + a_{12} a_{21} - 2 a_{31} a_{32} - 2 a_{41} a_{42} = 1 \tag{24}$$
$$a_{11} a_{23} + a_{13} a_{21} - 2 a_{31} a_{33} - 2 a_{41} a_{43} = 0 \tag{25}$$
$$a_{11} a_{24} + a_{14} a_{21} - 2 a_{31} a_{34} - 2 a_{41} a_{44} = 0 \tag{26}$$
$$a_{12} a_{23} + a_{13} a_{22} - 2 a_{32} a_{33} - 2 a_{42} a_{43} = 0 \tag{27}$$
$$a_{12} a_{24} + a_{14} a_{22} - 2 a_{32} a_{34} - 2 a_{42} a_{44} = 0 \tag{28}$$
$$a_{13} a_{24} + a_{14} a_{23} - 2 a_{33} a_{34} - 2 a_{43} a_{44} = 0 \tag{29}$$

Again by making similar use of (14) another set of ten identities as follows are obtained:

$$a_{23}^2 + a_{24}^2 - 4 a_{21} a_{22} = 0 \tag{30}$$
$$a_{13}^2 + a_{14}^2 - 4 a_{11} a_{12} = 0 \tag{31}$$
$$a_{33}^2 + a_{34}^2 - 4 a_{31} a_{32} = 1 \tag{32}$$
$$a_{43}^2 + a_{44}^2 - 4 a_{41} a_{42} = 1 \tag{33}$$
$$2 a_{22} a_{11} + 2 a_{12} a_{21} - a_{23} a_{13} - a_{24} a_{14} = 2 \tag{34}$$
$$2 a_{22} a_{31} + 2 a_{32} a_{21} - a_{23} a_{33} - a_{24} a_{34} = 0 \tag{35}$$
$$2 a_{22} a_{41} + 2 a_{42} a_{21} - a_{23} a_{43} - a_{24} a_{44} = 0 \tag{36}$$
$$2 a_{12} a_{31} + 2 a_{32} a_{11} - a_{13} a_{33} - a_{14} a_{34} = 0 \tag{37}$$
$$2 a_{12} a_{41} + 2 a_{42} a_{11} - a_{13} a_{43} - a_{14} a_{44} = 0 \tag{38}$$
$$2 a_{32} a_{41} + 2 a_{42} a_{31} - a_{33} a_{43} - a_{34} a_{44} = 0 \tag{39}$$

These evidently must be equivalent to the first set but are nevertheless as useful practically.

In obtaining formulas for particular conditions it often occurs that very great simplification in the result may be attained by their use. For example:

Suppose one wished to know the value of $y' \div z$ under conditions of maximum power $x'$ received for fixed transmitting $z$. Its value is

$$a_{41} + a_{42} \div (4\ a_{32}^2) + (2\ a_{42}\ a_{11} - a_{42}\ a_{23} - a_{44}\ a_{24}) \div (2\ a_{32})$$

But by using identity (39) it is found that all but the second term $a_{42} \div (4\ a_{32}^2)$ is identically zero.

These identities are also of value in checking the accuracy of the sixteen coefficients.

9. There may be instances where mean values of current-squared, voltage-squared, etc., along a transmission line are desired. The former is a measure of the conductor line loss as well as the line reactive volt-amperes due to inductance. The latter measures the reactive volt-amperes due to capacity as well as the insulation loss, if any, and may then perhaps serve also as a suitable comparative measure of the load to which the line insulators are subject if a single number is desired for this purpose. For this purpose the sixteen coefficients must be regarded not as the constants which they are in the case of the length of the whole line, ($s = 1$), but as functions of the variable $s$ for the point in question. Hence the set of four fundamental quantities, $z', w', x', y'$, are likewise functions of $s$. Then if bars above the symbols denote the corresponding quantities

$$\bar{z} = \int_0^1 z'\, d\, s = z \int_0^1 a_{11}\, d\, s + w \int_0^1 a_{12}\, d\, s + x \int_0^1 a_{13}\, d\, s + y \int_0^1 a_{14}\, d\, s \tag{40}$$

similarly for the others, and if we write

$$\int_0^1 a_{11}\, d\, s = \bar{a}_{11} \text{ etc.}$$

then

$$\begin{aligned} \bar{z} &= \bar{a}_{11} z + \bar{a}_{12} w + \bar{a}_{13} x + \bar{a}_{14} y \\ \bar{w} &= \bar{a}_{21} z + \bar{a}_{22} w + \bar{a}_{23} x + \bar{a}_{24} y \\ \bar{x} &= \bar{a}_{31} z + \bar{a}_{32} w + \bar{a}_{33} x + \bar{a}_{34} y \\ \bar{y} &= \bar{a}_{41} z + \bar{a}_{42} w + \bar{a}_{43} x + \bar{a}_{44} y \end{aligned}$$

In order to find these sixteen new coefficients conveniently introduce the following abbreviations:

$$A_0 + B_0 j = \sqrt{(R + X j)(G + B j)} \tag{42}$$
$$m + n j = \sqrt{Z} \div \sqrt{Y} \tag{43}$$
$$p + q j = \sqrt{Y} \div \sqrt{Z} \tag{44}$$
$$\lambda = \frac{1}{2}(\cosh 2 A_0 s - \cos 2 B_0 s) \tag{45}$$

Then at any point $s$ units from $A$ where unity is the length of the line we have

$$a_{11} = \frac{1}{2} \cosh 2 A_0 s + \frac{1}{2} \cos 2 B_0 s \tag{46}$$
$$a_{12} = (m^2 + n^2)\, \lambda \tag{47}$$
$$a_{13} = m \sinh 2 A_0 s - n \sin 2 B_0 s \tag{48}$$
$$a_{14} = - n \sinh 2 A_0 s - m \sin 2 B_0 s \tag{49}$$
$$a_{21} = (p^2 + q^2)\, \lambda \tag{50}$$
$$a_{22} = a_{11} \tag{51}$$
$$a_{23} = p \sinh 2 A_0 s - q \sin 2 B_0 s \tag{52}$$
$$a_{24} = q \sinh 2 A_0 s + p \sin 2 B_0 s \tag{53}$$
$$a_{31} = \frac{1}{2} a_{23} \tag{54}$$
$$a_{32} = \frac{1}{2} a_{13} \tag{55}$$
$$a_{33} = a_{11} + (p m + q n)\, \lambda \tag{56}$$
$$a_{34} = (q m - p n)\, \lambda \tag{57}$$
$$a_{41} = \frac{1}{2} a_{24} \tag{58}$$

$$a_{42} = \frac{1}{2} a_{14} \tag{59}$$

$$a_{43} = a_{34} \tag{60}$$

$$a_{44} = a_{11} - (p\,m + q\,n)\,\lambda \tag{61}$$

10. If now $\bar{a}_{ij} = \int_0^1 a_{ij}\, d\,s$ and we put

$$\bar{\lambda} = \frac{1}{4\,A_0} \sinh 2\,A_0 - \frac{1}{4\,B_0} \sin 2\,B_0 \tag{62}$$

we have mean values of the sixteen coefficients for the line:

$$\bar{a}_{11} = \frac{1}{4\,A_0} \sinh 2\,A_0 + \frac{1}{4\,B_0} \sin 2\,B_0 \tag{63}$$

$$\bar{a}_{12} = (m^2 + n^2)\,\bar{\lambda} \tag{64}$$

$$\bar{a}_{13} = \frac{m}{2\,A_0} (\cosh 2\,A_0 - 1) + \frac{n}{2\,B_0} (\cos 2\,B_0 - 1) \tag{65}$$

$$\bar{a}_{14} = -\frac{n}{2\,A_0} (\cosh 2\,A_0 - 1) + \frac{m}{2\,B_0} (\cos 2\,B_0 - 1) \tag{66}$$

$$\bar{a}_{21} = (p^2 + q^2)\,\bar{\lambda} \tag{67}$$

$$\bar{a}_{22} = \bar{a}_{11} \tag{68}$$

$$\bar{a}_{23} = \frac{p}{2\,A_0} (\cosh 2\,A_0 - 1) + \frac{q}{2\,B_0} (\cos 2\,B_0 - 1) \tag{69}$$

$$\bar{a}_{24} = \frac{q}{2\,A_0} (\cosh 2\,A_0 - 1) - \frac{p}{2\,B_0} (\cos 2\,B_0 - 1) \tag{70}$$

$$\bar{a}_{31} = \frac{1}{2} \bar{a}_{23} \tag{71}$$

$$\bar{a}_{32} = \frac{1}{2} \bar{a}_{13} \tag{72}$$

$$\bar{a}_{33} = \bar{a}_{11} + (p\,m + q\,n)\,\bar{\lambda} \tag{73}$$

$$\bar{a}_{34} = (q\,m - p\,n)\,\bar{\lambda} \tag{74}$$

$$\bar{a}_{41} = \frac{1}{2} \bar{a}_{24} \tag{75}$$

$$\bar{a}_{42} = \frac{1}{2} \bar{a}_{14} \tag{76}$$

$$\bar{a}_{43} = \bar{a}_{34} \tag{77}$$

$$\bar{a}_{44} = \bar{a}_{11} - (p\,m + q\,n)\,\bar{\lambda} \tag{78}$$

The loss of power in the line and the change in value of $y$ is evidently given as follows:

$$x' = x + R\,\bar{w} + G\,\bar{z}$$
$$y' = y + B\,\bar{z} - X\,\bar{w} \tag{79}$$

By solving the system of four pairs of equations which follow from these two equations, the following values of eight of the mean values may be found. These appear likely to be the most useful, and the check with the previous formulas may be applied. Where $K = 2\,A_0\,B_0$

$$\bar{a}_{11} = (a_{31}\,X + a_{41}\,R) \div K,\ \bar{a}_{21} = (a_{31}\,B - a_{41}\,G) \div K$$
$$\bar{a}_{12} = (a_{32}\,X + a_{42}\,R) \div K,\ \bar{a}_{22} = (a_{32}\,B - a_{42}\,G) \div K$$
$$\bar{a}_{13} = \{\,(a_{33} - 1)\,X + a_{43}\,R\,\} \div K.$$
$$\bar{a}_{23} = \{\,(a_{33} - 1)\,B - a_{43}\,G\,\} \div K$$
$$\bar{a}_{14} = \{\,a_{34}\,X + (a_{44} - 1)\,R\,\} \div K,$$
$$\bar{a}_{24} = \{\,a_{34}\,B - (a_{44} - 1)\,G\,\} \div K \tag{80}$$

and therefore

$$K\,\bar{z} = X\,(x' - x) + R\,(y' - y),$$
$$K\,\bar{w} = B\,(x' - x) - G\,(y' - y) \tag{81}$$

11. Just as in ordinary vector notation three numbers, namely the value of the current, the voltage, and the angle between their directions are necessary for specifying conditions at an end of a circuit, so here also three numbers are necessary and sufficient. Any three out of the four $z, w, x, y$, (barring the usual ambiguities arising from quadratics) will specify exactly the conditions. It may thence be seen that apart from possible ambiguity any three independent data about $z, w, x, y, z', w', x', y'$ (or for a simple transmission line, also $\bar{z}, \bar{w}, \bar{x}, \bar{y}$,) will fix all conditions. Thus if $L_1$, $L_2$, and $L_3$ be any three-linear functions of these eight (or twelve) variables, the fixing of these three $L$'s will in general serve. For the points of a model to represent definite states of the circuit three dimensions would then be needed and the values of $L_1\,L_2$ and $L_3$ would serve to define a point, the "state-point" of the system such that all other numerical data would be implied by its position.

Using only the twelve quantities above, simplex, there would be 220 choices of such models. However, the combinations $x, y, z$, or $x'\,y'\,z'$ have evident advantages, though something might be said for certain other combinations.

Now in view of the fact that all the equations of the $a$-set, the $b$-set and those of the mean value quantities, and the covariant conditions, are homogeneous in the variables, it follows that the equations deal essentially with ratios, and that these all hold when every quantity involved, namely $z, w, x, y$, or $z', w', x', y', \bar{z}, \bar{w}, \bar{x}, \bar{y}$ and consequently also $L_i$ (any homogeneous linear function of them) is multiplied by any common factor.

12. Any three-dimensional model of this type therefore will have the property that as the state-point moves on a straight line from the origin all the variables and hence all $L$'s will vary in direct proportion to its distance from the origin. The essence of any such model will therefore consist in the direction of the line from the origin to the state-point and this is indicated by the intersection of this line with any fixed plane not through the origin.

The simplest plane of representation in the $x\,y\,z$ model would be a plane for constant $z$. This amounts to what has been called the "Evans and Sels modified

diagram." However, the three-dimensional model which has been suggested uses $|E|$, that is, in the present notation the square root of $z$ for third dimension. This naturally does not possess the simple linear projective property described above.

Instead of straight lines in the model joining points, in the plane above mentioned, to the origin there would be parabolas and for circles in the plane instead of cones there would be complicated surfaces. Hence at least for visualization the model here proposed is preferable.

13. Now since all variables are functions of any three, and other consistent values of all may be found by using any constant factor, it follows that all ratios of variables are determined when any two ratios are given. It will also follow that if three ratios be given there will generally be an inconsistency in the data.

Taking $x \div z = u$ and $y \div z = v$, $u$ and $v$ are the representatives of $x$ and $y$ obtained by using the points where the line from the origin to the state-point $(x\ y\ z)$ intersects the plane $z = 1$.

Hence all the 28 ratios of the eight (or 66 of the twelve) variables have defined values for assigned $u$ and $v$.

So far as ratios are concerned the state-point may now be thought of as in this plane. At any rate the perspective image of the state-point lies there.

14. Although all the quantities thus dealt with in the $x$, $y$ or in the $u\ v$ plane are real, there are nevertheless vector relations at their basis which have not disappeared beyond recovery.

For $$E_1 = b\,.\,A\,S\,.\,E_0 \tag{82}$$
and $$I_1 = d\,.\,B\,S\,.\,E_0 \tag{83}$$

These relations which are to be interpreted vectorially may be obtained as follows:

For $$E_1 \div E_0 = b\,.\,(a/b + u + v\,j) \tag{84}$$
and (as vector)
$$A\,O = (a_{13} + a_{14}\,j) \div 2\,a_{12} = a/b \tag{85}$$
and $$u + v\,j = O\,S \tag{86}$$
hence (82) is true.

Also $$I_1 \div E_0 = d\,.\,(c/d + u + v\,j) \tag{87}$$
and (as vector)
$$B\,O = (a_{23} + a_{24}\,j) \div a_{22} = c/d \tag{88}$$
hence (83) follows.

That is the vectors $A\,S$ and $B\,S$ defined by the state-point $S$ fix $E_1$ and $I_1$ in proper vector relation to $E_0$ when respective base lines are used which take account of $b$ and $d$ respectively.

More precisely stated the vector ratio of $E_1$ to $E_0$ is that of $A\,S$ to $1/b$ and the vector ratio of $I_1$ to $E_0$ is that of $B\,S$ to $1/d$.

Thus a second interpretation which may be put on the $u$, $v$ plane is that it is a three-origin vector diagram. That is to say $O$, $A$, and $B$ are three origins from which vectors drawn to a point $S$ represent correctly in magnitude and phase (when properly referenced) $I_0$, $E_1$, and $I_1$ respectively.

15. The framework. Eight circles. Continuing with the ideas of Sec. 13 with a view to the general treatment of Sec. 16, it is noted that the fundamental quantities individually present the simplest instance of a linear function of their own values.

Thus $z, w, x, y, z', w', x', y'$ are each an $L$ where $L$ denotes a linear homogeneous function of such quantities.

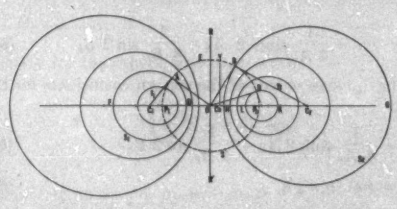

Fig. 1—Systems of Circular Loci with Common Radical Axis and $r^2$ Positive. Also Type Case $Q\,M_r$

Each of these is comprised in the equation
$$L \equiv a\,z + b\,w + c\,x + d\,y$$
where the coefficients are general.

Then putting as before $u = x \div z$, $v = y \div z$
$$S \equiv L \div z = a + b\,(u^2 + v^2) + c\,u + d\,v$$
Then $S = 0$ would, when $b \neq 0$, denote a circle in the $u, v$ plane, and this will be the case for $z'\ w'\ x'\ y'$ and $w$, at least in a formal sense. Also $S$ denotes for any given point $(u, v)$ the square of the tangent to the

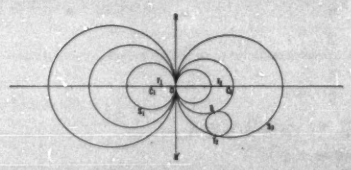

Fig. 2—Systems of Circular Loci with Common Radical Axis and $r^2$ Zero

given circle multiplied by $b$ when the point is external, or the negative of the square of half the chord which it bisects multiplied by $b$ when it is internal to a real circle.

For $L = x$ and $y$ respectively $S = u$ and $v$ respectively. Thus $L = 0$, and hence $S = 0$ denotes, here, one of five circles or two straight lines, the axes.

The case $L = z$ gives $S = L \div z = 1 \neq 0$. This case is called in geometry the "line at infinity." Here a better name would be "circle at infinity."

The center of $S = 0$ is at $u = -c \div (2\,b)$, $v = -d \div (2\,b)$ and its radius squared is $(c^2 + d^2 - 4\,a\,b) \div (4\,b^2)$.

The quantity $c^2 + d^2 - 4\,a\,b$ on reference to identities (31) (30) (32) and (33) will be seen to have the values, 0, 0, 1 and 1 for $z'$, $w'$, $x'$ and $y'$ respectively. The radii for these circles will then be 0, 0, $1 \div (2\,a_{32})$ and $1 \div (2\,a_{42})$.

If now the centers of these circles, $S = 0$ for $z'$, $w'$, $x'$ and $y'$ be located in the plane with the coordinates,

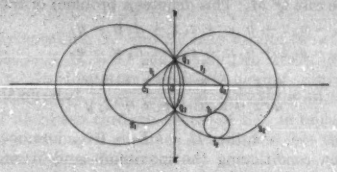

FIG. 3—SYSTEMS OF CIRCULAR LOCI WITH COMMON RADICAL AXIS AND $r^2$ NEGATIVE

for $z' = 0,\ -a_{13} \div (2\,a_{13})$ and $-a_{14} \div (2\,a_{12})$
" $w' = 0,\ -a_{23} \div (2\,a_{23})$ and $-a_{24} \div (2\,a_{22})$
" $x' = 0,\ -a_{33} \div (2\,a_{32})$ and $-a_{34} \div (2\,a_{32})$
" $y' = 0,\ -a_{43} \div (2\,a_{42})$ and $-a_{44} \div (2\,a_{42})$

these centers will appear as in the "kite" framework shown in Fig. 4 at $A$, $B$, $C$, and $D$ respectively. $A$ and $B$ will then be point circles while the circles $x' = 0$, $y' = 0$ must each pass through the points $z' = 0$, $w' = 0$, that is $A$ and $B$.

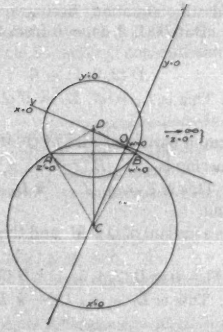

FIG. 4—THE FRAMEWORK. EIGHT CIRCLES THE BASIS FOR 28 FAMILIES OF CIRCULAR RATIO-LOCI

The other circles will be $w = 0$, a point circle at $O$ the two axes as infinite circles and the "circle at infinity."

By use of (12) and the identities given, the relative values of the fundamental quantities at the centers $A\,B\,C\,D$ and $O$ are as given in Table I where being relative only they have been arranged for convenience to avoid fractions.

TABLE I
RELATIVE VALUES OF

| At | $z$ | $w$ | $x$ | $y$ | $z'$ | $w'$ | $x'$ | $y'$ |
|---|---|---|---|---|---|---|---|---|
| $A$ | $2\,a_{12}$, | $2\,a_{11}$ | $-a_{13}$ | $-a_{14}$ | 0 | 2 | 0 | 0 |
| $B$ | $2\,a_{22}$, | $2\,a_{21}$ | $-a_{23}$ | $-a_{24}$ | 2 | 0 | 0 | 0 |
| $C$ | $4\,a_{32}^2$, | $1 + 4\,a_{31}\,a_{32}$, | $-2\,a_{33}\,a_{32}$, | $-2\,a_{34}\,a_{32}$, | $a_{12}$ | $a_{22}$ | $-a_{32}$ | $a_{42}$ |
| $D$ | $4\,a_{42}^2$, | $1 + 4\,a_{41}\,a_{42}$, | $-2\,a_{43}\,a_{42}$, | $-2\,a_{44}\,a_{42}$, | $a_{12}$ | $a_{22}$ | $a_{32}$ | $-a_{42}$ |
| $O$ | 1 | 0 | 0 | 0 | $a_{11}$ | $a_{21}$ | $a_{31}$ | $a_{41}$ |

The distances in Fig. 4 are given as follows:

$$A\,B^2 = 1 \div (a_{12}\,a_{22}),\ A\,C^2 = B\,C^2 = 1 \div (4\,a_{32}^2)$$

$$A\,D^2 = B\,D^2 = 1 \div (4\,a_{42}^2)$$

$$C\,D^2 = a_{12}\,a_{22} \div (4\,a_{32}^2\,a_{42}^2),\ A\,O^2 = a_{11} \div a_{12}$$

$$B\,O^2 = a_{21} \div a_{22}$$

$$C\,O^2 = A\,C^2 + a_{31} \div a_{32},\ D\,O^2 = A\,D^2 + a_{41} \div a_{42}$$

Since $C\,D^2 = C\,A^2 + A\,D^2$, by using (21), the angle $C\,A\,D$ is a right angle and the circles $x' = 0$, $y' = 0$ intersect orthogonally.

16. I. Problems involving linear functions, $L$ of the fundamental quantities $z$, $w$, $x$, and $y$ in such a way as to lead to fixed values of them may be classified into three divisions, in each of which definite solutions

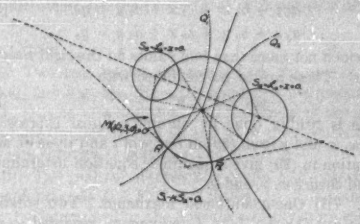

FIG. 5—TYPE CASE $Q^2\,M_r$. TWO QUANTITIES GIVEN. MAXIMUM OF RATIO AT $P_1\,P_2$

are possible both analytically and graphically. For simplicity the term maximum will here be used in place of extremum to include minimum.

(A) Three linear functions given numerically of which one at least is not zero.

(B) One-conditioned maximum. The type case is one linear function not zero given, and a ratio of two linear functions to have a maximum value.

(C) Two-conditioned maximum. The type case is two linear functions given of which one at least is not zero, and a ratio of two linear functions to have a maximum value.

II. Problems involving linear functions may also be presented with less data than as described above thus:

(D) Two linear functions given of which one at least is not zero.

(E) Two linear functions given equal to zero.

(F) One linear function given equal to zero.

While these do not lead to definite solutions they do lead to loci whose examination may be very instructive and yield much information.

17. Algebraic Solutions.

For convenience in the further examination of these six divisions let the linear functions be referred to as $L_1$ $L_2$ etc. with numerical values denoted by $q_1$, $q_2$ etc.

Let $Q$ denote a case of $L = q \neq 0$
$O$ denote a case of $L = 0$
$R$ denote a case of $L_1 \div L_2 = k$
$M_q$ denote a maximum of a quantity.
$M_r$ denote a maximum of a ratio.

An exponent is used to indicate the number of each kind of datum. Thus $Q^2 O$ denotes a case where two linear functions not equal to zero are given and one that is zero.

I. (A) This case of three data may then occur in the forms $Q^3$, $Q^2 O$, $Q O^2$ and to these may be added $Q^2 R$ and $Q R^2$ because $R$ means a relation of the type: $L_1 \div L_2 = k$, or $L_1 - k L_2 = 0$ that is $L = 0$ which is denoted by $O$.

In all these five cases then there are three equations such as

$$\begin{aligned} a_1 z + b_1 w + c_1 x + d_1 y &= q_1 \\ a_2 z + b_2 w + c_2 x + d_2 y &= q_2 \\ a_3 z + b_3 w + c_3 x + d_3 y &= q_3 \end{aligned} \tag{89}$$

of which not more than two values on the right may be zero. These are to be combined with

$$w z - x^2 - y^2 = 0 \tag{90}$$

This is readily done by obtaining linear expressions for $w$, $x$, and $y$ from (89) in terms of $z$ and these on substitution in (90) give a quadratic equation determining $z$ and thence $w$, $x$, and $y$.

I. (B) One-conditioned maximum. Two subdivisions are (1), $L_1$, $L_2 \div L_3$ maximum, regarded as the type case $Q M_r$ and (2) $Q M_q$ which may also be presented in the form $Q M_r$.

For $Q M_q$ means $L_1 = q_1$, and $L_2$ to be maximum. Now this is equivalent to $L_2 \div L_1$ to be maximum. Hence it may be thus put into the form $Q M_r$.

A solution of the type case $Q M_r$ gives the following matrix equal to zero:

$$\begin{bmatrix} a_2 & b_2 & c_2 & d_2 \\ a_3 & b_3 & c_3 & d_3 \\ w & z & -2x & -2y \end{bmatrix} \tag{91}$$

in the sense that each of the three-rowed square determinants which can be made from it is zero. Omitting the first column the line of centers for the two circles $S_2$ and $S_3$ associated with $L_2$ and $L_3$ respectively is found and omitting any other column a circle is found which intersects this line of centers in the limit-points of the system.

For brevity the matrix conditions above (91) may be denoted by $M\ (2, 3) = 0$.

Then since the second case $Q M_q$ corresponds as mentioned above to a denominator $L_1$ instead of $L_2$ the condition for it must be $M\ (2, 1) = 0$.

In both these cases the matrix gives a linear and also a quadratic equation in $u$ and $v$ which are thus sufficient to determine them, and then the covariantive equation and the equation $L_1 = q_1$ together fix $z$, $w$, $x$ and $y$.

I. (C) Two-conditioned maximum. The type case is $Q^2 M_r$, the other cases being $Q^2 M_q$, $Q O M_r$, $Q R M_r$ $Q R M_q$ and $Q O M_q$. For as in the previous divisions, an $R$ condition may be put in the $O$ form and an $M_q$ in the $M_r$ form.

Type case $Q^2 M_r$: This denotes a problem of the form

$$L_1 = a_1 z + b_1 w + c_1 x + d_1 y = q_1$$
$$L_2 = a_2 z + b_2 w + c_2 x + d_2 y = q_2$$

$$L_3 \div L_4 = \frac{a_3 z + b_3 w + c_3 x + d_3 y}{a_4 z + b_4 w + c_4 x + d_4 y} \text{ to be maximum.}$$

Let $q_2 \div q_1 = k$, then $L_2 - k L_1 = 0$ is a homogeneous equation conditioning the maximum and it may be shown that $D\ (2 - k\ 1, 3, 4) = 0$ is the solution where this for brevity denotes that the following determinant is zero:

$$\begin{vmatrix} a_2 - k\,a_1, & b_2 - k\,b_1, & c_2 - k\,c_1, & d_2 - k\,d_1 \\ a_3 & b_3 & c_3 & d_3 \\ a_4 & b_4 & c_4 & d_4 \\ w & z & -2x & -2y \end{vmatrix} = 0 \tag{92}$$

This may be expressed also as

$$D\ (2, 3, 4) = k\ D\ (1, 3, 4) \tag{93}$$

The other cases may then be dealt with as follows:

Case $Q^2 M_q$:

Say that $L_1 = q_1$, $L_2 = q_2$ and that $L_3$ is to be maximum and therefore also $L_3 \div L_1$. $L_1$ now may replace $L_4$ and the equation becomes $D\ (2, 3, 1) = k\ D\ (1, 3, 1)$. But $D\ (1, 3, 1) = 0$ from the properties of determinants.

Therefore $$D\ (2, 3, 1) = 0 \tag{94}$$

Case $Q O M_r$: This is $L_1 = q_1$, $L_2 = 0$, $L_3 \div L_4$ to be maximum.

That is to say a particular case of $Q^2 M_r$ with $k = 0$.

Hence the equation is $$D\ (2, 3, 4) = 0 \tag{95}$$

Case $Q R M_r$: This is $L_1 = q_1$, $L_2 - k L_3 = 0$, $L_4 \div L_3$ to be maximum.

That is, it is a variant of $Q O M_r$ and the equation will be

$$D\ (2 - k\,3, 4, 5) = 0 \text{ or } D\ (2, 4, 5) = k\ D\ (3, 4, 5) \tag{96}$$

Case $Q R M_q$: This is $L_1 = q_1$, $L_2 - k L_3 = 0$, $L_4$ to be maximum.

Substituting for the latter $L_4 \div L_1$ to be maximum, the equation becomes

$$D\ (2 - k\,3, 4, 1) = 0, \text{ or } D\ (2, 4, 1) = k\ D\ (3, 4, 1) \tag{97}$$

Case $Q O M_q$: This is $L_1 = q_1$, $L_2 = 0$, $L_3$ to be maximum.

Since the conditions are as in $Q^2 M_q$, with $k = 0$ (which however does not alter the result) the equation is

$$D\ (2, 3, 1) = 0 \tag{98}$$

18. Geometrical Solutions. The ratio relation $L_1 = k L_2$, leads to

$$S_1' - k S_2' = 0$$

and thus to the corresponding loci. As sufficient detail is not readily found, if at all, in standard works on analytical geometry, a classification of the different forms, real and imaginary, which the locus $S_1' - k S_2' = 0$ may assume, follows. It is useful in suggesting geometrical constructions.

Here $S_1' = b_1 (x^2 + y^2) + c_1 x + d_1 y + a_1$

$S_2' = b_2 (x^2 + y^2) + c_2 x + d_2 y + a_2$

Broadly speaking $S_1'$ and $S_2'$ may denote two straight lines ($b_1 = 0$, $b_2 = 0$) and finally two circles ($b_1 = 1$, $b_2 = 1$). In this latter case it will be more convenient by transforming to an origin at the center of $S_1'$ and axis of abscissas through center of $S_2'$, to replace $S_1'$ and $S_2'$ (when the distance between centers $C_1 C_2$ is equal to $a$) by the form

$$S_1 : x^2 + y^2 - r_1^2$$
$$S_2 : (x - a)^2 + y^2 - r_2^2$$

In the first eight cases below it is not difficult to determine the members of the system geometrically. In the remaining cases the geometrical constructions are for the most part cumbersome and it is desirable to determine the radical axis analytically. Its equation will be, in the new coordinates,

$$S_1 - S_2 = 0 \text{ or } 2\,a\,x = r_1^2 - r_2^2 + a^2 \qquad (99)$$

and this will intersect the line of centers at a point $O$ distant $\frac{a}{2} + \frac{r_1^2 - r_2^2}{2\,a}$ from the center $C_1$ of $S_1$.

Evidently the radical axis is always real. The limit points $P_1$, $P_2$ of the system will be given by the intersection of a circle $S$, center $O$ and radius $r$, where

$$r^2 = \frac{a^2}{4} - \frac{1}{2}(r_1^2 + r_2^2) + (r_1^2 - r_2^2)^2 \div (2\,a) \qquad (100)$$

with the line of centers, $C_1 C_2$.

Hence the points $P_1$ and $P_2$ are real coincident, or imaginary according as $r^2$ is positive zero or negative, *i. e.* as $O$ is exterior, on or interior to every circle of the system.

*Two straight lines* $b_1 = b_2 = 0$

(1) $c_1 = d_1 = c_2 = d_2 = 0$. Both at infinity. As the expressions are both constants there is no problem here.

(2) $c_1 = 0$, $d_1 = 0$, or else $c_2 = 0$, $d_2 = 0$. One only at infinity. The other members of the system are then parallel to that at finite distance.

(3) $d_1/c_1 = d_2/c_2$. Two parallel lines at a finite distance. The system consists of all lines parallel to them.

(4) $d_1/c_1 \neq d_2/c_2$. Two intersecting lines. The system consists of all lines through their intersection.

*Straight line and a circle* ($b_1 = 0$, $b_2 = 1$.)

(5) ($c_1 = 0$, $d_1 = 0$). Line at infinity and circle, (real, imaginary, or point). The system consists of all concentric circles (real, imaginary, or point).

(6) Line at finite distance and real circle which it intersects. The system consists of all circles through these points of intersection.

(7) Line at finite distance and real or point circle which it does not intersect. The system will consist of all the circles which taken with the given circle have the line as radical axis.

In Fig. 1, $R\,O\,R'$ is the given line, $D\,A\,F$ the given circle, center $C_1$, $C_1 O$ perpendicular to $R\,O\,R'$, $O\,A$ tangent to $D\,A\,F$ at $A$. The circle $P_1 E P_2$ center $O$ determines the limit points $P_1 P_2$ which are the point circles of the system. This circle $P_1 E P_2$ is, further, orthogonal to every member of the system, some of which are shown in Fig. 1 and which of course have centers on the "line of centers" $P_1 O P_2$.

(8) Line at finite distance and imaginary circle. In Fig. 1 $R\,O\,R'$ is the given line, $C_0$ the center of the imaginary circle and $C_0 Y$ the amplitude of the imaginary radius, $C_0 O$ being perpendicular and $C_0 Y$ parallel to $R\,O\,R'$. The circle, center $O$, and radius $O\,Y$ determines $P_1$ and $P_2$ the point circles of the system and all others by the property of orthogonality as in Fig. 1.

*Two Circles.* $b_1 = b_2 = 1$.

(9) Two real circles intersecting in the points $Q_1$ and $Q_2$ (see Fig. 3). Here the point $O$ is the midpoint of $Q_1$, $Q_2$, and $r^2$ is negative. All the circles of the system pass through $Q_1$ and $Q_2$ and have their centers on the line through $O$ perpendicular to $Q_1 Q_2$.

(10) Two real non-intersecting circles $S_1 S_2$, external to each other as $D\,A\,F$, $G\,B\,H$ in Fig. 1. The point $O$ may be determined by the formula possibly more easily than by graphical means and the orthogonal circle is real. The members of the system have their centers on $C_1 C_2$ and are orthogonal to $S$.

(11) Two real non-intersecting circles, $S_1$ being internal to $S_2$, as $K\,D\,L$, $G\,B\,H$ in Fig. 1. This case is essentially the same as the preceding, number (10), and the point $O$ and $S$ may be determined as before.

(12) Two real circles touching each other at the point $O$ (Fig. 2). The radical axis consists of the common tangent, and every circle of the system is tangent to it at the point $O$. The circle $S$ is now a point circle, $r^2 = 0$.

(13) One real circle as $D\,A\,F$ and one imaginary circle $S_0$, center $C_0$ and amplitude of imaginary radius $C_0 Y$, Fig. 1, where $C_0 Y$ is drawn perpendicular to $C_0 C_1$ and $Y$ lies on $S$.

The center of $S_0$, namely $C_0$, may be outside on, or inside $S_1$, but in either case the radical axis is readily found by the formula or graphically and the circle $S$ is always real.

(14) Two imaginary circles. Here both $r_1^2$ and $r_2^2$ are negative and $r^2$ is always positive.

19. Geometrical Solutions. Use of circular loci. The preceding section contains a classification of

loci corresponding to variable ratios of $L_1$ to $L_2$ according to the circular or linear characters of $S_1$ and $S_2$ corresponding to them. They correspond to the families of circles of which examples are to be seen in Figs. 1, 2, and 3. They are characterized by having a common radical axis associated with and determined by $L_1$ and $L_2$.

Cases $O$ and $R$: Cases $L = 0$, and $L_1 - k L_2 = 0$ in which $k$ is fixed, which correspond, to $O$ and $R$ of Sec. 17, may be represented geometrically by putting them in the form $S = 0$ from which the center and radius may be found as in Sec. 15 if it is a real circle, otherwise as a straight line by usual methods.

Section 17 I (A). Cases $Q^2$, $Q^2 O$, $Q O^2$: These may for the present purpose all be expressed as $Q O^2$.

Each $O$ will then define a circle (in general) which may be drawn. The intersection point or points will then give the values of $u$ and $v$ and thence all the ratios. The values are then given by $Q$, namely $L_1 = q_1$ that is $S_1 z = q_1$ or $z = q_1 \div S_1$. Then $q_1$ being known and $S_1$ being a given function of $u$ and $v$ is known also for the intersection determined. Now that $z$ is known the ratios found determine all the quantities.

Section 17 I (B). The type case of one-conditioned maximum $Q M_r$ viewed geometrically calls essentially for the maximum of a ratio to be determined, that is some limiting number for $k$ in $S_2 - k S_2 = 0$ is to be found. Such numbers, however, do not exist when $S_2$ and $S_3$ belong to the families of circles shown in Fig. 2, intersecting in two points, or in Fig. 3 with common point of tangency, but only in Fig. 1. In Figs. 2 and 3, $k$ may have any value while in Fig. 1 the limit points $P_1$ and $P_2$ correspond to extreme values of $k$.

If then $L_2$ and $L_3$ are related as in Fig. 1, and external to each other the radical axis $R O R'$ may be found since it bisects the common tangent and the two limit points are then on the line of centers at distance $O A$ from $O$ where $A$ is a point of tangency on either circle. In any case the formulas of Sec. 18 may be used to locate the limit points and thus all ratios. Then $z = q_1 \div S_1$ will give all the quantities required.

An approximation that may be convenient in a case of two circles relatively small and moderately distant, of radii $r_1$ and $r_2$ and distance between centers $d$, is that measuring along the line of centers from the first center the nearer limit-point is at the distance given by the continued fraction whose repeating period is $(r_1^2/d - r_2^2/d -)$.

Also if one be a circle of radius $r$ and the other a straight line at distance $p$ from the center then the nearer limit point will be at distance $p - \sqrt{p^2 - r^2}$ or if $r \div p = \sin\theta$ then at distance $2\, p \sin^2(\theta/2)$.

Section 17 I (C). Two-conditioned maximum. Type Case $Q^2 M_r$. As before this means $L_1 = q_1$, $L_2 = q_2$ and $L_3 \div L_4$ to be maximum. Putting in the form $Q O M_r$ and leaving $Q$ for final consideration, there remains $O M_r$. The equation $O$ is $S_3 q_1 - S_1 q_2 = 0$, or say $S_{31} = 0$. $M_r$ means $S_3 - m S_4 = 0$ with $m$ a maximum. Consequently the extreme members of the family $S_3$, $S_4$ are sought which are consistent with $S_{31}$: a geometrical problem of three circles.

If $S_3$ and $S_4$ are given such as to belong to the system of Fig. 3, and $S_{31}$ is the circle $T_1 T_2$ then the graphical problem is to draw a circle through $Q_1$ and $Q_2$ the points of intersection of $S_3$ and $S_4$ so as to be tangent to the circle $T_1 T_2$. This can be done in two ways and hence $T_1$, $T_2$ found, thus determining the ratios and then as above the quantities.

Similarly if $S_3$ and $S_4$ belong to the system of Fig. 2, two circles of the system tangent to their radical axis at $O$ and also to the circle $T_1 T_2$ at $T_1$ and $T_2$ respectively may be found graphically.

If, however, $S_3$ and $S_4$ belong to the system of Fig. 1, as in Fig. 5, then taking them with the other circle, namely $S_1 - k S_2$, pair by pair, they will have three radical axes meeting in a point, the radical center. This point has the property that a circle having it for center intersects orthogonally every member of each of the three systems of circles with these radical axes. Hence drawing tangents from the radical center to the circle $S_1 - k S_2$ the points $(P_1, P_2)$ fulfill the required condition. The ratios are thus fixed and $z = q_1 \div S_1 = q_2 \div S_2$ then fixes the quantities.

In Section 16, II (D) (E) (F), cases $Q O$, $O^2$ and $O$ are mentioned of data per se insufficient to determine a definite solution. Some of these arise from ratios; they may be $Q R$, $R^2$ and $R$. Consider some of the principal ratio cases.

For transmission lines possibly the ratios arising from equivalent $R$, $X$, $G$, $B$, and $Z$ at either end may not appear particularly natural, but the principles here developed apply to all circuits including those of communication engineering, so that these conditions are of importance. In any case the ideas are fundamental.

Other ratios of importance are efficiency, regulation, and power factor. Efficiency is either $x'/x$ or $x/x'$ according to circumstances. Regulation is neither $z'/z$ nor $z/z'$ but is definitely associated with these numbers, so that the regulation is constant when $z'/z$ is. Power factor is given by $y/x$ at one end and $y'/x'$ at the other. These are the tangents of the phase angle and hence fix the power factor by the cosine. By using the principles stated it is possible to obtain very easily some of the fundamental loci. These are in general circles and belong to the system defined by the numerator and the denominator as illustrated in the "kite" framework of Fig. 4.

Regulation index $z'/z$: Circles center $A$.

Efficiency index $x'/x$: $x = 0$ is radical axis of the system.

$x' = 0$ is shown with center $C$. The loci for variable efficiency are circles with this radical axis and one limit point at $\sqrt{p^2 - r^2}$ to the left of $x = 0$, that is at distance $\sqrt{a_{32}^2 - 1} \div (2\, a_{32})$.

$R$ at $A$: This is $x/w$: Radical axis $x = 0$. Point circle $w = 0$. Loci are circles tangent to $x = 0$ at $O$.

$X$ at $A$: This is $y/w$: Radical axis $y = 0$. Point circle $w = 0$. Loci are circles tangent to $y = 0$ at $O$.

$G$ at $A$: This is $x/z$: $x = 0$ is infinite circle. $z = 0$ circle at infinity. Loci are lines parallel to $x = 0$ (as is evident).

$B$ at $A$: this is $y/z$: $y = 0$ is infinite circle. Loci are lines parallel to it.

$Z$ at $A$: this is $z/w$: Loci concentric circles around $O$.

$R$ at $B$ end: this is $x'/w$: Point circle $w' = 0$ is on circle $x' = 0$. Loci are circles, centers on $C\,B$ passing through $B$. $D\,B$ is a member.

$G$ at $B$: this is $x'/z'$: Loci are circles, centers on $C\,A$ passing through $A$. $A\,D$ is a member.

$X$ at $B$: this is $y'/w'$: Loci are circles, centers on $D\,B$ passing through $B$. $C\,B$ is a member.

$B$ at $B$: this is $y'/z'$: Loci are circles, centers on $D\,A$ passing through $A$. $C\,A$ is a member.

$Z$ at $B$: this is $z'/w'$: Loci with $A\,D$ as limit points and radical axis the perpendicular bisector of $A\,D$. This line also is a member.

This last diagram is the same as for lines of magnetic flux with $A$ and $B$ as parallel conductors.

Power factor at $A$ given by $y/x = \tan\theta$. Loci are lines through $O$.

Power factor at $B$ given by $y'/x' = \tan\theta$. Loci are arcs of the system through $A$ and $B$. Relative phases of current and voltage at $B$ are preserved by the directions of the tangents to these arcs at the point $B$.

20. Interconnection of algebraic and geometrical methods. It is not necessary to dwell on the fact that in practical problems according to circumstances one of these methods or the other may prove more convenient, nor that it is of advantage always to have methods as different as possible so as to make certain of the result by a check.

Section 17 I (B) Case $Q\,M_r$: One-conditioned maximum. Here the algebraic solution is by $M\,(2, 3) = 0$ and the graphical by finding the limit points. They agree because the matrix gives equations which describe the line of centers and three circles intersecting this line in the limit-points, one circle being sufficient to define them.

Section 17 I (C) Case $Q^2\,M_r$: Two-conditioned maximum. Here $D\,(2, 3, 4)\,q_1 = D\,(1, 3, 4)\,q_2$ is the equation of the circle intersecting $S_{21}$, $S_3$ and $S_4$ orthogonally. By dispensing with the maximum condition and using this determinantal equation with the other algebraic conditions or else this circle with the geometrical conditions the same result should be obtained.

21. Examples.

(a) The voltage at Paugan Falls being 225.2 kv. (line) what are the conditions there when the loss on the line is the minimum possible?

First consider as a general circuit problem detached from its special features. It is a case of $Q\,M_e$ in Section 17 I (B) and is therefore solved by $M\,(2, 1) = 0$.

Here $L_1 = z' = q_1$ and $L_2 = x' - x$ is to be minimum.

Then $M\,(2, 1) = 0$ means

$$\begin{bmatrix} 1, & 0, & 0, & 0, \\ -b_{31} & -b_{32} & (1-b_{33}) & -b_{34} \\ w' & z' & -2\,x' & -2\,y' \end{bmatrix} = 0$$

That is

$$z' + (-b_{31}) = -2\,x' + (1 - b_{33}) = 2\,y' + b_{34}$$

or $\quad z' + a_{13} = x' + (a_{33} - 1) = y' + a_{43}$

is the solution of the *general circuit problem*. For the *problem proposed* $q_1 = 1.69$.

Hence

$x' = 0.001001$ or 10.01 kw. $y' = 0.431$ or 4310 kv-a.

$w' = 0.1122$ or 1122 amperes-squared that is 33.5 amperes.

The power factor would be 0.0023 (leading).

This problem might have been considered as determined by the center of the circle $x_1' - x = 0$, or $R\,\bar{w} + G\,\bar{z} = 0$. As is evident from the latter form it is an imaginary circle but has a real center.

(b) The voltage being 225.2 on the same line at the $S$-end and the power factor at the $R$-end being 0.85 (lagging) find the maximum power that can be delivered.

As a general circuit problem this may be put in the form

$L_1 = z' = q_1$, $L_2 = x$, $L_3 = y$, where $y/x = \tan\theta$ and $L_4 = L_2$ to be maximum, a case of $Q\,R\,M_e$ of Sec. 17 I (C). The determinantal condition simplifies to $D\,(1, 2, 3) = 0$ that is

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ w & z & -2\,x & -2\,y \end{vmatrix} = 0$$

this reduces to $w = z\,a_{11} + a_{12}$. Let $a_{11} + a_{12} = c^2$

Then

$u^2 + v^2 = c^2$, $v/u = \tan\theta$, hence $u = c\cos\theta$, $v = c\sin\theta$

Then $\quad z = q_1 + S_1$ where

$$S_1 = 2\,a_{11} + c\,a_{13}\cos\theta + c\,a_{14}\sin\theta$$

Thus $\quad x = u\,z = q_1\,c\cos\theta + S_1$

$$y = v\,z = q_1\,c\sin\theta + S_1$$

In the special values of this problem $q_1 = 1.69$, $\cos\theta = 0.85$ hence $\sin\theta = -0.52679$.

Then

$x = 5.1125$ or 51125 kw. $y = -3.169$ or 31690 kv-a. (lagging)

$z = 0.4924$ corresponding to 121.5 kv. line volts.

In both this and the preceding example the results as worked out are for one phase both as to current and voltage, the data however are supposed given for line voltage.

22. In conclusion the author wishes to thank Mr. V. G. Smith and Mr. G. de B. Robinson for assistance in the preparation of this paper.

## Discussion

**V. G. Smith:** It will be noticed that Professor Rosebrugh uses $\mathbf{I}\hat{\mathbf{E}} = P + j\,Q$ throughout. This makes $Q$ positive for leading power factors. It is to be hoped that this definition will be adopted as it makes the power diagrams similar to the usual vector diagrams.

In using this work it should be remembered that while $z$, $w$, $x$, $y$ and $z'$, $w'$, $x'$, $y'$ are defined as the received and transmitted quantities respectively the definition is algebraic. Negative power received is positive power transmitted and vice versa. Similarly for the reactive volt-amperes.

Mr. L. A. Paine has invented the name of "Quads" for reactive volt-amperes. The name seems apt as it comes from the conception of quadrature power and has $Q$ for its initial letter.

Professor Rosebrugh has confined his diagrams to the admittance $(u, v)$ plane. There is a number of real quantity diagrams and all of them have a vector meaning which should be kept in mind.

Table I shows the vector basis of six diagrams which have an obvious electrical meaning and the equation of the circular locus for a constant value of any linear function of the four quantities $z$, $w$, $x$, $y$ or a constant value of the ratio of any two linear functions. The position of the center and the radius is obvious in each case from the equation. A similar set of diagrams for the transmitting end may be determined in the same manner.

It will be noticed that either the voltage or the current is assumed known. Usually the voltage will be known which makes the first three diagrams the most useful. A particular problem, however, may call for any one of the six as the best means of attack.

By considering the diagrams as vector diagrams with loci placed upon them, the phase relations as well as magnitudes are seen, which is a great convenience.

**T. R. Rosebrugh:** Mr. V. G. Smith has raised a question of standardization of meaning of terms. Besides the definition of positive sense for $Q$ and of a short name for the quantity to which he refers, there is a number of other instances. There are the four "general circuit constants," as in the equations (1), the sixteen coefficients of equations (12) and the inverse set of equations (14). In view of their number it would not appear desirable to attempt to assign individual names to these 32 coefficients but to leave them to be designated by a symbol with standard subscripts as here.

Each set of sixteen coefficients consists in fact of six absolute ratios, four impedances, four admittances, two of the nature of

TABLE I

$L = a\,z + b\,w + c\,x + d\,y$ or $L_1 - k\,L_2 = 0$ which is $L = 0$

| Vector basis | Where | Equation of the circular locus for constant $L$ and $z$ or $w$ | Name of the diagram |
|---|---|---|---|
| $\frac{\mathbf{E}_1}{\mathbf{B}\,\mathbf{E}_o} = \frac{\mathbf{A}}{\mathbf{B}} + \mathbf{Y}_o$ <br> $\frac{\mathbf{I}_1}{\mathbf{D}\,\mathbf{E}_o} = \frac{\mathbf{C}}{\mathbf{D}} + \mathbf{Y}_o$ | $\mathbf{Y}_o = \frac{\mathbf{I}_o}{\mathbf{E}_o}$ <br> $\mathbf{Y}_o = G_o + j\,B_o$ | $\left(G_o + \frac{c}{2\,b}\right)^2 + \left(B_o + \frac{d}{2\,b}\right)^2 = \frac{L}{b\,z} + \frac{c^2 + d^2 - 4\,a\,b}{4\,b^2}$ | Admittance or Shand or Evans and Seis modified |
| $\frac{\mathbf{E}_1}{\mathbf{B}} = \frac{\mathbf{A}}{\mathbf{B}}\,\mathbf{E}_o + \mathbf{I}_o$ <br> $\frac{\mathbf{I}_1}{\mathbf{D}} = \frac{\mathbf{C}}{\mathbf{D}}\,\mathbf{E}_o + \mathbf{I}_o$ | $\mathbf{I}_o = I_a + j\,I_r$ | $\left(I_a + \frac{c\sqrt{z}}{2\,b}\right)^2 + \left(I_r + \frac{d\sqrt{z}}{2\,b}\right)^2 = \frac{L}{b} + \frac{c^2 + d^2 - 4\,a\,b}{4\,b^2}\,z$ | Current |
| $\frac{\mathbf{E}_1\,\hat{\mathbf{E}}_o}{\mathbf{B}} = \frac{\mathbf{A}}{\mathbf{B}}\,\mathbf{E}_o^2 + P_o + j\,Q_o$ <br> $\frac{\mathbf{I}_1\,\mathbf{E}_o}{\mathbf{D}} = \frac{\mathbf{C}}{\mathbf{D}}\,\mathbf{E}_o^2 + P_o + j\,Q_o$ | $\mathbf{I}_o\,\hat{\mathbf{E}}_o = P_o + j\,Q$ | $\left(P_o + \frac{c\,z}{2\,b}\right)^2 + \left(Q_o + \frac{d\,z}{2\,b}\right)^2 = \frac{L}{b}\,z + \frac{c^2 + d^2 - 4\,a\,b}{4\,b^2}\,z^2$ | Volt-ampere or Evans and Seis |
| $\frac{\mathbf{E}_1}{\mathbf{A}\,\mathbf{I}_o} = \frac{\mathbf{B}}{\mathbf{A}} + \mathbf{Z}_o$ <br> $\frac{\mathbf{I}_1}{\mathbf{C}\,\mathbf{I}_o} = \frac{\mathbf{D}}{\mathbf{C}} + \mathbf{Z}_o$ | $\mathbf{Z}_o = \frac{\mathbf{E}_o}{\mathbf{I}_o}$ <br> $\mathbf{Z}_o = R_o + j\,X_o$ | $\left(R_o + \frac{c}{2\,a}\right)^2 + \left(X_o + \frac{d}{2\,a}\right)^2 = \frac{L}{a\,w} + \frac{c^2 + d^2 - 4\,a\,b}{4\,a^2}$ | Impedance |
| $\frac{\mathbf{E}_1}{\mathbf{A}} = \frac{\mathbf{B}}{\mathbf{A}}\,\mathbf{I}_o + \mathbf{E}_o$ <br> $\frac{\mathbf{I}_1}{\mathbf{C}} = \frac{\mathbf{D}}{\mathbf{C}}\,\mathbf{I}_o + \mathbf{E}_o$ | $\mathbf{E}_o = E_a + j\,E_r$ | $\left(E_a + \frac{c\sqrt{w}}{2\,a}\right)^2 + \left(E_r + \frac{d\sqrt{w}}{2\,a}\right)^2 = \frac{L}{a} + \frac{c^2 + d^2 - 4\,a\,b}{4\,a^2}\,w$ | Voltage |
| $\frac{\hat{\mathbf{E}}_1\,\mathbf{I}_o}{\mathbf{A}} = \frac{\hat{\mathbf{B}}}{\mathbf{A}}\,I_o^2 + P_o + j\,Q_o$ <br> $\frac{\hat{\mathbf{I}}_1\,\mathbf{I}_o}{\mathbf{C}} = \frac{\hat{\mathbf{D}}}{\mathbf{C}}\,\mathbf{I}_o^2 + P_o + j\,Q_o$ | $\hat{\mathbf{E}}_o\,\mathbf{I}_o = P_o + j\,Q_o$ | $\left(P_o + \frac{c\,w}{2\,a}\right)^2 + \left(Q_o + \frac{d\,w}{2\,a}\right)^2 = \frac{L}{a}\,w + \frac{c^2 + d^2 - 4\,a\,b}{4\,a^2}\,w^2$ | Volt-ampere |

Six vector diagrams and the equations for determining circular loci on them for a constant value of any linear function of the four quantities $z$, $w$, $x$, $y$

impedance-squared and two of admittance-squared. But the four "general circuit constants" might very well have characteristic names given to them instead of calling them by letters.

It might be suggested that *voltage-transformance* and *current-transformance* would suitably describe the first and the fourth general circuit constants, while another name of the resistance class such as *obstructance* would do for the second and perhaps *percolance* (suggesting conductance) would do for the third.

Mr. Smith has made a substantial contribution to the value of the paper by his analysis of the possible diagrams having simultaneously vector and real quantity interpretations. The analytical portion of my paper would of course apply equally, however the data might be represented graphically. While the interconnection of graphics and analysis as treated in the paper is worked out solely for the first diagram of Mr. Smith's table, there would also be formal agreement of a similar kind in the case of the fourth of his list. The situation would be different for the other diagrams but these I have not considered.

# Study of the Effect of Short Lengths of Cable on Traveling Waves

BY K. B. McEACHRON,* J. G. HEMSTREET,† and H. P. SEELYE‡
Member, A. I. E. E. Associate, A. I. E. E. Member, A. I. E. E.

*Synopsis.—Cathode ray oscillographic tests were made of traveling waves passing from an overhead line into short lengths of cable. Single-phase cable lengths of 500 and 1000 ft. were used. Tests were made with a wide variety of conditions, such as cable at end of line, cable between two sections of line, etc. The tests demonstrated that a short length of cable does not act as an effective protective device when connected between station and incoming line. When the traveling wave on the incoming line has a long flat top, several times the cable length, the crest of the wave passing the cable is decreased only a few per cent by the presence of the cable, although the wave-front is sloped off if it was originally very steep. When the wavelength is approximately the same as the cable length, the cable can reduce the transient voltage to less than half of the value without the cable. Recent measurements on transmission lines show that waves do occur with approximately flat tops which are several thousand feet in length. Therefore the cables do not permit the omission of lightning arresters which are means of reducing the potential of overvoltage surges. This confirms the theoretical calculations and the practise of using lightning arresters with cables.*

*The resistance of the ground connection of the cable sheath was found to have important effects. With the cable sheath at the end grounded through 28 ohms, a potential of 82 kv. was measured at the sheath and 105 kv. at the cable conductor.*

*The protective action of lightning arresters was demonstrated by using a gap and various values of series resistance.*

*The velocity of propagation in the cable was found to be about 61 per cent of the velocity of light. The surge impedance of the cable was determined by several methods. Calculations based on the measured propagation velocity and measured capacitance in accordance with the formula*

$$Z = \frac{1}{C v}$$

*gave a value of about 50 ohms. Some of the other methods gave values of about 100 ohms.*

* * * * *

THERE has been much discussion for many years concerning the effectiveness of cable in reducing the potential of incoming surges, and as a result considerable uncertainty has existed as to whether or not current practises are correct with regard to methods of protection, both of the cable itself and of apparatus connected to the cable.

Recognizing this problem as being of great importance to both manufacturers and operators, a joint investigation by the General Electric Company, the Consumers Power Company, and the Detroit Edison Company was arranged late in the summer of 1929.

The General Electric Company furnished a portable impulse generator and sphere-gaps for measuring voltage. The Consumers Power Company supplied the S-19 transmission line, a portable power supply, communication and trucking facilities. The Detroit Edison Company furnished 1000 ft. of 24,000-volt lead sheath cable and a portable cathode ray oscillograph.

The tests were conducted at Croton Dam, Michigan, between August 26, 1929 and November 7, 1929.

The tests dealt with the following subjects:

1. Free waves on the transmission line.
2. Effect of 500 ft. of cable.
3. Effect of 1000 ft. of cable.
4. Effect of bus between two sections of cable, each 500 ft. long.
5. Effect of terminal conditions with 500 ft. of cable.
6. Effect of terminal conditions with 1000 ft. of cable.
7. Effect of grounds on sheath of the cable.
8. Effect of lightning arrester—gap setting and resistance.
9. Effect of lightning arrester—on the wave, on the line, and with bus between two sections of cable.

*Impulse Generator.* The portable impulse generator[1] used in these tests consisted of 40 banks of capacitors each having a capacity of 0.5 $\mu$f. The banks were charged in parallel to 20 kv. each and discharged in series according to the well known Marx circuit. During most of these tests the potential of the generator was reduced by disconnecting part of the banks to prevent breakdown of the cable or arcing over the potheads.

*Transmission Line.* The transmission line used for the tests was a section of the S-19 line of the Consumers Power Company, a description of which has already been published.[2] The location of the cable for the tests was at towers 53 to 55, a distance of 5.16 to 5.36 miles from the impulse generator which was at the Croton end of the line. The main impulse was sent out on the middle conductor and the bottom conductor was used to carry an initiating impulse.

Strain insulators were installed on towers 53, 54, and 55 to enable a section of the cable to be inserted between sections of the line.

*Oscillograph.* The oscillograph used for measuring the wave-shapes was of the hot cathode type described by George.[3] The oscillograph and its auxiliaries were easily portable, being mounted on a truck. (See Fig. 1.)

*Cable.* The cable used for these tests consisted of 1000 ft. of lead sheath cable having 21/32-in. manila

*General Electric Company, Pittsfield, Mass.
†Consumers Power Company, Jackson, Mich.
‡Detroit Edison Company, Detroit, Mich.

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1. For references see Bibliography.



30-121

paper insulation, and a single conductor consisting of a number 00 seventeen-strand copper. The capacity of the cable as measured with a capacity bridge was 0.03734 $\mu$f. per 1000 ft. The voltage rating of the cable was 24,000 volts.

The potheads at the cable terminals were the type used by the Detroit Edison Company, and were installed by their cable men.

*Sphere-Gaps.* Several sizes of sphere-gaps, ranging

Fig. 1—Illustration of Impulse Generator Truck

from 2.5 cm. to 25 cm. diameter were used to measure crest voltage.

## Methods

*Cable Divider.* A cable divider similar to the one which was described by Gabor[4] was used to reduce the voltage to a safe value for use on the deflecting plates of the oscillograph. By using the cable divider, it was possible to make measurements at each end of the cable without moving the oscillograph, which was a decided advantage.

The cable divider consisted of a section of *B X* cable No. 14 double conductor 500 ft. in length. One conductor was tied to the sheath and grounded at each end. The other conductor was used to conduct the transient to the deflecting plates of the oscillograph. At the oscillograph end of the *B X* cable a resistance equal to the surge impedance of the cable was placed to ground. At the other end of the cable a high resistance was placed from the conductor to the point where the transient was to be measured. The ratio between the resistances at the two ends of the cable is the ratio of the voltage division. After making a number of comparative tests with the cable divider and capacity divider, the conclusion was reached that the cable divider reproduced the transient with sufficient accuracy, and that it was dependable in its operation. In Gabor's description of the cable divider, there was a capacity at each end of the cable. These capacities are used to suppress the 60-cycle current in the measuring circuit, but were not necessary in these tests since there was no 60-cycle voltage on the line. However, check tests were made using capacities. It was necessary to check the high-resistance water tube at the line end of the measuring cable at frequent intervals to prevent changes in the ratio due to temperature.

*Determination of Time Scales and Sweeping Speeds.* In order to eliminate any doubt as to timing, a 500-kilocycle wave was superimposed on one measured wave for each condition tested. The frequency of the oscillator was checked with a precision wave meter. This method gives a check on the sweeping speed of the oscillograph, and a time scale for the transient. Usually the transients were taken, one with 500 kilocycle superimposed, and one without, to give a continuous check on the calibration which changes somewhat with changes in vacuum. Many oscillograms in this paper show the 500-kilocycle superimposed wave.

*Sphere-Gap Measurements.* Sphere-gap measurements were taken for each test condition to give the crest value of the voltage. Because dirty gaps are apt to be erratic, the gaps were cleaned at frequent intervals.

*Operation of the Oscillograph and Impulse Generator.* Fig. 2 is a schematic diagram showing the operation of the circuits which were used with the oscillograph. The transients waves were sent out at scheduled intervals by an operator at the impulse generator station, who closed a switch in the initiating circuit. The initiating circuit was arranged to send a 20-kv. impulse out on the line (bottom conductor) and to start the main impulse of the generator (middle conductor). There was a short delay between the 20-kv. initiating impulse and the main impulse which depended upon the time constant of the circuit coupling the two impulse circuits.

At the oscillograph the shutter was opened and the

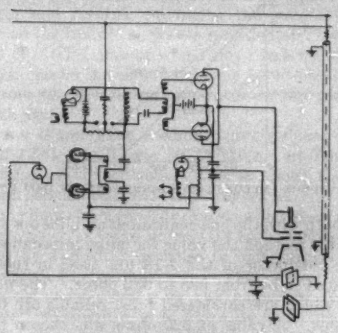

Fig. 2—Circuit Diagram

circuits energized before the main transient was due. The 20-kv. initiating impulse arriving before the main transient, tripped a three-electrode gap, thus starting oscillations in a local circuit. The grids of the tubes in the sweeping and electron gun circuits were coupled to the oscillating circuit so that they became energized when the local circuit began oscillating. The electron gun circuit turned on the beam and the sweep circuit

moved the beam across the film giving the time scale. The time interval between the arrival of the 20-kv. initiating impulse and the main impulse was made such that the deflection due to the main transient began after the beam had moved a short distance along the zero line. This made it possible to record the start of the transient under investigation.

*Test Wave Forms.* At different times as many as five different waves were used. The form of these different waves is given in Table I. All the waves used were of negative polarity.

TABLE I
DATA ON WAVE FORMS USED

| Designation | Voltage crest at Tower 53 | Time to reach crest ms. | Time to decay to 50% crest ms. | No. of generator banks used | Series inductance henrys |
|---|---|---|---|---|---|
| Steep wave low voltage. | 92 | 8 | 55 | 7 | 0 |
| Medium wave low voltage | 120 | 13-15 | 40 | 10 | 0.002 |
| Slow wave low voltage | 124 | 27 | 50 | 14 | 0.011 |
| Steep wave high voltage | 225 | 8 | 15 | 32 | 0 |
| Medium wave high voltage | 223 | 10 | 20 | 32 | 0.002 |

## Preliminary Measurements

*Surge Impedance of the Line.* Surge impedance measurements were made by connecting a water tube of varying resistance from line to ground and measuring the $I\,R$ drop across the water tube and the voltage from the line to true ground.* Measurements were

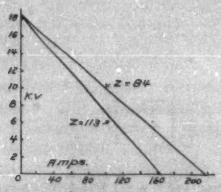


Fig. 3—Surge Impedance Measurement on 1000 Ft. Cable

made both with the line continuous and line open.

By this method the value for surge impedance of the middle conductor of the S-19 line used in these tests was found to be from 595 to 685 ohms. The measurements which are considered most reliable are 610 and 624 ohms. A value of 620 ohms was chosen for purposes of calculation.

*Surge Impedance of the Cable.* The surge impedance of the cable was determined by several methods. Each method will be described briefly and the results summarized.

The first method was similar to that used for surge impedance measurements on the transmission line. The steep wave was used and was chopped by a gap at Tower 48 which was considered to be far enough away so that reflections would not affect the result. The success of this method depends on the wave being short enough so that reflections between the two ends of the cable do not affect the measurements. In general the space wave in the cable should be less than twice the cable length although a longer wave might give the same results depending on the shape of the tail. Fig. 3 shows two values obtained, 84 and 113 ohms.

The second method is based on the reduction of voltage which occurs when a steep wave enters the cable. In Fig. 4 are shown two oscillograms, taken at Tower 53, one with the line continuous and the other with

Wave on continuous line at Tower 53 — Wave entering 1000-ft. cable at Tower 53

Fig. 4—Oscillograms of Effect of 1000-Ft. Cable on Traveling Wave

1000 ft. of cable in circuit, but with the far end of the cable open. The effect of the cable was to reduce the wave from 92 kv. to 30 kv. on the first reflection. This was subsequently increased by successive reflections. The surge impedance of the line was determined by previous tests to be about 620 ohms. Then the surge impedance of the cable was calculated from the formula $Z_c' = E_t Z_1\, 2/E_o - E_t = 121$ ohms. This value of surge impedance may be considered as consisting of the actual surge impedance of the cable plus the resistance between the sheath and ground at the start, which in this case is 28 ohms. Subtracting: $Z_c = Z_c' - 28 = 93$ ohms.

The second method was also applied to measurements at the far end of the cable using sphere-gap values. It was unnecessary to take oscillograms for this case because the chopped wave which was used was short compared to the cable length, so there was no building up of the voltage by successive reflections. The values obtained by this method were 38 to 54 ohms. These values are probably too low due to attenuation of the voltage through the cable, and to difficulty of measuring accurately such a short wave with sphere-gaps.

The third method was to calculate the surge impedance by using the measured propagation velocity of the wave through the cable and the measured capacity in the formula: $Z = 1/(C\,v)$. The propagation velocity was calculated from the reflections on film C-20-8, Plate VI, and was found to be 61.2 per cent of the velocity of light. The capacity of the cable as measured

*This method is described in greater detail in Reference 2.

by a bridge was 0.0373 $\mu$f. The surge impedance calculated by this method is 44.5 ohms.

In the fourth method the impedance was calculated from the geometrical constants of the cable, which were as follows:

| | |
|---|---|
| Diameter of conductor (No. 00) | 0.413 in. |
| Thickness of insulation | 0.656 in. |
| Dielectric constant (assumed) | 3.0 |

Applying the usual formulas to these constants gives a surge impedance of 47.3 ohms.

SUMMARY OF RESULTS ON SURGE IMPEDANCE

| Method | Z in Ohms |
|---|---|
| Varying terminal impedance | 84 to 113 |
| Transmitted wave, sphere-gap measured far end | 38 to 54 |
| Transmitted wave oscillogram, near end | 93 |
| Calculated based on propagation velocity | 44.5 |
| Calculated based on geometrical constants | 47.3 |

These figures for the surge impedance seem to fall into two groups, one about 50, and the other approximately 100 ohms. It is believed that this discrepancy is not due entirely to errors in taking the data, but rather to factors which are not considered.

## RESULTS OF TESTS

The results of the tests are shown in a series of plates on which the oscillograms dealing with each of the subjects studied are grouped. Each of the plates will be discussed separately, and a summary of results given at the end of the paper. On some of the plates oscillograms are repeated from other plates so that those on any one plate are complete and comparable. In all tests with the cable the sheath was grounded at both ends unless otherwise specified.

*Plate I. Shape of the Waves and Effect of Distance*

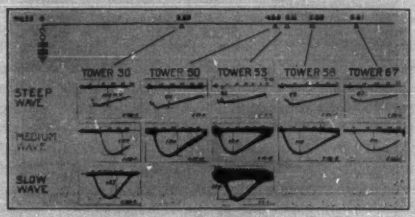


PLATE I. SHAPE OF THE WAVES AND EFFECT OF DISTANCE TRAVELED

*Traveled.* The oscillograms on Plate I show the time voltage characteristics of the three waves used during the tests as recorded by the oscillograph at several locations on the line. These curves represent free traveling waves on the line and were recorded with a continuous line from the lightning generator at Croton to the Wealthy Street Plant at Grand Rapids. No equipment other than measuring apparatus was connected to the line at the time the tests were made.

*Steep Wave.* From the oscillograms, Plate I, it can be seen that the voltage was reduced from 103 kv. at Tower 30 to 87 kv. at Tower 67, a reduction of 14.7 per cent in 3.7 miles. The wave is made up of a very sudden rise at the start, followed by a slower rise having imposed on it an oscillation which continues until crest value is reached. After crest value, the voltage reduces along a smooth curve reaching 50 per cent of crest value in about 50 microseconds. It may be noted that the recorded wave-front is somewhat different at the various

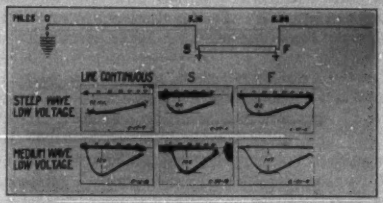


PLATE II. WAVE PASSING THROUGH 500 FT. OF CABLE

tower positions, possibly due to differences in phase relation between the fundamental wave-shape and an oscillation on the front. On the waves recorded at Towers 30 and 53, the oscillation and the fundamental appear to add together in such a manner that the initial rise of voltage is almost equal to the crest value. The oscillation apparently attenuates rapidly and is of low magnitude at Tower 67.

Measuring equipment connected to the line apparently caused a partial reflection which goes back to the generator and returns, producing the sudden rise in voltage on the tail of the waves recorded at Towers 30, 50, and 53. The time at which this rise is recorded in each case checks the calculated time for the travel of a wave from the measuring apparatus to the generator and back again.

*Medium Wave.* The medium wave reduces from a value of 129 kv. at Tower 30, to 110 kv. at Tower 67, a reduction of 15 per cent. This is about the same reduction as was noted with the steep wave.

The medium wave consists of a smooth rise in voltage from zero to crest value in from 13 to 15 microseconds followed by a gradual decrease to half voltage in approximately 40 microseconds. This wave can be represented very closely by the equation: $e = 240\ \epsilon^{-0.0321t} - \epsilon^{-0.1241t}$ where $e$ is in kilovolts and $t$ in microseconds. Comparison of oscillograms made at various locations (Plate I) show no perceptible change in wave-shape due to travel along the line.

*Slow Wave.* The slow wave is smooth throughout and reaches a crest value at approximately 27 microseconds and decreases to 50 per cent crest voltage at 50 microseconds as indicated by the oscillogram taken at Tower 30. (The time scale of oscillogram C-9-2 is not reliable.) The crest voltage is 124 kv. at Tower 53.

*Plate II. Wave Passing Through 500 Ft. of Cable.*

When the wave enters a 500-ft. section of cable, the oscillograms show that the time for the voltage to rise to its crest value with the steep wave (8-microsecond front) was 1[9] to 15 microseconds. The crest voltage was reduced from 92 to 80 kv. or about 12 per cent. The amount of reduction depends principally on the shape of the tail of the incident wave. If the voltage drops rapidly, it will limit the voltage which can be built up in the cable. The wave-front of the medium wave was slow enough so that the cable did

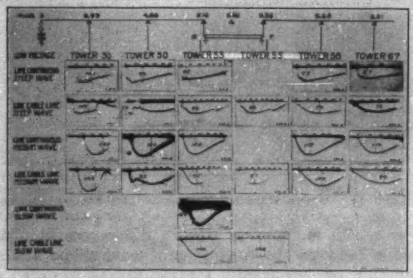


PLATE III. WAVE PASSING THROUGH 1000 FT. OF CABLE

not have any effect on its shape, although the potential was reduced from 120 kv. to 105 kv.

*Plate III. Wave Passing Through 1000 Ft. of Cable.* When a 1000-ft. section of cable was inserted into the line the crest voltage was reduced from 92 kv. on the free line to 70 kv. for the steep wave with the cable inserted, a reduction of 24 per cent. The wave front was changed from 8 microseconds on the free line to 22 microseconds.

In the case of the medium wave the crest value was reduced from 120 kv. to 92 kv., a reduction of 23.3 per cent. The wave-front was changed from 15 microseconds to 25 microseconds.

The reduction in crest value of the slow wave was from 124 kv. to 102 kv., a reduction of 18 per cent.

The oscillograms taken at Towers 30 and 50 (Plate III) show the effect of the reflection from the cable on the incident wave. Of course as the oscillograph location approaches the end of the cable the reflections approach the front of the incoming wave. Oscillogram C-29-2, taken at Tower 30, shows the reflection returning from the cable about 24 microseconds from the beginning of the incident wave.

The magnitude of the reflected wave is about 50 kv. At Tower 50 the reflected wave is nearer the crest of the incident wave.

The medium and slow waves show reflections which are similar to those of the steep wave.

*Wave-Shape on Line Beyond Cable.* There was no distinguishable change in wave-shape along the line after the wave passed through the cable. The oscillograms taken beyond the cable at Towers 55, 58, and 67 are similar for the three waves. The rate at which the voltage builds up in the cable by successive reflections is shown most clearly by oscillogram C-25-15 at Tower 58.

*Plate IV. Effect of Bus Between Cable Sections.* For the steep wave low-voltage condition, a comparison of the two cases where a 1000-ft. section or two 500-ft. sections is inserted in the line, shows that with the incident wave of 92 kv. and a front of 8 microseconds, the 1000-ft. section reduces the crest voltage to 66 kv., while with the two 500-ft. sections, the crest is 71 kv. For this test the two 500-ft. sections of cable were connected together by a short jumper about 20 ft. in length. In general, the 1000-ft. section and the two 500-ft. sections have practically the same influence on the wave. The only apparent difference in the shape of the two waves is in the oscillations which appear at the front of the wave (C-40-2 and C-46-18).

Oscillogram C-41-4 which shows the wave-shape at the junction of the two cable sections, indicates that voltage conditions at this point are almost identical with the conditions at the ends of the combined sections. As may be noted, the wave at the start of the cable is practically identical with the wave at the finish of the cable on both the 1000-ft. and the two 500-ft. cable sections.

The third group of oscillograms on Plate IV were taken with a set-up consisting of two 500-ft. sections of cable connected together through a 500-ft. section of

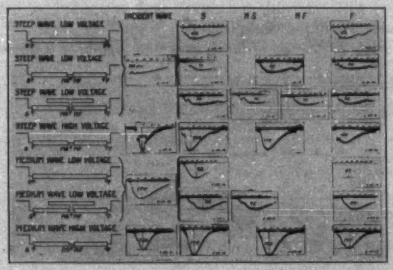


PLATE IV. EFFECT OF BUS BETWEEN CABLE SECTIONS

overhead line to simulate a station bus. The shape of the wave was altered at each end of the first section of cable by reflections from the second section which cut into the front of the wave and caused it to drop momentarily.

The crest values of voltage 70 to 72 kv. measured at the four positions with two sections of cable and a section of bus between, have approximately the same value at all of the positions. This value of crest voltage is practically the same as that for the 1000-ft. length, which is 66 to 70 kv.

*Steep Wave High Voltage.* The results in this case were similar to the ones discussed for the steep wave, low-voltage. When high voltages were applied to two 500-ft. sections of cable the oscillograms showed essentially the same magnitude and wave-shape at the start, the junction, and the finish of the two cable sections. The principal difference in the wave-shape at these points was a variation in the phase relations between the fundamental and an oscillation which appears on the wave-front.

By inserting the 1000-ft. length of cable in the line, the crest voltage was reduced from 225 kv. to 120 kv.,

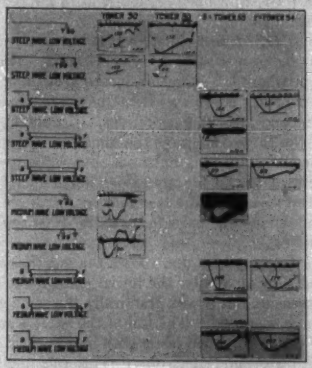

Plate V. Effect of Terminal Conditions

which is 53 per cent. The wave-front also was changed from 8 microseconds to 15 microseconds. This case is to be compared with the steep wave low-voltage case. It will be noted that the change occurring in the wave-front is slightly different for the two cases. In the case of the high-voltage wave, the section at approximately crest value is very short, and the decay is very rapid. As a result, the incident voltage begins to drop before the voltage in the cable has had sufficient time to build up to its ultimate value. The low-voltage wave had a much longer duration at approximately crest value. Hence the voltage in the cable has a longer time to build up to its crest value before the incident wave begins its rapid decay. For this reason the reduction in crest voltage was greater for the high-voltage wave than for the low-voltage wave.

*Medium Wave, Low Voltage.* The bus between the cable sections had the same general effect as was found with the steep wave, although the reflections were not as pronounced. The relations between crest voltages at the various points were similar to those found on the steep wave tests.

*Medium Wave, High Voltage.* When the medium wave, high voltage was applied to the two sections of cable with no bus between, the wave-front of the resultant wave had an 18-microsecond front as compared with 10 microseconds for the incident wave. The crest voltage was reduced from 233 kv. to 146 kv., a reduction of 37.2 per cent.

*Plate V. Effect of Terminal Conditions.* In Plate V oscillograms are shown for a variety of terminal conditions, with and without the 500-ft. length of cable in circuit.

With line open and with it connected to ground the reflections both with the steep wave and with the medium wave are clearly defined. With the line open the reflection adds, while with the line closed to ground the reflection subtracts.

*Ground at "F."* The ground at *F* on the cable conductor holds the voltage at both ends to a low value. With the steep wave, the initial rise in voltage (13 kv.) and two reflections were measured.

*Line to Cable to Line, and Line to Cable (Low Voltage).* Comparing the conditions where a line is open to the case where the line is connected to a cable, the far end of the cable being open, we find that the cable has reduced the crest voltage from 170 kv. to 132 kv., a reduction of 22.3 per cent. By having the cable inserted between two sections of line the voltage is reduced to 80 kv.

The medium wave tests show the voltage of the line-cable condition 70 per cent higher than that of the line-cable-line condition. Oscillogram C-39-12 shows a chopped wave resulting from an accidental arc-over of one of the leads to the cable pot-head.

*Plate VI. Terminal Conditions with 1000-Ft. Cable.* Oscillogram C-28-18 with the steep wave shows the incident wave and the reflections at Tower 30, which was about 2.3 miles from the start of the cable. For

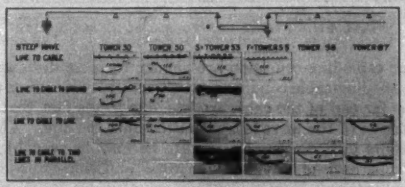


Plate VI. Terminal Conditions with 1000 Ft. Cable

the first 25-microseconds the wave was unaffected by reflections and corresponds to the incident wave. At 25 microseconds a negative reflection with respect to the incident wave comes back as a result of the incident wave passing into the cable which is of lower surge impedance than that of the line. The voltage then remains almost constant for about 3 microseconds, which represents the time required for the wave to pass through the cable and be reflected to double voltage. The sudden rise in voltage at 33 microseconds is due to the first reflection from the far end of the cable. The

voltage then continues to rise by steps as the wave reflects back and forth in the cable, approaching its maximum value. The second of this series of steps occurs at 37 microseconds. The oscillograms taken at Towers 50, 53, and 55 show the same effect as that shown in the oscillograms previously discussed, the only difference being in the time relation between the incident wave and the reflections.

It may be seen that the voltage at the far end of the cable for the line-cable condition was 110 kv. or 120 per cent of the incident wave, which was 92 kv., as seen from Plate I. The voltage did not rise to twice the value of the incident wave because the incident wave was of relatively short length. The decay of voltage on the tail of the wave was at approximately the same rate as the build-up of voltage through the cable.

The medium wave and the slow wave which are reproduced here showed similar behavior except that the reflections are not as well defined.

*Line to Cable to Line.* The oscillograms shown in the

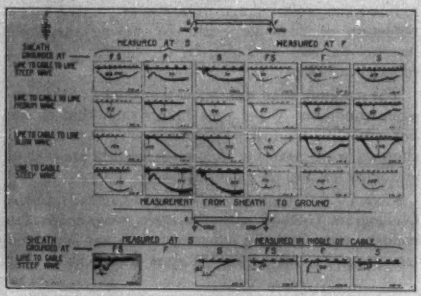


Plate VII. Effect of Grounds on Cable Sheath

line-cable-line condition are similar to those discussed in the line-cable condition except that the reflections at the far end of the cable are less, due to the fact that a portion of the wave is transmitted onto the line. This results in a decrease in voltage as may be seen by a comparison of the line to cable and line-cable-line conditions at Tower 55 (steep wave) which shows the voltage to be 110 kv. for the line-cable condition as compared to 66-70 kv. for the line-cable-line condition, a reduction of 40 per cent. Comparison of corresponding oscillograms for the medium and slow waves shows similar behavior, the reduction being 40 per cent for the medium wave, and 39 per cent for the slow wave.

Waves measured at Towers 58 and 67, beyond the cable, give essentially the same wave-shapes as those at the far end of the cable.

It may be seen at the start end of the cable that the steep wave reaches its crest in 25 to 30 microseconds for the line-cable line condition.

*Line to Cable to Ground.* Waves recorded for the line to cable to ground condition are identical to those of the line to cable condition up to the time of the first reflection from the far end of the cable. This reflection comes back negative (with respect to the incident wave) instead of positive. The result was an oscillation in the cable as is shown on oscillogram C-24-3. The first rise in voltage goes to 26 kv. followed by seven reflections which are readable on the original film.

*Line to Cable to Two Lines in Parallel.* The difference in shape of the wave with two lines in parallel when compared to one line, is too small to be detected on the oscillograms. The voltage was lowered from 70 to 60 kv. (Plate VI) which is a reduction of 14 per cent when measured at *F*.

*Plate VII. Effect of Grounds on Cable Sheath. Voltage Between Conductor and Ground.* The only condition where the variation in the grounding of the sheath had any effect was with the steep wave, line-cable-line and line-cable conditions. Grounding at the start of the cable only, gave the same result as grounds at both the start and finish of the cable, whereas grounding at the finish only gave a much higher initial rise in the voltage at the beginning of the wave. The final wave-shape was the same as in the other conditions of grounding.

*Sheath to Ground Voltage.* With the sheath grounded at *F* and *S* or at *S* only, the initial voltage rise on the sheath measured at *S* was practically the same when a steep wave was used. The tail of the wave was lower and the voltage dropped faster with both ends grounded than with a ground at *S* only. This was due to the lower resistance of the two cable sheath grounds in parallel. The voltage which appears at *S*, when *S* is grounded, is due to ground resistance.

Measurements made at the middle of the sheath to ground show very little difference in the voltage to ground when *F* and *S* are both grounded over the case where *S* only is grounded. The measured voltages were essentially the same, being 13 and 14 kv.

With a ground at *F* only, the initial voltage rise was 40 kv. However, the duration of the wave was nearly the same as for the grounding conditions previously discussed.

It may be noted that the duration of the wave when measured at the middle of the cable sheath was much shorter than when measured at *S*. It may be noted that the measurements made in the middle of the cable were made with a capacity divider.

*Plate VIII. Lightning Arresters.* In these tests the lightning arresters were composed of a gap in series with a water tube resistance which was connected between the cable conductor and the sheath. Both the gap settings and the resistances were varied during these tests, thus making calculations possible for an arrester having any value of resistance.

*Resistance.* When a gap with no series resistance was placed between the conductor and sheath, spark-over of the gap started an oscillation in the cable, the fre-

quency of which was determined by the constants of the cable (C-23-18).

With the arrester at $F$ and measurements at $S$, the reduction in voltage due to the arrester takes place 3 microseconds later than for the case where the arrester was at $S$. (C-19-2 and 12.)

With the arrester at $S$, the wave which passed the

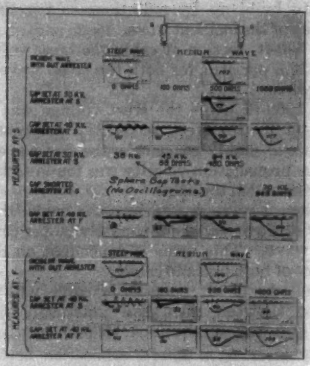

Plate VIII. Lightning Arresters

arrester was reflected when it reached the open end of the cable, as is shown in C-20-16. The increase in voltage over the gap setting was 15 kv.

*Plate IX. Lightning Arresters, Wave Along Line.*

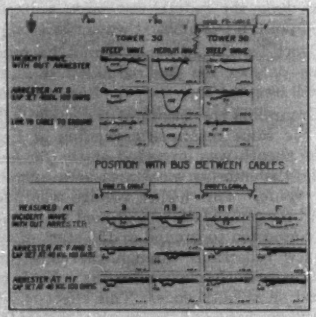

Plate IX. Lightning Arresters, Wave Along Line

It will be seen that the reflections with the arrester are intermediate between the conditions with no arrester and with a low resistance ground at the cable end. The degree of similarity with one or the other condition depends on the arrester resistance.

*Condition with Bus Between Cables.* For this condition the voltage at both ends of the first section of cable was 6 to 7 kv. higher than the arrester gap setting, while the voltage at the start of the second section, at the arrester location, was practically the same as the gap setting. This increase in voltage at points distant from the arrester can be explained for the first section as due to the increase in voltage taking place before the wave of reduction returns from the arrester.

## Theoretical Discussion

*Calculation of the Wave Shape.* To calculate the effect that the 1000-ft. length of cable would have on one of the waves and to check the actual oscillograms taken, the following graphical method was used:

The equations for the waves at a transition point are:

Incident wave: $e$ = value at time $t$.

Reflected wave: $$e' = e\,\frac{1 - \dfrac{Z_1}{Z_2}}{1 + \dfrac{Z_1}{Z_2}}$$

Transmitted wave: $$e'' = e\,\frac{2}{1 + \dfrac{Z_1}{Z_2}}$$

The impedance of the transmission line is taken as

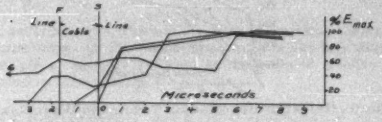


Fig. 5—Graphical Solution of Traveling Wave-Shape

approximately 620 ohms, and that of the cable as 103 ohms or 1/6 that of the line, which gives:

$e' = -\ 5/7\ e$ for Line to Cable.
$e' = \ \ 5/7\ e$ for Cable to Line.
$e'' = \ \ 2/7\ e$ for Line to Cable.
$e'' = 1\ 5/7\ e$ for Cable to Line.

The steep wave as shown by Oscillogram C-27-8 Plate I, is approximately shown by a straight line from zero to 70 per cent in one microsecond, a straight line from 70 per cent to 100 per cent in 6 microseconds, and from 100 per cent to 68 per cent in 23 microseconds. Being measured on a continuous line and neglecting attenuation, this is also the space wave incident to the cable.

The length of time for a point on the wave to travel from one end of the cable to the other is $1\frac{2}{3}$ microseconds in space. For the transmission line 1000 ft. is represented by 1 microsecond. In Fig. 5 space waves are shown for various intervals in microseconds after the incident wave has reached the cable, each interval being chosen so that sudden changes at places to be measured will show in the final curves. Each space

wave is made up graphically by drawing the reflected waves with the transmitted wave and adding them together. This becomes a very laborious process after a few reflections have passed back and forth through the cable.

From these space waves curves showing voltage with time can be taken at any point on the line. Fig. 6 shows such curves for positions at the start end of the cable *S*, the finish end of the cable *F*, and for Tower 50. Comparing these curves with the actual oscillograms C-22-14, C-22-8, and C-27-2 as shown on Plate III, the shapes of the waves agree. C-25-15 Plate III, is probably a better picture of what happens at *F*, being only 1500 ft. from *F* and more nearly agrees with the calculated curves. The reduction in voltage shows from 24 per cent to 28 per cent for the oscillograms and 12 per cent for the calculated values. The time for the voltages to reach crest value agrees.

## Summary of Results and Conclusions

1. There was no appreciable change in wave-shape with distance for the section of line used. The crest voltage of the waves were close to the critical corona voltage of the line. Hence no great attenuation of crest voltage appears, and very little change in the wave-front. The distance covered by measurement with sphere-gaps and oscillograms was 3.7 miles.

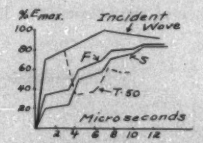


Fig. 6—Graphical Solution of Traveling Wave Shape

2. Attenuation of crest voltage was small. In traveling 3.68 miles the steep wave was reduced 15.5 per cent, and the medium wave was reduced 14.7 per cent.

3. High-frequency oscillations which appear on the front of a steep wave are damped as the wave travels along the line.

4. A wave having a front whose length is short compared to the time required for the voltage to build up in the cable, will be less steep after passing through a cable.

5. The amount of change in wave-front for a wave passing through a cable will depend on:

(a) The steepness of the wave-front.

(b) The length of the crest or near crest of the wave.

(c) The length of the cable.

(d) The values of surge impedance for line and cable.

For a 500-ft. cable the 8-50* wave was changed from an 8-microsecond front to a 12-microsecond front when entering the cable from the line.

For a 1000-ft. cable the 8-50 wave was changed from an 8-microsecond front to a 24-microsecond front when entering the cable from the line.

6. A wave passing through a section of cable will have its crest value reduced unless the wave has a flat top long enough to cover the time required for the cable voltage to build up by reflections to practically the crest value of the incident wave.

For a 500-ft. section of cable the crest voltage was reduced 10.8 per cent for both the steep wave and the medium wave.

For a 1000-ft. cable the crest voltage was reduced 24 per cent for the steep wave, 23.3 per cent for the medium wave, and 17 per cent for the slow wave.

7. The propagation velocity was found to be 600 ft. per microsecond in the cable.

8. When a wave passed into the cable, the initial transmitted wave was approximately 30 per cent of the incident wave. This value is dependent on the surge impedance of both line and cable.

9. The two 500-ft. lengths of cable with a short connection between them had practically the same influence on a wave as the single 1000-ft. length of cable.

10. By inserting a 500-ft. connection between the two sections of cable an oscillation was introduced on the front of the wave passing through the cables. The crest voltages were unchanged by this addition.

11. A short section of cable acts like a concentrated capacity at the open end of a line or at an intermediate point in a line, provided the length of the wave-front is long when compared to the time required for the wave to be reflected through the cable. Such a cable or capacitor does not reduce the surge voltage at the connected point if the incident wave has a long flat top.

12. Short lengths of cable cannot be regarded as protective devices for the reduction of overvoltage surges with long flat tops such as often occur in service.

13. Grounding the sheath of the cable at the start *S* gives the same result as grounding at both ends. When the sheath was grounded at the far end of the cable only, the entering wave, measured to ground, had a higher value. This higher voltage was due to the potential between sheath and ground when the sheath was not connected to ground at the start of the cable. After a few reflections through the cable, the wave assumes the same shape whether the cable is grounded at one end or at both ends. This effect is dependent upon the wave-shape and the length of the cable.

14. A traveling wave in a section of cable may be calculated graphically, if the incident wave is given, and the calculated wave will check the measured waves closely.

15. Arrester operation for any type of arrester may be calculated from the volt-ampere curves obtained under similar conditions.

*Rises to 8 microseconds and decays to half value in 50 microseconds.

16. The increase in voltage at the other end of the cable from the arrester location was about 15 kv. This increase depends upon the steepness of the wave and the length of the cable, and may be estimated for any specific case.

The authors wish to express their appreciation to Messrs. E. J. Wade, W. J. Rudge, F. Osgerby, and J. R. Eaton, of the cooperating companies who conducted the field tests and furnished valuable assistance in preparing the paper.

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## Discussion

**H. Halperin and K. W. Miller:** About a year ago the question of surges entering cable from an overhead line arose in connection with the installation of 3300 circuit ft. of 132-kv. single-conductor oil-filled cable. The cable was to be on the end of a forty mile transmission line with 2000 ft. more of overhead line between the cable and the station transformer terminal. Careful theoretical study was given to this problem and the following conclusions were reached:

1. Assuming the cable is perfectly grounded, any incoming surge would be immediately reduced at the cable pothead by an amount corresponding to the standard formulas for surges at a point of change of surge impedance in a line.

2. If the cable, or the entrance end of the cable, were not grounded, the potential of the sheath would rise in such a way that the surge voltage across the cable insulation would be in the ratio of the surge impedance of the cable (conductor to sheath) to the surge impedance of the cable conductor to earth (sheath assumed absent), which is again a great reduction.

3. Intermediate grounding would produce effects intermediate between Items No. 1 and No. 2, but always produce a large immediate reduction of voltage on entrance in accordance with the accepted surge impedance ratio theories.

4. After the surge enters the cable the voltage will build up by reflections in accordance with theory.

5. Except for attenuation effects (which would probably be comparatively small at the reduced voltages with oil-filled cables of high insulation, leakage resistance, and little or no ionization equivalent to corona) the surge voltages produced at all points of the cable would be about equal, and, therefore, there is no useful purpose served in over-insulating the one or two cable lengths adjacent to the potheads.

It is gratifying to read of the carefully conducted experiments of the authors, which substantiate these conclusions based on standard theories.

It is interesting to note the several different values of surge impedance of the test cable which was obtained by the authors from the various methods of measurement. We believe this is due to the fact that the cable sheath cannot be considered as "perfectly" grounded during surges, and, therefore, the actual cable surge impedance lies somewhere between the values obtained from Items No. 1 and No. 2 above, which, in general, are different numerically.

Lastly, it is apparent that the final reduced value of an incoming line surge, including the effects of reflections, will be roughly proportional to the ratio of cable to overhead line surge impedance and inversely proportional to the cable length. For high voltage cables the surge impedance will be about one-half that of the small test cable used by the authors, and the length will ordinarily be from 3000 to 75,000 ft.; so that the final cable voltage will usually be a much smaller fraction of the incoming surge than that found in the authors' tests.

With judicious use of arresters there does not appear to be any excessive danger to the cable in such installations. In some cases, especially for the extra high voltage installations with lengths of underground cable equal to or greater than the length of the surge, arresters appear unnecessary at the junction of the overhead and underground lines. Regarding direct strokes at the junction, which would be very rare, arresters would probably be of little value.

**H. G. Brinton:** From a theoretical standpoint the effect of a short length of cable is best determined by considering a long rectangular traveling wave. Any other wave shape may be considered as the superposition of a number of rectangular waves.

Considering first the case of an incoming wave $E_1$ on a line of surge impedance $Z_1$ passing into a cable $Z_2$ with no outgoing line connected at the far end. The first wave entering the cable is

$$E_1 \frac{2 Z_2}{Z_1 + Z_2}$$

This wave is totally reflected at the far end of the cable, doubling the voltage. When the reflected wave reaches the junction with the overhead line, a second wave enters the cable which is $\frac{Z_1 - Z_2}{Z_1 + Z_2}$ times the first entering wave. Similarly there is a third entering wave which is the same factor times the second entering wave, or the factor squared times the first entering wave, etc. Therefore the sum of the series of entering and reflected waves is given by the formula

$$E_2 = 2 E_1 \frac{2 Z_2}{Z_1 + Z_2} \left[ 1 + \left( \frac{Z_1 - Z_2}{Z_1 + Z_2} \right) + \left( \frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2 + \text{etc.} \right]$$

Comparing this equation with

$$\frac{1}{1 - b} = 1 + b + b^2 + b^3 + \text{etc.}$$

we see that for a wave $E_1$ of infinite length

$$E_2 = 2 E_1 \frac{2 Z_2}{Z_1 + Z_2} \frac{1}{1 - \frac{Z_1 - Z_2}{Z_1 + Z_2}} = 2 E_1$$

If the wave $E_1$ is long compared with the cable length, the maximum value of $E_2$ will approach $2 E_1$ but if the wave $E_1$ is comparatively short $E_2$ will be considerably less than $E_1$ as there will be only a few terms of the above series to be considered. However, in practise it is necessary to consider waves with long flat tops as well as short waves.

Considering next the case of an outgoing line $Z_3$ at the far end of the cable. The first entering wave is the same as before. The reflected wave starting at $Z_2$ is equal to the factor $\frac{Z_2 - Z_3}{Z_2 + Z_3}$ times the entering wave and the factor giving the sum of the entering and reflected wave is $\left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3}\right)$. Each enter-

ing wave (except the first) is equal to $\left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\,\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)$ times the preceding entering wave. Therefore the formula for $E_2$ is

$$E_2 = E_1 \frac{2\,Z_2}{Z_1 + Z_2}\left(1 + \frac{Z_2 - Z_1}{Z_2 + Z_1}\right)\left[1 + \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\,\frac{Z_1 - Z_2}{Z_1 + Z_2}\right) + \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\,\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 + \text{etc.}\right]$$

For an infinitely long wave $E_1$ the maximum value of $E_2$ is (at far end of cable at junction with $Z_1$, $E_2 = E_3$)

$$E_2 = E_3 = \frac{2}{1 + \frac{Z_1}{Z_2}}\,E_1$$

This is equal to $2\,E_1$ when $Z_2$ is infinity as in the first case considered, and is equal to $E_1$ when $Z_2 = Z_1$ but is independent of the value of $Z_3$. Thus we see that for a long flat topped wave the passing of the wave through a short length of cable slopes off the wave front but does not decrease the maximum potential of the wave. This statement also holds for wave of sloping front and long flat top because they can be considered as the superposition of a number of rectangular waves.

**L. V. Bewley:** The principal difficulty in computing the effect of short lengths of cable inserted in a transmission line circuit, is to keep track of the multiplicity of reflections which occur at the junctions. I have prepared a paper, to be presented at the Pacific Coast Convention, in which a lattice is described which is uniquely adapted to the solution of such problems in multiple reflection of traveling waves. As an example of its use consider the case of Plate IX in the author's paper, where two short lengths of cable (500 ft.) separated by a short length of line (also 500 ft.) are inserted in the circuit. Let

| Line | | Cable |
|---|---|---|
| $Z_1$ | Surge impedance | $Z_2$ |
| $v_1$ | Velocity of propagation | $v_2$ |
| $L_1$ | Length of section | $L_2$ |
| $T_1 = L_1/v_1$ | Time of transit | $T_2 = L_2/v_2$ |
| $\alpha$ | Attenuation of section | $\beta$ |
| $-a = \frac{Z_2 - Z_1}{Z_2 + Z_1}$ | Reflection operator | $a = \frac{Z_1 - Z_2}{Z_1 + Z_2}$ |
| $b = \frac{2\,Z_2}{Z_2 + Z_1}$ | Refraction operator | $c = \frac{2\,Z_1}{Z_1 + Z_2}$ |

Now, if the distortion of wave shape due to losses be neglected, then all reflected and transmitted waves have identically the same shape, but differ in magnitude due to attenuation and division at the junction. Referring to the lattice shown in the figure of this discussion, the following facts are evident:

1. All incident, reflected and transmitted waves are traveling "down hill," so that
2. The vertical time scale at the left of the lattice shows the time of arrival of all waves at all junctions.
3. The length of each line or cable section is given in terms of the times $T_1$ and $T_2$ that it takes a wave to travel over the section at its velocity of propagation $v_1$ or $v_2$. A time axis of length is preferable to a distance axis, because it preserves the slope of the diagonals in the lattice, and thereby avoids considerable interference.
4. Waves on a line section suffer an attenuation ($\alpha$).
5. Waves on a cable section suffer an attenuation ($\beta$).
6. Waves reflect from a line-cable junction by a fraction ($-a$).
7. Waves reflect from a cable-line junction by a fraction ($a$).
8. Waves transmit across a line-cable junction by a fraction ($b$).
9. Waves transmit across a cable-line junction by a fraction ($c$).
10. The lattice "converges" to a constant density of diagonals.
11. The total voltage at any junction at any time is obtained by superimposing all waves on one side of that junction, displaced from each other by the time lag representing their instants of arrival at the junction.

Equations for the total voltage at each junction, as function of time, are given on the lattice. In these equations $f(t)$ is the shape of the initial incident wave arriving at junction $A$, and $f(t - T)$ represents exactly this same wave arriving at any junction an instant $T$ later. However, each of these functions are multiplied by some fraction involving the reflection and refraction operators $a$, $b$, $c$.

As an example of how the waves are added, the first three waves arriving at junction $A$ are shown superimposed at their proper time intervals at the bottom of the figure.

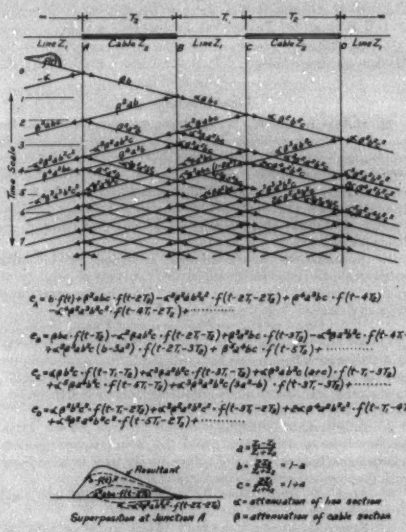


FIG. 1

It is obvious that it soon becomes impracticable to show all the coefficients directly on the lattice itself, but this disadvantage can be circumvented by numbering the arms of the lattice, and computing the actual coefficients in a table. In fact, it is usually possible to devise tabular methods (with the lattice as a basis) in which the procedure is automatic.

The scheme does not take into account the distortion which the waves experience as they travel along the circuit.

The lattice may be applied to complex junctions, including combinations of inductance and capacitance, but in such cases the reflection and refraction coefficients become operational expressions involving the time derivative ($d/d\,t$).

**C. Francis Harding:** Three distinct and most valuable contributions to the understanding of extra high voltage phenomena have been presented in this paper:

1. The cathode-ray oscillograph, particularly that operating

upon the hot-cathode principle developed by Mr. R. H. George of Purdue University has been thoroughly tried out and found to be not only dependable but practically irreplaceable as an instrument for either laboratory or field investigations of extra high voltage surges which have a duration of from one to 100 microseconds. Previous investigations making use of this same type of oscillograph considered in conjunction with the disclosures of this paper demonstrate its practicability for reproducing with accurate calibration the magnitude of such potentials and the time of duration of steep-wave-front surges whether of natural lightning or of those initiated by means of a lightning surge generator.

2. The theoretical calculations of the attenuation and reflection of steep-wave impulses, which in the past have been made with some doubt regarding the accuracy of the assumptions necessary for a concrete solution, have now been definitely confirmed by practical test values. The calculations of the past therefore take on more authenticity, and those of the future, although rendered less necessary than before, will be undertaken with more confidence.

3. The practicability of predetermining the constants of inductive reactance and equivalent resistance necessary to produce surges of desired wave-fronts and duration, duplicating typical lightning exposures, and the readiness with which such impulses are repeated time and time again with the surge generator for comparative testing purposes in the field are now well established.

With these possibilities demonstrated, it should not be long before surge tests of transmission lines and cables, insulation, lightning arresters, etc., may be more accurately standardized and their laboratory tests more readily duplicated.

Unfortunately, we are still dependent upon the rather unsatisfactory standard making use of the sphere-gap for high voltage measurement. Particularly with small spheres and steep-wave-fronts of relatively low voltages, such as from one to fifty kilovolts, such instruments are too variable for use as standards. This is especially true for use in the field where preionization of the gap is not always practicable.

The writer has found in the high-voltage laboratory of Purdue University, for example, that in the sphere-gap measurement of such ranges of potential of steep waves, impressed upon a circuit by the lightning generator, several experienced investigators may introduce a personal error of from fifteen to twenty-five per cent if the gap is not preionized and artificially ventilated, whereas the addition of such precautions would reduce the error of six such observers to within two per cent.

Although the relative values set forth in this paper did not require a high degree of accuracy, the statement that small sphere-gaps were used for some measurements raised a question which should be given careful consideration in subsequent laboratory testing, particularly in the standardization of extra high voltage measurements and their application to lightning arresters, insulators, etc., which are to be subjected to surge potential exposures.

**K. B. McEachron:** It is interesting to note the agreement which Messrs. Halperin and Miller find between their calculations and the field tests. Their conclusion that the final value of the incoming surge will be roughly proportional to the ratio of cable to overhead line surge impedance and inversely proportional to the cable length is true for a given length of incoming surge. It is, however, apparent that the ratio of surge length to cable length is important; the greater this ratio the higher the cable voltage will be. Thus with very long transients the cable potential may finally equal the incoming surge potential.

The lattice which Mr. Bewley describes is useful when calculating the effect of reflections at transition points, and should help to simplify the rather laborious process of calculating reflections of traveling waves.

Professor Harding is rather more pessimistic about the accuracy of sphere gap measurements than our experience indicates. A rather wide experience with gaps has demonstrated to us that cleaning the electrodes frequently will give reasonably constant results with better consistency than indicated by Professor Harding.

**H. P. Seelye:** The method indicated in this paper of making a graphical analysis of the passage of a lightning surge through a short section of cable is of practical value in studying many other cases of a similar nature. For example, it has been used in investigating the effect of short lengths of ground wire and of both ground wire and cable at the station end of a line.

The application of this method, although involving some complications in the multiplicity of reflections involved, as pointed out by Mr. Bewley, is relatively simple in theory and not unduly difficult to carry out.

It has the advantage over the use of a rectangular wave in that the wave with sloping front and finite tail more nearly simulates the actual lightning wave. The slope of the front, height of crest and length may be chosen to best fit the conditions of the problem, *i. e.*, to show the worst condition, the average condition, a wave chopped by lightning arresters, or any other variation. Since the field test proved the accuracy of the underlying assumptions and theory, the results of such a study may be depended upon as a true picture of the actual action of the wave chosen.

# Dancing Conductors

BY A. E. DAVISON*

Associate, A. I. E. E.

***Synopsis.***—*The phenomenon of dancing cables is discussed; the merits of different theories are considered, reference being made to the theory that vibrations of small amplitude, but relatively high frequency, travel along the line to points where the constants of the line change as at dead-ending insulators and there reflect and combine into slower waves of great amplitude. The suggestion is made that much experimental work should be done with regard to these theories before drawing any definite conclusions.*

*Reference is made to Magnus effect and to the "lift" of ice-coated cables in wind storms. This lift, perpendicular to the direction of the wind, is carefully considered, and diagrams show experimental values of this lift on models similar to the ice-coated cables. The diagrams indicate variations and reversals of this thrust due to small changes of angle of the specimen to the direction of the wind. The suggestion is made that these alternate lifting and depressing effects should be considered as the cause of some, if not a large percentage, of the phenomenal movements of ice-coated conductors in relatively light winds.*

*As in most earlier reports and discussions there does not seem to be any remedy as a result of this study, other than that of heating the conductor electrically throughout sleet-forming periods to such a temperature that the sleet cannot form on the wires.*

## Introduction

DANCING or galloping conductors have been recognized and studied for a number of years. The problem is mechanical, but it is of great interest to electrical engineers. The phenomenon commands attention because of the serious outages and resulting damages and losses which it is liable to cause. With the exception of earthquakes and holocausts, it is, in the opinion of some, the most serious although not the most frequent cause of outages on important transmission lines. When the phenomenon occurs, the cable span oscillates sometimes as a whole, but more frequently with one or more nodes in a span. It is frequently described as whipping, jumping, floating, dancing, or galloping. When the oscillations become severe, the cables will move irregularly, but freely, through vertical distances of as much as 20 to 25 ft. in spans of 500 ft. An elliptical motion with longer axis of the ellipse vertical is usually observed as the motion of a point on the cable with the result that at any moment two wires of a circuit may come in contact, especially if there is vertical configuration of the conductors. Furthermore, even if the conductors do not come in contact electrically, the movement is sometimes sufficient to tear the cables from the fastenings. Mechanical failures may not always occur; however, if the weather conditions continue for any length of time, the movements are liable to cause such deterioration and loosening of the structures and fastenings that it is necessary to overhaul the whole section of the line affected.

The phenomenon cannot be observed every day, nor can it be seen at any specific place; it appears and disappears suddenly and we have good reason to believe that weather conditions may account for most of the trouble. The difficulty of being "on the spot" when galloping occurs may account for the small amount of accurate data and observations on which we have to work. Few indeed who have studied the phenomenon have ever seen it more than once. It is therefore necessary that the transmission engineer arrange laboratory equipment by which the condition may be reproduced at will, after which he can set himself the task of devising a remedy.

## Review of Theoretical Considerations and Published Data

Attempts have frequently been made to connect this galloping with the minor vibrations which are always or nearly always present in catenaries, especially during very light winds (four miles per hour) and presumably during rising temperatures. It is argued by some that these accumulate in the vicinity of dead-ends, or other changes in the characteristics of the line. By reflection, or other condition, amplitude and wavelength are multiplied many times and finally with many irregular movements they break up by doing work upon the fastenings.

Varney[1] has familiarized engineers with these small vibrations (a sort of resonance condition) while making studies to reduce the effects which these smaller vibrations have upon the conductors at clamps and other points where the mechanical constants change.

Knowlton[2] discusses the application of Magnus theory as accounting for these smaller vibrations much as it is used herein to account for the irregular movements of greater magnitudes.

Semenza is credited with having first advanced a quite different theory that these smaller motions (sometimes called the natural or fundamental vibration of a line) are caused by longitudinal mechanical pulsations put into the line by changes in the mechanical tensions due to the swinging of the cables in light winds.

A span may be swinging at some relatively slow angular velocity during each cycle of which there are changes of tension in that particular span. The local tension is a maximum near the lowest point of the swing and least, reaching almost zero, when the motion

*Transmission Eng., Hydro-Electric Power Commission of Ontario, Toronto, Ont., Can.

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1. For references see Bibliography.

reverses, especially if the arc of the swing should become greater than 180 deg. These alternate increments and decrements of tension send out into adjoining spans pulses of varying frequencies depending upon such physical conditions as length of spans, wind velocities, and temperatures.

When several groups of these mechanical pulses are transmitted the increments and decrements of tension are in some cases counteracted and in other cases they combine to give rise to a resultant well-defined wave of tension. The question of how much damping occurs during this process of combination and eliminations to give the resultant natural frequency wave has not been studied but if, as some appear to believe, this tension wave can travel along the line without much loss of energy, then it may travel great distances. Semenza may not have carried the idea further. However, if the frequency of this wave be the natural frequency of one of the spans through which it passes, then it is conceivable that this span will respond to this high frequency and start oscillating as a whole or with only one or two nodes at much lower frequency.

Darling[3] accounts for a particular case which was on a wood pole line, by assuming that the swaying of the poles in the wind caused the trouble and that the remedy was therefore to brace the poles in the direction of the line.

Hawley[4] discusses an interesting case which he saw near a railroad. He thinks that the direction of the wind in relation to the direction of the line is important, as only those spans running diagonally with the wind were dancing. The motion was mainly vertical. He suggests that in practically all cases two or more adjacent spans were jumping. The exceptional feature was that the temperature was well above freezing and there was a "pulsating" wind blowing. He is definitely of the opinion that the energy was supplied by horizontal air movements upon conductors having uniform surface throughout the circumference. He seems of the opinion that the pulse of wind striking first one span and then the next was the cause of the motion.

Sothman[5] goes so far as to assume a critical temperature in the cable and considers the ice to function as insulating covering. He later lays great emphasis on a critical tension as being the cause of dancing and also does not regard an ice-coating as essential. Electrical causes such as surges are also discussed in his letter. Surges undoubtedly do cause abnormal movements. He calls attention analogously to the uplift in underground cables due to electrical causes throwing cables six inches out of the ground after some months of operation.

Another suggested cause of dancing is the vibration caused by railway trains or other like jarring movements, such as power generating plants or manufacturing plants connected with the wires. Causes of this type are discussed by Ferrier and Haussadis[6] and by Archbold.[7] Extraordinary movements may be started by gusts of wind actually lifting parts of a span or by large pieces of melting ice falling from a cable. Movements of this sort, as well as those resulting from electrical surges, are not usually sustained and repeated many times. Such conditions may be familiar to observers and are consistent with the effects which might be expected from abnormal atmospheric or other disturbances. These conditions are, however, well out of mind when the observer is watching "galloping" conductors. Quite another set of conditions is evident and happenings are phenomenal.

Many of the suggestions and theoretical considerations reviewed above regarding causes and effects have merit and it is not intended that efforts should be abandoned to connect up the small rapid vibrations with boisterous galloping, which is almost sure to cause short circuits and grounds and even do mechanical damage to structures. Standing waves and almost every sort of odd and exaggerated performance may be observed in 100 ft. or so of a light rope or line, supported at intervals by vertical strings comparable to suspension insulators, when very small mechanical impulses are put into the line at one end, the other end being fixed. These vibrations can be introduced quite effectually as the result of either longitudinal or transverse impulses. The latter especially require very little effort. As a result of this review of data, it becomes evident that no theory has yet been found by which the accumulation of small vibrations into galloping can be substantiated by calculations and experiment. This may, however, be done later by the use of satisfying assumptions, and through further experiments and supporting calculations. Further work along this line will doubtless be quite profitable and it is not intended that any suggestion or result recorded in this paper should in any way check further study and development of these ideas.

## Comparative Study of Phenomenal Movements

In the meantime, two instances of extraordinary movements of conductors were reported by E. G. Archer of the Hydro-Electric Power Commission during the latter part of 1927, one at Whitby and one at Niagara Falls. The case at Whitby showed violent swinging. The temperature was well above 60 deg. fahr. and there was a gale. Conditions were evidently quite similar to those which Haussadis had in mind.

At Niagara Falls, with a wind of approximately 30 mi. per hour blowing nearly at right angles to the line and accompanied by a fine sleet, a condition was observed which was so peculiar that it commanded attention. Two tower lines supported one circuit each and a third tower line carried two circuits. All cables were supported by suspension insulators and the tower lines paralleled one another closely. One circuit on a single-tower line and one of the circuits on the double-circuit line were dancing. The other circuit on the double-circuit line had been reported as dancing earlier in the day but had stopped. The dancing was localized

to one span and the motions did not appear to be transmitted to the adjacent spans. The suspension insulators were not moved out of line although the dancing appeared to carry the cables vertically at center of four to five hundred foot spans approximately 15 ft.

These two observations separated by only a few months were so different as to weather conditions and resulting phenomena that the observer suggested that some explanation should be sought for the extraordinary

Fig. 1—Whipping of Conductors at Hamilton

whipping during relatively light winds at Niagara Falls.

He suggested that so long as the cables were smoothly glazed on one side and left rough, as in stranding, on the other side, there would be galloping due to Magnus effect. If later the cables, due to moving around freely under these conditions, became coated all over then that particular span would show much less movement.

## Records of Galloping

H. J. Muehleman of the Hydro-Electric Power Commission was fortunate in securing a photographic record of extraordinary movements of conductors—605,000-cir. mil A. C. S. R., 110-kv. crossing at Hamilton, Ontario, Fig. 1. This photograph was taken at the same time that Archer was observing galloping at Niagara Falls, some 40 mi. east. Muehleman reports a thin coating of ice on parts of the conductors. As is usually observed when conductors are moving violently, one or more wires are quiet in each span. In some cases the conductor on each side of the dead-end is vibrating while in other cases it is vibrating on one side of the tower and not on the other.

The span on the right is 200 ft. long, that on the left approximately 500 ft. Both spans were dead-ended at each end and there was a change of tension as well as a change of direction in the line of 10 deg. at the towers which appear in the photograph.

## Lift of Partially Coated Conductors Investigated

Archer urged the taking of measurements, to confirm these assumptions, in a wind tunnel which was available at the University of Toronto. A specimen was prepared. It consisted of a piece of conductor left rough over one half of its circumference. The other side was made smooth and varnished, approximating the partial coating of glaze which was noticed on the conductors. Experiments of this sort had already been suggested by Knowlton.[3] This was done and the results are indicated in Fig. 2. It is clear from the diagram that for certain quite small angles of rotation of the coated conductor in a steady wind the variations in lift and in depressing effects are relatively large and rapid.

In Fig. 2, it can be seen that on either side of zero degrees, there are changes in lift from minus 0.085 to plus 0.088, and from minus 0.13 to plus 0.07, being 15 to 20 per cent of the weight of the cable. Catenaries, especially when supported by suspension insulators which readily swing away from and into the span, are not very stable when subjected to rapidly reversing vertical forces even if these forces are relatively small, as compared with the weight of the cable and as in the case of the cotton line may be expected to dance or gallop as a result of application of the relatively small but rapidly reversing forces. There was as a result of this investigation considerable evidence that the partial coat of glaze might be a sufficient explanation of the extraordinary conditions observed at Niagara Falls.

## Relation between Glaze Storms and Galloping and Classification of Data

A study of reports by over thirty observers, including those reported by Archbold which is by far the largest group, establishes the fact that in 78 to 80 per cent of the cases reported sleet existed on the wires, was being

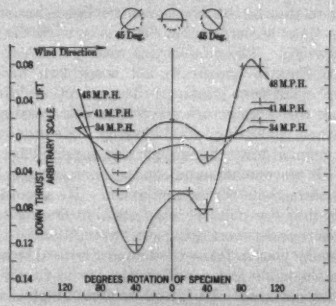


Fig. 2—"Lift" Curves for Conductors Thinly Glazed One Side Only

Half surface smoothed with plasticene to represent ice

deposited in the district, or might be expected because the temperature was 32 deg. and the weather misty and damp.

Archer's observations cover two classes of whipping, the first being in warm weather with violent winds and with flyings moving about freely. He expected that the wires would be shorted or grounded, because of comparatively restricted clearance. They, however, did not go out of service.

In the other case there was no reasonable explanation immediately available, so far as weather was concerned,

why the conductors should be so "possessed" or why some wires in a span were quiet, and others moved vertically as much as, or more than, the total sag at rest. Fine mist or rain was falling and there was a wind storm but no such wind storm as had been recently observed at Whitby. There was, however, no likelihood of the circuits remaining in service at Niagara as long as the weather conditions continued as they were.

It is therefore proposed that in general, reports of abnormal movements in conductors shall for purposes of analysis be classified and as far as can reasonably be done, grouped with one or other of these two observations of which the latter typifies the larger group. If ice is to remain on the conductors for any length of time, then the group represented by the observations at Niagara Falls is by a considerable amount the most important as far as outages are concerned.

## Varying Shapes and Cross-Sections of Ice-Coating on Conductors

During several days centering around December 19, 1929, a rather extended and troublesome sleet storm occurred in New York and Ontario districts, centering as far as effects upon transmission lines were concerned in the Niagara River area. There were in this area many opportunities, extending in some cases over more than one day, to study galloping conductors and the effects of these extraordinary movements on conductors and structures. The writer was fortunate to be at Allanburg, which is near the mid-point of the Welland Canal, Fig. 3, on the morning of the twentieth. Repair men were, with great difficulty because of ice on towers, cold weather, snow, and wind, restoring a

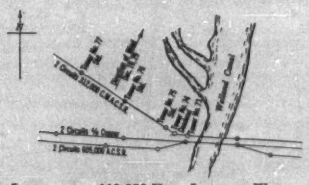


Fig. 3—Location of 110,000-Volt Lines at Welland Canal Crossing

312,000-cir. mil A. C. S. R. conductor which had been burned off near the end of the middle third of a 630-ft. span. This circuit some 40 mi. in length had given practically uninterrupted service for 18 years, excepting occasional momentary outages due to lightning. Two wires of a 110-kv. circuit were in a nearly vertical plane with 8 ft. separation, being part of a triangular configuration.

The conductor which had parted, along with many other conductors and static wires, forming parts of seven quite closely associated high-voltage circuits, were all coated with smooth ice of quite variable cross-section, which had apparently been considerably worn down by wind and weather, having been deposited one or two days previously. In some typical cross-sections which were about 2 in. long, there were two fairly sharp points at each end of the ice envelope. One of these evidently was a drip or series of icicles, and was a maximum radial distance of ¾ in. from the surface of the conductor. The other abrupt angle was opposite the drip and was not nearly so marked. It was generally not more than ⅜ in. radial distance from the surface of the conductor. Usually there was a thin coating of glaze on all sides of the conductor. A typical cross-

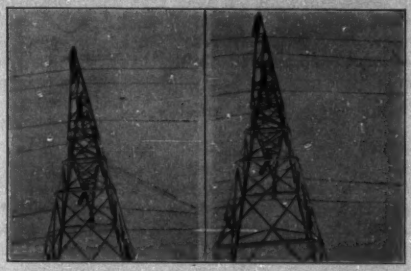

Fig. 4—Insulator Swinging Along Line—Middle Phase Near Side of Tower—Companion Illustration

section might, to some, look like a small bird crouching or clinging close to the conductor.

The 312,000-cir. mil A. C. S. R. conductors which remained intact in this span were moving about very freely in a comparatively light wind, 30 mi. per hour, at 75 deg. to line, to such an extent that repair men were scarcely in a position to report the circuits as available for operation or test under load after repairs had been completed. The phases with vertical configuration were not always clear of one another so long as weather conditions continued as they were. With a loaded sag, equivalent to a uniform ice-coating of about 7/16 in. radial thickness, of 18 to 20 ft. the conductors were moving through vertical distances reported after study by several as from 20 to 25 ft. There was a slow elliptical motion, with a small horizontal axis of the ellipse. The period was irregular but generally three seconds for a cycle. The suspension insulators were moving away from and into the span as much as 30 in. total swing at the point of support of the conductors, as may be observed in the companion photographs, Fig. 4, by referring to the middle phase near side of tower. The cycle of insulator swing was about three seconds. In most cases the whole span was moving upwards and downwards with irregular speeds, especially in the upper portions of the cycle. In other nearby spans, the conditions were much the same with some evidence of a sort of galloping, that is, one-third of a span would lift and as it reached its highest point and commenced to fall the central part of the span

would be moving up towards its high point and so on, giving the effect of a traveling wave. This continued until in the course of several hours the wind changed.

During all this time, the 5/16 in. static wires on each of three nearly parallel lines of towers, including this one, the pair of 4/0 copper conductor circuits and six 605,000-cir. mil A. C. S. R. conductors of the third pair of towers, were all quiet. That is, they were swinging

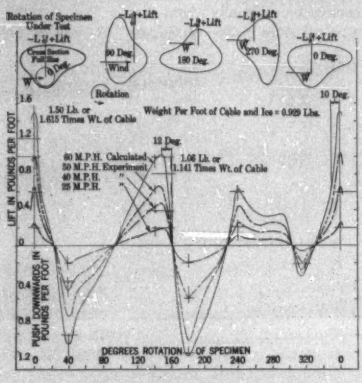


FIG. 5—"LIFT" CURVES FOR SPECIAL SHAPE OF ICE-COATING ON CONDUCTORS

Data from tests on model of ice covered transmission wire by Dept. of Mechanical Engineering, University of Toronto (Gravity balanced out)

out of plumb about 20 deg. and moving about only a little in that position on account of a somewhat variable wind.

## EFFECT OF WIND UPON CABLE AND ICE HAVING IRREGULAR OUTLINE OF CROSS-SECTION

It was evidently necessary, as the result of these observations, to study some of these irregular shapes and cross-sections in the wind tunnel. The succeeding cross-sections along the conductor were very irregular, resulting in a somewhat saw-toothed effect on account of the drip and icicles. A typical shape was chosen and a specimen 18 in. long was made of full size cross-section. Gravity was balanced out as is customary in examining airplane models and the curves shown in Fig. 5 were secured for 25, 40, and 50 mi. per hour, these having been corrected to per foot basis so as to compare with recorded cable data. A curve for 60 mi. per hour was calculated and added.

With this type of cross-section, the resulting lifts and the pressing down were very much greater than Fig. 1. Selecting for study the extreme case of 60 mi. per hour, there are for changes in rotation of 10 deg., a total change in lift of from plus 0.65 lb. per foot to plus 1.50 lb. per foot, or a total change of 0.85 lb. or 0.91 times the weight of the cable and ice combined. Taking another part of the curve there is for changes in rotation of 45 deg., a total change in lift from minus 0.38 lb. to plus 1.50 lb. This is 2.02 times the weight of the cable and ice combined. Examining lift only, it is evident that there would be at 60 mi. per hour and at considerably lower velocities, sufficient lift to carry the cable with its load upwards indefinitely so long as the angle of presentation to the wind can be maintained within close limits.

Variations in angles of effective presentation of ice surface to wind of 10 deg. and 45 deg. are mentioned. The more effective lifts are, however, confined to much smaller changes of angles of presentation just as in airplane work there is little margin in maintaining equilibrium at critical flying speeds. It would therefore appear that the neighboring copper conductors, the larger aluminum conductors, and the three ground wires, including that one serving the conductors in question, did not naturally present that critical angle, limited say to 6 deg. in 360 (one in 60 chances) for effective lift. They remained relatively quiet, although they did carry somewhat similar ice-coatings. The cables causing trouble were apparently poised so that the lift was effective when the forces due to horizontal

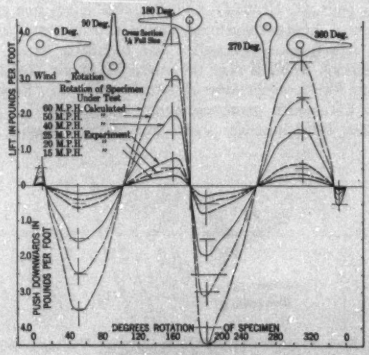


FIG. 6—"LIFT" FOR HEAVY SYMMETRICAL COATING OF ICE ON CONDUCTORS

Data from tests on model of ice covered transmission wire

wind pressure and gravity were stabilized. As the cable rises due to the lift becoming effective, the angle of presentation is actually changed a few degrees because of rotation of pendulum of the catenary around the point of support of insulator at the tower. The tension in the conductor may have been so changed that there is also a slight rotation because of uncoiling of lay of the cable; this latter feature, however, has not been investigated. The result of this slight change of angle is that the cable is relieved of the upward force and falls by gravity. It may even be thrust down by the wind, the rotation and

resulting change in presentation having gone through the neutral point of the lift curve.

A shape of ice-coated conductor which gave much trouble during the storm of 1922 was taken from the records of that storm and a specimen for test was made. This cross-section was much more regular and was symmetrical. These tests, Fig. 6, show characteristics somewhat similar to those found in Fig. 1.

Natural forces duplicating the lifting effect observed in galloping conductors have been demonstrated in the wind-tunnel and have been calibrated and recorded. The phenomena may be intelligently reproduced at will and may be studied and measured. Once problematical conditions can be duplicated experimentally in the laboratory and measured they are in a fair way toward being understood and solved. These curves are submitted for further study with a view to ultimately disposing of a quite serious menace to continuity of service of important overhead trunk transmission lines.

## Remedies

As in Archbold's letter to the technical press, so here there does not appear to be any ready remedy for the conditions reviewed in the latter part of this paper other than to arrange that during sleet periods, where wind is involved, important circuits shall be kept by artificial electrical loads, or otherwise, at temperatures at which sleet cannot form on them. Operating companies have had considerable experience melting sleet off wires after it has formed, but this is dangerous if there is any vertical configuration, because the sleet load in falling may so relieve a conductor that it will jump up sufficiently close to another conductor which is still carrying a sleet load to cause a short circuit even if there be no wind.

It is possible to keep conductors at temperatures by which sleet will not form. The year 1922 was rather disastrous in the Niagara district as far as transmission lines were concerned. Practically every tree in many square miles was more or less seriously damaged by sleet. Early in that storm overloads reaching 100,000 kv-a., 1900 amperes per sq. in., were placed on this 312,000-cir. mil A. C. S. R. circuit which experienced an outage in 1929. It gave uninterrupted service at that time through two quite long sleet storms during which there was much trouble in other circuits, especially in a paralleling pair of 4/0 copper circuits which were new and had not up to that time been placed in service. Reports from various sources indicate that sleet will melt off slowly and fall when copper is carrying 4000 to 6000 amperes per sq. in. Apparently ice having formed can be melted sufficiently to fall from aluminum conductors after they have carried from 2000 to 2500 amperes for a time even when the air temperatures are 10 or more degrees below freezing. This latter statement compares favorably with the figure of 1900 amperes per sq. in. which was an actual operating condition for many hours. From 4000 to 6000 amperes per sq. in. is not good practise for any purpose as joints may be overloaded.

## Conclusion

The stated purpose of this paper was to record the steps necessary to reproduce the conditions observed in the field and provide a yard-stick by which studies can be made to develop effective means of insuring service during sleet storms. This purpose has to some extent at least been accomplished. Some procedure should be developed by further studies which will be less hazardous, difficult, and inconvenient than that of overloading the circuits.

## Acknowledgment

The suggestions made by Mr. E. G. Archer account very largely for the work done in preparing the data for this paper. His assistance in assembling the data for the article is also gratefully acknowledged.

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# Rationalization of Station Insulating Structures

## With Respect to Insulation of the Transmission Line

BY C. L. FORTESCUE[1]

Fellow, A. I. E. E.

*Synopsis.—The purpose of this paper is to present a logical basis for the insulation of transmission lines and substations using as a basis the characteristics of traveling waves produced by lightning discharges. The method presented was formulated from the data obtained from the cathode ray oscillograms of actual line surges and upon the laboratory work in which the impulse flashover characteristics of insulating structures was determined. The breakdown volt—time characteristics of various forms of insulation are presented. Using these curves of various forms of gaps in the known characteristics of traveling waves, insulation of the transmission line at various distances from the gap is determined so that flashover will be unlikely to occur at these points. A similar method of analysis is made upon substations and lines protected by lightning arresters, but with the known characteristics of lightning arresters, the insulation on the line up to points 1000 to 5000 ft. away can be apportioned so that the lightning arrester will take the discharge, preventing the flashover of insulation. The system set forth in the paper enables the transmission engineer to design the line and substation in an economical manner and obtain adequate protection for all points desired.*

### Introduction

THE increased amount of information on lightning phenomena which has been obtained during the last few years has given engineers a new insight into the problems of insulating transmission lines and station insulating structures against lightning. It is now becoming common practise to vary the insulation of the transmission line itself to correspond with the severity of the exposures which occur at different points along their lengths. The improvement in the insulation of transmission lines has created some concern in the minds of manufacturers of transformers as to the severity of the surges which as a result of the increased insulation will have to be met by the insulation of station apparatus, and it would be wise to limit the insulation of the transmission line to correspond with the voltage class of the apparatus installed in conformity with the results of past experience with apparatus in the field. The suggestion has been made to limit the insulation of the transmission line for a half a mile outside the station.

### Comments on Proposed Procedure

There has been some criticism of this procedure on the part of some engineers on the score that where lightning arresters are used to protect the station apparatus it is unnecessary to cut down the insulation of the transmission line in the neighborhood of the station. However, this argument is not very logical for the reason that as regards insulation the presence of the lightning arrester in itself cuts down the requirements of the substation and nearby points on the transmission line for the reason that the protection afforded by the lightning arrester extends to some distance from its point of instalment. The particular phase of this subject dealing with the protection afforded by lightning arresters at points some distance away will be discussed later on in this paper.

1. Consulting Transmission Engineer, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

### The Use of Lightning Arresters Mandatory

At this time the author wishes to point out that as a protective measure for the transformers, the reduced insulation is not intended to replace the lightning arrester, but is intended as a back-up protection and in case something happens to the lightning arrester. It should not be assumed that an insulator string constitutes a good lightning arrester, as its flashover time lag characteristics are not conducive to its functioning as a lightning arrester. This will be easily seen by reference to Fig. 1 in which the flashover of a string of insulators and the surge potential of the corresponding

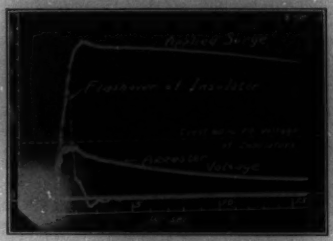


Fig. 1

lightning arrester are shown, as well as the full wave to which they were subjected. A further consideration of the characteristic curves of insulating structures will make this still clearer.

### Wave Shape of Lightning Surges as Shown by Lightning Investigations

The lightning investigations carried out in 1928 and 1929 show that contrary to previous ideas, the lightning wave is not of short duration, but may last for 50 microseconds. In particular the wave obtained in 1928 at the Tennessee lightning investigation station had a duration of 50 or 60 microseconds and its value was reduced from its crest by less than 20 per cent. The



30-86

waves obtained in our lightning investigation station at Stillwater and other waves obtained in Tennessee have confirmed the general shape of this particular lightning wave. With few exceptions, the more severe waves are of considerable length. To illustrate, some of the waves obtained at Stillwater and Tennessee are reproduced here from the paper by Cox and Beck[2] as Fig. 2.

## Laboratory Work to Determine Impulse Flashover Characteristics of Insulating Structures

Our laboratory work on lightning has been carried out on the proposition that the characteristics of insulating strings should be based on the most severe type of lightning that is likely to be encountered. This has a further advantage, in that the curves obtained in this manner are drawn in volts and time lag of flashover, and completely specify the impulse time lag characteristics of the insulating structure or insulator without regard to the shape of the wave, and the behavior of the insulator string for any shape of wave can be very easily obtained from these characteristics.

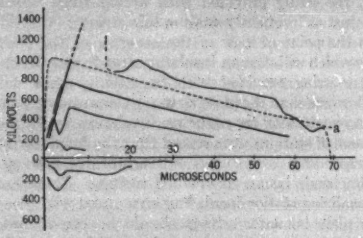



Fig. 2—Lightning Waves

"A"—Trafford Laboratory Wave

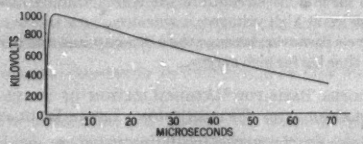



Fig. 3

The laboratory work on impulse characteristics was done with the wave shown in Fig. 3. It will be seen that this wave corresponds very closely to a square-topped wave, and is not very different from the wave shape of the lightning surge obtained in Tennessee in 1928, except that the front of the latter may have been longer than indicated. The procedure for obtaining flashover voltage time-lag characteristics is completely described in a contemporary paper by J. J. Torok.[3] It is obviously of great importance for transmission engineers to know the flashover voltage time-lag characteristics of the various types of insulating structures that enter into their transmission line and station designs. During the past two years, a great many data of this type covering the flashover voltage time-lag characteristics of the various types of insulation which are presented in Torok's paper have been obtained in the Trafford High-Voltage Laboratory. For the purpose of illustration in the discussion on application which follows, some of the curves are reproduced here. Fig. 4 shows the impulse ratio time lag of suspension insulators and needle-gaps in air. Fig. 5 shows the flashover voltage time-lag curves of suspension insulators with and without arcing rings and Fig. 6 shows the same information plotted in terms of impulse ratio. The work done in investigating the time-lag flashover characteristics of needle-gaps and sphere-gaps of various sizes at wide spacings in air is particularly important in connection with the determination of the best form of relief gap to be used in connection with the rationalization of the station insulation and the line insulation, in cases where it is not feasible to reduce the latter for a distance of one-half mile outside the station. It should be noted that the divergence in characteristics of needle-gaps in air for large and small gaps is extremely small. With spheres the

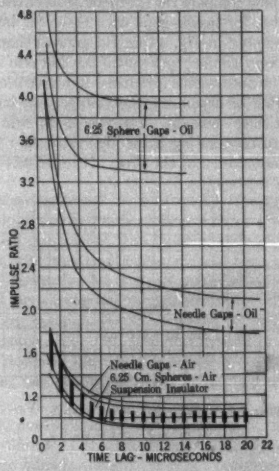



Fig. 4—Impulse Ratio Curves for Insulators and Spark-Gaps

Negative Terminal Grounded

2. J. H. Cox and Edward Beck, *Cathode Ray Oscillograph Studies of Lightning on Transmission Lines*, Winter Convention A. I. E. E., 1930.

3. J. J. Torok, *Surge Characteristics of Insulators and Gaps*, Presented at the Winter Convention A. I. E. E., 1930.

divergence is larger. It will be noted in Fig. 4 that the divergence in impulse characteristics for suspension insulators in going from two-unit to 16-unit strings is extremely small. Fig. 7, which gives the data on suspension insulators drawn in a somewhat different manner, shows comparison of our Trafford laboratory data with laboratory data published by Peek,[4] which comprises the values he obtained with three types of wave; namely 5, 20, and 80 microsecond waves according to his definition.

## Discussion of Flashover Time-Lag Characteristics

Let us now compare the characteristics of the impulse ratio curves for needle-gaps with those for insulators. It will be noted in Fig. 4 that the general shape of the curves is very similar, and that if the 60-cycle flashover point of the needle-gaps is reduced 12 per cent over that of the string of insulators, the voltage time-lag curves will practically coincide. The needle-gap will show a slightly greater time lag at the high voltages. In Fig. 6 it will be observed that the effect of the arcing rings is to

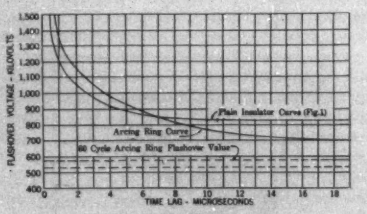



Fig. 5—Time-Lag Curve for 24-in. x 30-in. Arcing Rings

Nine No. 641 units: 43.5-in. spacing

very greatly increase the time lag for a given ratio of surge voltage above the 60-cycle flashover voltage. However, for a given string of insulators, the effect of the arcing rings is also to decrease the 60-cycle flashover as shown in Fig. 5. Consequently, the flashover voltage time-lag curve of the insulator string provided with arcing rings will cross that of the plain string somewhere in the neighborhood of eight microseconds; hence for waves that take more than eight microseconds to flash over the plain string, the string provided with arcing rings will have a shorter time lag, and will therefore flash over before the plain string, but for surges that take less than eight microseconds to flash over the plain string, the string provided with arcing rings will have a greater time lag, and therefore such a string will take a higher voltage to flash it over with the same time lag. Since about the longest time lag for a lightning wave to flash over an insulator string is 15 microseconds, in order to bring the impulse flashover strength of the two to equality at this point, the string provided with arcing rings would have to have its 60-cycle flashover raised in inverse proportion to the relative-value of the impulse ratio at this time lag.

It does not follow that because an insulator string provided with arcing rings and with its 60-cycle voltage raised so as to produce equal impulse strength at 15 microseconds has higher time lag for waves which flash over at less than 15 microseconds, it will result in lower outages on a line than the simple string. It is true that with lightning waves of short duration, this will be the case; but such lightning waves are not sufficiently numerous to be of any great consequence in determining outage factors. With high surges of long duration, the string provided with arcing rings will flash over just as frequently as the plain string. Considered from the point of view of the severity of the chopped wave which will pass an insulator after flashover, the insulator string provided with the arcing rings will be much worse than the plain string. Consequently, in the recommendations for reducing insulation in the neighborhood of stations, it is stated that the insulator string corresponding to the class of transformer used at the station shall be an unshielded string. Therefore, in rationalizing station insulating structures with the line, only plain insulator strings should be considered; or if shielded strings are used, the 60-cycle flashover should be sufficiently reduced so that the time lag at the higher surge is no greater than that of the plain string specified. It should be pointed out that the horn-gap, chosen to be used as a relief gap in cases where it is not practicable to reduce the line insulation, has a low 60-cycle flashover as compared with the corresponding insulator string. The reason also in this case is that in order to assure that the impulse strength of the gap will not be greater than the impulse strength of the corresponding insulating string at high voltages, it was necessary to use a low 60-cycle flashover, because the horn-gap has a relatively long time lag for high surges.

## Proper Basis for Rationalization of Station Insulation and Transmission Line Insulation

Obviously, the station insulating structure should be rationalized wherever possible with respect to the transmission line and not with respect to any extraneous device such as the horn-gap, since the object is to insure that the station insulation will be at least as strong as the line insulators adjacent to the station so that if a flashover should occur, it will occur on a line and not on station apparatus. In contrast to the line flashover which occurs and is suppressed without damage, flashover in the station insulating structure may involve more than the particular structure which flashes over, and may result in serious damage to the station and a prolonged outage. Measurements have been made in the laboratory of the impulse ratio range of pillar type insulators, and it has been determined that this range is above that of suspension insulator strings; consequently, if at 15 microseconds the 60-cycle flashover of

4. F. W. Peek, Jr., *Progress in Lightning Research*, A. I. E. E. Quarterly Transactions, April 1929, p. 436.

the pillar type insulator is slightly higher than that of the insulator strings near the station, the pillar type insulator will be properly rationalized with respect to the transmission insulation. Other important insulating structures used in stations are outlet bushings which form part of circuit interrupters and transformers. The impulse ratio time-lag characteristics of bushings may be modified by proper terminal arrangements so that they will have the same flashover voltage time-lag characteristics as the insulator string over a range of 20 microseconds; and if the flashover voltage at each value of time lag is made 5 per cent higher than that of the transmission line insulators, the conditions of rationalization are satisfied.

With lightning arresters at the station, the necessity for rationalizing the insulating structures with the line is sometimes questioned, but cases have been known where a direct stroke at the station has resulted in destruction of the lightning arresters, in which case for subsequent operation,—until the arresters are replaced, —the station has to fall back on the impulse flashover of the insulators to limit the surge potential to which the apparatus is subjected. Furthermore, with lightning arresters it is not actually necessary to have the insulation of the adjacent portions of the line as strong as the rest of the line, for the reason that the protective effect of the lightning arresters extends for some distance. It may be assumed that with a lightning arrester properly chosen and of proper characteristics, no flashover will ever take place in the station insulating structures except with some exceptional condition such as a direct stroke of unusual magnitude; but even in such cases, with a modern station provided with proper overhead ground wire protection it is very unlikely that a direct stroke to the station will cause a flashover of the station insulating structures when the station is protected by adequate lightning arresters.

## Lightning Arrester as Protection of Line Against Flashover

To understand the manner in which a lightning arrester protects insulating structures along the transmission line some distance from the point of installation, it is necessary to understand the action of a lightning arrester in protecting an insulating structure or piece of apparatus. When an incident surge strikes a lightning arrester of the valve type, the arrester at once discharges, and in so doing, produces a low resistance path to earth. In the true valve type arrester, the actual resistance of the path is extremely low, but the arrester itself has a counter e. m. f. equal to the glow or corona potential which, together with the resistance of the arrester, limits the crest value of the surge passing the arrester to a certain definite value. The action of breakdown, or short circuit, causes a negative wave which might be called the protective wave to flow along the transmission line in the opposite direction to the incident wave. This wave is equal to the difference between the wave that passes the arrester and the incident wave. As a result, if an insulating structure is distant from the lightning arrester at a length equivalent to one light microsecond, the insulating structure will have the full value of the surge impressed on it during the time the surge takes to reach the lightning arrester and the time the protective wave takes to reach the insulating structure; that is to say, two microseconds. Consequently, the insulating structure will have the full value of the surge for two microseconds, after which it will be reduced by the protective wave to a safe value. We may therefore say that the insulator string is protected from all waves that take more than two microseconds to flash it over. If the insulator or insulating structure is distant from the lightning arrester two light microseconds, then it will have the full wave impressed on it for four microseconds before the protective wave reaches it and it will therefore be protected against all surges that take more than four microseconds to flash it over. It follows that since the longest time lag in the flashover of an insulator due to a lightning surge is of the order of 15 microseconds, some measure of protection is obtained for transmission line insulators from lightning arresters located at stations for distances of more than one-half mile from the station. Consequently, the insulation of the transmission line can be graded for one-half mile outside the station without increasing the outage factor for this portion of the transmission line as compared to the rest of the transmission line. In fact the insulation could be graded down to the insulator string or structure which would be just protected by the lightning arrester at the station.

It will now be evident that the proposed rule to grade the insulation of the transmission line down for one-half mile outside the station is not purely an arbitrary decision, but has good theoretical basis because while the arrester is at the station, it is not necessary to have the full insulation at points near the lightning arrester in order to maintain the outage factor and if the arrester is absent for some reason it is essential as a back-up. Of course, at the station the outage factor with a properly designed and applied lightning arrester is zero, and at a short distance out from the station with the proposed reduced insulation, the outage factor becomes the same as that of the transmission line. From that point out to the end of the half mile distance, the outage factor will be somewhat greater, the average over the whole half mile being about the same as that of the line.

## Protection of Transmission Lines by Means of Arresters

The impulse time-lag curves of transmission line insulators may be very usefully applied to the protection of transmission lines by means of lightning arresters. The range over which a lightning arrester will afford protection to a transmission line depends to a

great extent on the wave form of the surge. However, if we assume the most severe type of lightning surge, which is one that comes to its maximum in a relatively short time,—say not more than one microsecond,—and at the end of twenty microseconds has a value of not less than 75 per cent of the crest value, we find that the protection afforded by a lightning arrester may be quite simply estimated on the following basis. We shall divide the line into sections, approximately one microsecond light intervals from the arrester. Let us take a point three microseconds distant from the arrester and let us suppose that the surge approaches the arrester from the direction of this point; then this point will be subjected to the full value of the wave for three microseconds before it reaches the arrester. The action of the arrester, as we have indicated above, consists in absorbing part of the energy of the surge and reflecting the remainder so that the wave that passes the arrester is the difference between the actual wave and the reflected portion. It will be noted that if we take the energy of the portion that

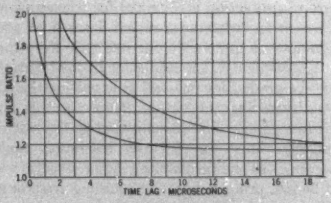



Fig. 6—Impulse Ratio Curves for Nine Suspension Units No.641 and 24-in. x 30-in. Arcing Rings

passes, plus the energy of the portion that is reflected, this will be less than the total energy of the incident wave; the difference between the two values is the energy absorbed by the arrester. This reflected wave will take three microseconds to reach the given point so that the total time during which this point is subjected to the full value of the wave is six microseconds. Let us now refer to Fig. 6; we find that with six microseconds given in the lower curve, the insulator string will have an impulse ratio of 1.23, and the conclusion is that all waves of this type having a crest value above 1.23 times the 60-cycle flashover of the insulator string will cause a flashover, and waves below this value will not cause a flashover. By using the probability curve of lightning surge occurrence in the manner discussed by H. L. Wallau,[5] we can estimate the probable reduction in outages at this point as a result of the presence of the lightning arresters placed three light microseconds from this point. If the lightning arresters are placed six light microseconds apart, this value will be the outage factor for the middle points between the lightning arresters. We may proceed with other points closer to the lightning arresters; for instance, consider the point two light microseconds from the arrester. This point would have the full wave for four microseconds which on the curve shows an impulse factor of 1.3 so that it would only flash over for waves 1.3 times the 60-cycle flashover value of an insulator string at this point. This, from the probability curve, will give a lower outage factor than the first point, and taking each insulator string in turn and the arithmetical average of the outage factors we obtain the outage factor of the line. It should be noted that for a surge coming from one direction, all the insulators on the farther side of the lightning arrester are protected from flashover; but this does not affect the actual outage factor, as this is also true of all methods of reducing the outage factor of transmission lines such as overhead ground wires.

## Rationalization of Transmission Line Insulation in Proportion to Protection

Another way of applying the line type arresters is to equalize the outage factors by varying the insulation. The lightning arrester that is used in protecting a transmission line will have a cut-off voltage equal to the normal line voltage; the crest voltage will therefore be 2.0 to 2.5 times the line voltage. We may assume that if the crest value of the wave which remains after the arrester has functioned is impressed on the insulator string for more than 15 microseconds, it will just cause flashover. We therefore take 15 microseconds on the curve of Fig. 6, and find that the impulse ratio is 1.15. We therefore assume that the insulator string, in order to receive 100 per cent protection from the transmission line, must have a 60-cycle flashover equal to 2.2 times line voltage. On this basis, a 132-kv. line will require only five insulators at the arrester point. Let us assume that we wish to protect the point farthest from the lightning arrester from all waves which have a crest value less than 1500 kv. At six microseconds we have an impulse factor of 1.23, so that the 60-cycle crest value must therefore be 1500 divided by 1.23 or a root-mean-square value of 860 which would require a string of insulators of 16 units. For the insulator string two light microseconds away, the time lag is four microseconds and the impulse factor 1.3, which gives a 60-cycle flashover of the string of 815 kv. which will require 15 units. For the insulator string one light microsecond away, the time lag will be two, and the impulse factor will be 1.56 which requires an insulator string having 60-cycle flashover of 680 kv. This requires a string having 12 units. The average number of units will therefore be 13, and the system will be protected against all lightning surges of maximum severity below 1500 kv.

The above example has been based on practically square-topped waves. The actual protection for waves having slopes of two to three microseconds will be

5. H. L. Wallau, "Relative Frequency of Voltage Surges Induced by Charged Clouds," *Electric Journal*, August 1928.

much better. It has also been assumed that the string was a straight string without arcing rings. When arcing rings are used the protection is still further increased and fewer units may be used. For example, if strap type rings are used (Fig. 6) the impulse factor at 15 microseconds is 1.24 as compared to 1.15.

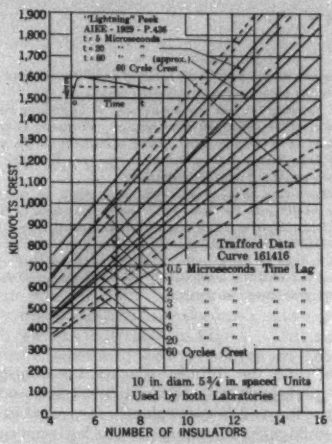



FIG. 7—COMPARATIVE SURGE DATA (GENERAL ELECTRIC COMPANY—WESTINGHOUSE ELEC. & MFG. CO.)

This would mean practically that the five-unit string would probably be satisfactory at this point. At the point three light microseconds away with strap type rings, we would have an impulse factor of 1.54 which corresponds to a 60-cycle flashover of 685 kv. with arcing rings, or a plain string flashover of 760 kv. which would therefore require 14 units instead of 16 with the plain string. At the point two light microseconds away the time lag is four microseconds and the impulse factor is 1.8 which gives a 60-cycle flashover of 590 for the string with strap rings corresponding to 670 for a plain string. This would require a string of 12 units. At the tower one light microsecond away we shall have a time lag of two microseconds and an impulse factor of 2.3. This gives a 60-cycle flashover of 460 kv. with arcing rings corresponding to 530 kv. for a plain string which requires a string of nine units. This gives an average length of string of less than 11 insulators.

This method of rationalizing the insulation in relation to the amount of protection it receives from the arrester gives the lowest outage factor for a given average length of string. It will be necessary, however, in practical construction work to consider other elements, such as the tower design, but it appears that by properly organizing the construction work several towers of different size could be used with an average cost of tower not appreciably greater than if flat insulation were used so a great reduction in actual outage factor due to lightning should be possible with little added cost. It should be remarked that the performance of the 132-kv. line, as has been indicated, would be better than that of a line without arresters having a flat insulation of 16 units. In other words, the arrester-protected line with graded insulation would give insulation superior to a line over-insulated with 16 units. It should be noted that in this case the arresters are placed seven light microseconds

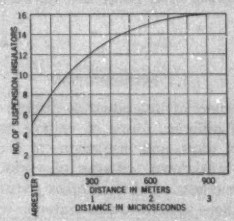



FIG. 8—CURVE SHOWING INSULATION REQUIRED AT VARIOUS DISTANCES FROM LIGHTNING ARRESTER FOR 132-KV. LINE FOR PROTECTION AGAINST A VOLTAGE OF 1500 KV.

apart. With closer spacings, fewer insulators will be required for the same standard of protection. A curve may be plotted giving 60-cycle voltage or number of insulators against distance or light microseconds. Such a curve is shown in Fig. 8, illustrating the above example. With such a curve, the cost of arresters and insulators with different spacings of arresters along the line may be readily obtained.

## Discussion

For discussion of this paper see page 1496.

# The Effect of Transient Voltages on Dielectrics—IV

## Law of Impulse Spark-over and Time Lag

### *Relative Effects of Different Wave Shapes—Comparison of Lightning Waves and Laboratory Waves—Coordination of Line Insulation*

F. W. PEEK, JR.*

Fellow, A. I. E. E.

***Synopsis.***—*The law of time lag and impulse breakdown is derived from experimental data. This law, which appears to be rational, shows that a given amount of energy is required to cause breakdown of a given gap and that voltage and time are interdependent. It is quite in accord with the work in the original paper and applies to breakdown on rectangular waves, on the front of slanting waves, or to overvoltages on standard waves.*[1] *By means of simple formulas the results for any wave can be calculated or the effects of different waves correlated.*

*Three general types of impulse tests, dependent on the form of wave used and the spark-over point selected, are discussed as follows:*

*1. The so-called "rectangular" wave with spark-over on the top*

*2. The uniformly rising voltage with spark-over on fronts of various slopes*

*3. The use of a "standard" wave of logarithmic front and tail with spark-over occurring at any desired point on it.*

*Method 3, using the full standard wave, is by far the simplest to apply and gives the most consistent results. It is also shown that it may be used in a way to give effects equivalent to the other two methods. Interesting energy relationships for impulse failures of gaps are brought out in this connection.*

*Field experience with actual lightning waves is compared to laboratory results with the "standard" wave and found to check very closely. A statistical study is described in this connection which now allows considering the lightning problem from an economic aspect.*

*The advantages of coordination of line and apparatus insulation are pointed out and the adaptability of the "standard" laboratory wave to such procedure is described.*

* * * * *

### I. Introduction

It is the object of this paper to discuss the relative effects of different forms of voltage transients on insulators, gaps, and insulation; to show how the effects and breakdown voltages of various types of transients are related; and to compare natural lightning waves with those used in the laboratory. Such knowledge is necessary in making a comparison of insulators, insulation, and in coordination. The law of impulse spark-over has been determined and formulas have been developed to predetermine time lag and breakdown voltage for the various types of transients.

When voltage is applied between electrodes in air or other gaseous insulation and slowly increased, breakdown eventually occurs. This is the minimum voltage that will cause failure for the given conditions. With a rapidly increasing voltage, breakdown does not take place when this minimum value is reached but the voltage rises to some higher value before failure occurs. A voltage higher than the minimum value is also required when the time of application is in any way limited. This follows because energy and therefore time is required to cause breakdown. The ratio of the impulse spark-over voltage to the minimum or continuously applied spark-over voltage is called the impulse ratio; the interval from the time the impulse reaches the continuously applied spark-over voltage until breakdown occurs is termed the lag and is conveniently measured in microseconds (millionths of seconds). The lag is not constant for a given arrangement but decreases with increasing rate of application of voltage. Thus breakdown is a function of both voltage and time. The shorter the time, the higher the voltage. There is a time lag for all types of electrodes but it is minimum for electrodes causing approximately uniform fields, such as spheres, and is a maximum for electrodes causing non-uniform fields, such as needle-gaps. For dissimilar electrodes, impulse spark-over takes place at the lowest voltage when the electrode in the denser field is positive. Accordingly, it follows that the impulse spark-over voltage of gaps and insulators is always higher than the continuously applied or 60-cycle voltage so that the impulse ratio is greater than unity. In general the impulse breakdown voltage for liquid and solid insulations is also higher than the continuously applied breakdown voltage.

The above paragraph is practically a quotation from the first paper on this subject (to which this paper may be considered a supplement).[1] The early results still obtain. Although when that investigation was made there was no oscillographic means of measuring waves of such short duration, the lags in millionths of seconds were determined as a result of calculations and indirect methods and the mechanism of breakdown was correctly pictured. Recent high-voltage research with the Du-

*Consulting Engineer, General Electric Company, Pittsfield, Massachusetts.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

1. For references see Bibliography.

four type of cathode ray oscillograph has simplified the problem and verified the early results.

## II. Types of Impulse Tests

There are three general types of impulse tests, as follows:

*1. Rectangular Wave.* The rectangular wave method

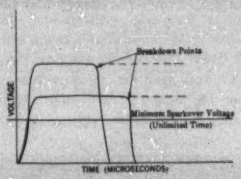



Fig. 1—Rectangular Form of Impulse Wave

is illustrated in Fig. 1. A theoretical rectangular wave would rise instantly to a given value and remain constant until breakdown occurred. However, such a wave can generally only be approximated in practise. Actually, about one-half microsecond is usually required to reach crest as illustrated in Fig. 1. This method is interesting theoretically but the waves are not typical of the usual high-voltage surges.

*2. Uniformly Rising Voltage.* Spark-over for a uniformly rising voltage is illustrated in Fig. 2. The time and voltage are indicated at spark-over. Note that when the minimum spark-over voltage is reached breakdown does not occur immediately because con-

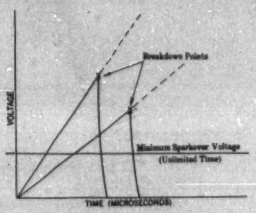



Fig. 2—Sparkover on Front of Waves of Various Slopes

siderable time is required at that voltage. The wave accordingly rises above this value. The more rapidly the voltage is applied, the higher the breakdown voltage is, and the less the lag. This is a condition that occurs in practise when the lightning voltage is much higher than the breakdown value of the insulation and spark-over occurs on the front.

*3. Standard Wave of Fixed Shape.* In this method a fixed or standard wave of the form shown in Fig. 11 is used and there are several ways in which the test may be made.[1,2] By the proper application of this method the whole range of breakdown effects caused by the rectangular wave, the uniformly rising voltage or any other wave can be obtained. The two general methods are:

*a. Full-Wave Method.* The given wave is applied and the voltage is gradually increased until spark-over occurs on 50 per cent of the applications. Breakdown is then taking place on the tail as shown in (*a*) Fig. 3. Since the voltage is just high enough to cause sparking, the full wave is utilized. This method gives the most reliable and consistent results and is the simplest to carry out. The only measuring device necessary is a parallel sphere-gap which gives accurate results where the full wave is used.

*b. Overvoltage Method.* This is the same as the above except that an overvoltage is applied which may be any given percentage in excess of the full wave value.[1,2] The time of spark-over at (*b*) may be measured by a cathode ray oscillograph. Either a short or long wave may be used as shown in Fig. 3. The standard wave overvoltage method (with long wave) has been compared with, or described as a rectangular

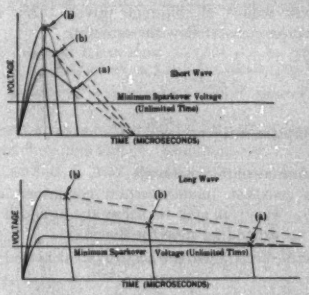



Fig. 3—Sparkovers on Tails of Short and Long Waves

wave method with steep front and horizontal top. However, the two methods do not give the same results.

## III. The Effects and Relative Breakdown Values of Various Types of Waves—Law of Impulse Spark-Over and Time Lag

The effects and relative breakdown values of the various types of waves will now be discussed in more detail.

*1. Rectangular Wave.* An investigation with this type of wave is of theoretical interest. If the front could be made perpendicular and the top horizontal, two variables would be eliminated. However, it is not practical to accomplish this and in general it is difficult to produce a front reaching maximum in less than one-half microsecond. It is thus the same as any other fixed in this respect, is more difficult to obtain and is sensitive to changes in front.

Oscillograms of such a wave with one-half microsecond front are shown in Fig. 4. The results of insula-

tor spark-over voltages are given with impulse ratio in Fig. 5. It is seen that the values for the various lengths of insulator strings fall well on this curve. This impulse ratio-time curve has particular interest because it seems to offer a means of correlating the

FIG. 4—OSCILLOGRAM OF SPARK-OVER OF POINT-GAP WITH RECTANGULAR WAVES OF DIFFERENT VOLTAGES

spark-over values of different waves. This follows because these curves follow the equation

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right) \tag{1}$$

$\beta$ = impulse ratio = $\dfrac{e}{e_0}$

$t$ = time lag in microseconds

$a$ = a constant (under certain conditions $a$ may vary; it may be necessary to add a factor depending upon the spacing)

when $\beta$ and $a$ are known, the lag can be calculated:

$$t = \left(\frac{a}{\beta - 1}\right)^2 \tag{2}$$

The impulse spark-over voltage is

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right) \tag{3}$$

where $e_0$ is the continuously applied breakdown value.

For convenience in practical application, the 60-cycle crest spark-over value has been taken as $e_0$. If the impulse ratio is known, the impulse spark-over value is then found by multiplying $\beta$ by $e_0$. For certain dissymmetrical electrode arrangements the spark-over voltage may be materially lower when the non-grounded electrode (or the one in the denser field) is positive. For a theoretical study it would in such cases be preferable to use the corresponding (+) and (−) direct current, $e_0$ voltages. This would tend to bring the (+) and (−) impulse ratios more nearly together since both the impulse spark-over voltage and the continuously applied spark-over voltage are affected in the same way by polarity.

This equation is of further interest because it appears to be rational. In the original paper on this subject it was pointed out that energy, and therefore voltage and time, were necessary to rupture insulation.[1]

It may be assumed that a given amount of energy is necessary to break a given gap. This requires a definite ionization apparent as corona and corona loss. Corona loss, according to the quadratic law, is:

$$p = (e - e_0)^2 k$$

For the rectangular wave the energy may be expressed

$$w = (e - e_0)^2 k t$$

or

$$\sqrt{w} = (e - e_0)\sqrt{k t}$$

$$e - e_0 = \sqrt{\frac{w}{k t}}$$

$$e = e_0 + \sqrt{\frac{w}{k t}}$$

$$e = e_0\left(1 + \sqrt{\frac{w}{e_0^2 k t}}\right)$$

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right)$$

where $a^2 = \dfrac{w}{k e_0^2} = \dfrac{w}{k_1 l^2}$

$l$ = length of gap

When the impulse ratio is constant, $a$ is constant and it then follows that $w$ varies as the square of the $e_0$ voltage or approximately as the square of the gap length. This also follows when $\beta$ is constant with

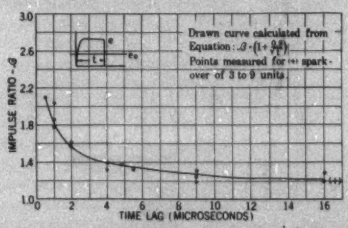



FIG. 5—IMPULSE RATIO-TIME LAG CURVE OF INSULATOR SPARKOVER WITH RECTANGULAR WAVE OF ½-MICROSECOND FRONT

(Standard 5¼-in. spacing—10-in. diameter insulators)

varying gap length in the case of the fixed wave. (See Figs. 9 and 16.)

Thus

$$\frac{e}{e_0} = \left(1 + \frac{a}{\sqrt{t}}\right) = \beta$$

The drawn curve in Fig. 5 was plotted from the equation

$$\beta = \left(1 + \frac{0.8}{\sqrt{t}}\right)$$

Similar results are obtained for needle-gaps, etc., with different values of ($a$); $a$ is usually higher when the electrode in the denser field is (−). The author has checked this law on other data and it seems to apply.[5]

*2. Breakdown on Uniformly Rising Voltage.* Breakdown or spark-over on the front of a uniformly rising voltage is illustrated by the oscillogram in Fig. 6. While the sphere-gap has very little time lag, and is quite accurate for measuring the crest voltage of a full wave, it is not always sufficiently accurate to measure the breakdown voltage on a very steep front. The error in time and voltage will vary but may be of the order of 10 per cent low if correction is not made. Oscillographic measurements or sphere-gap corrections

A

B

FIG. 6—OSCILLOGRAMS SHOWING SPARK-OVERS ON FRONTS OF IMPULSE WAVES

(a) Spark-over of point-gap:
(b) Spark-over of insulators: A. Complete wave
B. Spark-over of 5 units
C. Spark-over of 3 units

should therefore be made for every point when this method is used. The sphere-gap is also subject to correction for polarity for the larger spacings. This correction, which may be opposite the point-plane effect, becomes of importance when it is desired to determine a small (+) and (−) difference on other gaps.

The results of tests on insulators and point-gaps are given in Figs. 7 and 8. It will be noted that for any given time for breakdown the impulse ratio is practically constant and for a wide range of the length of string or gap. Any difference in impulse ratio with length or number of units usually becomes appreciable only for short spacings. The same general law connecting voltage and time lag applies for breakdown on the rising front as for the rectangular wave. For suspension insulators it is:

$$\beta = \left(1 + \frac{.9}{\sqrt{t}}\right)(+)$$

$$\beta = \left(1 + \frac{1.2}{\sqrt{t}}\right)(-)$$

The difference between (+) and (−) for insulators

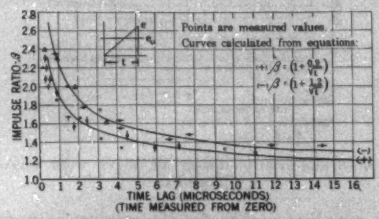



FIG. 7—IMPULSE RATIO-TIME LAG CURVE OF INSULATOR SPARKOVER ON FRONT OF WAVE

(Standard 5¾ in. spacing—10 in. diameter insulators)

represents a range rather than a definite division, with (−) maximum high and (+) minimum low. Individual (+) values of $\beta$ may be approximately 5 per cent

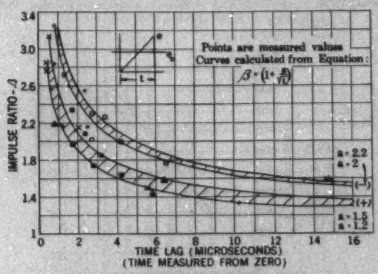



FIG. 8—IMPULSE RATIO-TIME LAG CURVE OF POINT-GAP SPARK-OVER ON FRONT OF WAVE

higher than the calculated and (−) values 5 per cent lower.

For point-gap

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right)$$

where $a$ = 1.2 to 1.5 (+) and $a$ = 2.0 to 2.2 (−) depending upon the type of gap. The lower (+) curve approaches a point-plane condition which gives the minimum spark-over.

For spark-over on the front, time, $t$, has been taken

for convenience from zero to breakdown. However, this requires some explanation since the effective time of corona formation, $(t - t_0)$ in Fig. 2, is different from that for the rectangular wave. In this case the voltage is not constant but is a function of time so that the expression for energy loss following the quadratic law is

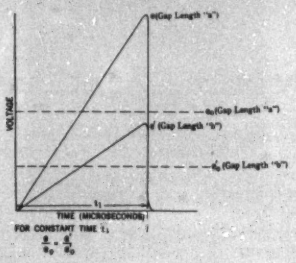



FIG. 9—SPARK-OVER ON FRONT OF WAVE WITH CONSTANT TIME LAG

more complicated than for the rectangular wave as given above. It is

$$w = \int_{t_0}^{t} (e - e_0)^2 \, d\,t = \int_{t_0}^{t} (e_0 \, \delta \, t - e_0)^2 \, d\,t$$

which reduces to

$$(\beta^3 - 3\,\beta^2 + 3\,\beta) = \left(3\,\delta \frac{w}{e_0^2} + 1\right)$$

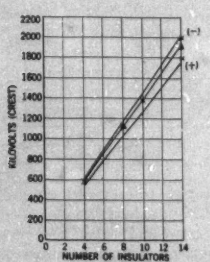



FIG. 10—COMPARISON OF SPARK-OVER VOLTAGES OF SUSPENSION INSULATORS WITH BREAKDOWN ON FRONT OF UNIFORMLY RISING WAVE IN TWO MICROSECONDS AND ON TAIL OF ½/5 STANDARD WAVE (50 PER CENT SPARKING)

Crosses (×) indicate spark-over values from natural lightning
Two microseconds (time-zero to spark-over)
½/5 Standard wave (from Fig. 12)—average
Two microseconds (time-zero to spark-over)

where

$w$ = rupturing energy of gap
$e_0$ = minimum spark-over voltage (unlimited time)
$\delta$ = slope factor
$\beta$ = impulse ratio

It can be shown that this expression gives equivalent results to Equation (1), particularly for small values of $t$, where diffusion losses during breakdown do not appreciably affect the energy. Equation (1) more closely follows measured values. The tests show that for a given type of gap or insulator the ratio $\frac{e}{e_0}$ remains approximately constant with change in gap length for a constant $t$. This is illustrated in Fig. 9. Since the rate at which a voltage rises is

$$\alpha = e\,/t = \text{kv/m. s.}$$

the spark-over voltage for any given $\beta$ can be calculated.

Curves calculated by Equation (1) for spark-over on the rising front for insulators are given in Fig. 10, for (+) and (−) waves and for spark-over times $t$ of 2 microseconds. The crosses show measured spark-over voltages for natural lightning on transmission lines. Note that the two microsecond curve on the rising front corresponds approximately to the ½/5 microsecond* wave of Fig. 12.

FIG. 11—OSCILLOGRAM SHOWING SPARK-OVER ON TAIL OF WAVE

Insulator spark-overs on transmission lines frequently occur on the rising front of the wave. It is, therefore, a practical condition.

*3. Breakdown on the Standard Wave.* Breakdown on the tail or crest of a fixed wave is illustrated in Fig. 3. The front is taken as the time from zero to crest and the length as the time from crest to half voltage on the tail; it is a convenient means of designating the wave. This method, using the full wave, has been most useful in comparing the lightning strengths of different types of gaps, insulators, and insulation. The test is very simple to make and good results can be obtained, as already noted, without the cathode ray oscillograph. The general method is to apply successive waves of increasing crest values until spark-over occurs on 50 per cent of the applications. An oscillogram illustrating this method is given in Fig. 11. Spark-over

*In this expression, which will be used for designating standard waves, the first number signifies front, while the second signifies time from crest to one-half voltage on the tail. Thus, ½/5/(+) means ½ microsecond front, 5 microsecond tail, and positive polarity on the non-grounded electrode. This method of designating was first suggested by K. B. McEachron.

curves are given in Figs. 12 and 13. Full line curves represent values for transmission line conditions. The crosses give natural lightning spark-over voltages measured on transmission lines. Note that the effects are closely approximated by the standard ½/5- and ½/20-microsecond waves. These curves are the average of (+) and (−) spark-over values.* Fig. 14 records the results of tests of insulators and point-gaps in parallel. The gaps were adjusted for equal sparking on points and insulators. The waves used cover an impulse ratio range of 2 to 1.2 and unity at 60 cycles. Practically the same relation between insulators and points holds throughout the range.

When a fixed wave is used, the ratio $\frac{e}{e_0}$ is approximately constant over a large range of lengths of a given

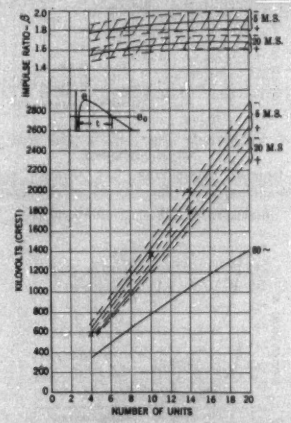



FIG. 12—SPARKOVER VOLTAGES OF SUSPENSION INSULATORS WITH "STANDARD" WAVE—50 PER CENT SPARKING

(Standard 5¼-in. spacing, 10-in. diameter insulators). The full curves should be used for transmission line conditions

gap or insulator string. This applies particularly for the longer gaps. Fig. 10 shows that the same effects can be obtained with the full wave as with sparking on the rising front; it is a matter of making the proper selection. However, the fixed wave method is much more satisfactory for practical tests.

A very wide range of impulse ratios can be obtained with a fixed wave by making the partial sparking test using the full wave, and also by applying voltages in excess of this value or overvoltages so that spark-over takes place nearer the crest as illustrated in Figs. 3 and 15. These tests can be made at 50 per cent sparking (that is, the full-wave method) and also at a given percentage of voltage above this value. For a given percentage of overvoltage on a fixed wave the impulse ratio $\frac{e}{e_0}$ is practically constant over a wide range of gap setting or insulator lengths, as illustrated in Fig. 16. The time lag $t$, for the different overvoltages can be plotted with the impulse ratio as in Figs. 17 and 18. When this is done it will be found that the voltage and

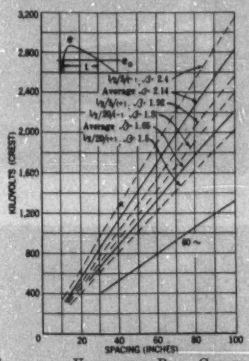



FIG. 13—SPARK-OVER VOLTAGES OF POINT GAP-WITH STANDARD WAVE—50 PER CENT SPARKING

The full curves represent transmission line conditions. The lower (+) curves approach a point-plane arrangement

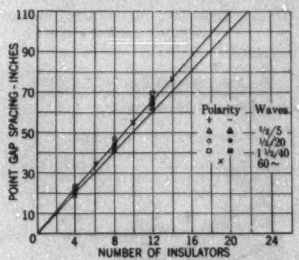



FIG. 14—CURVES SHOWING RESULTS OF PARALLEL TESTS ON STANDARD SUSPENSION INSULATORS

(5¼-in. spacing—10-in. diameter) and point-gaps, made to determine equivalent sparkover values. Curves represent range between 60-cycle and ½/5-microsecond waves

impulse ratio for relatively long and steep waves can be expressed by

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right)$$

or

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right)$$

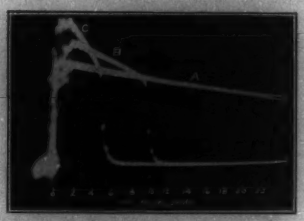
*These curves differ somewhat from the original 5- and 20-microsecond curves because the original curves were based on a ¼-microsecond front while these are for ½-microsecond front.

where $e_0$ = 60-cycle spark-over (crest)

$t$ = time above 60-cycle spark-over voltage

The expression applies for values of $t$ less than approximately

$$\frac{(\beta - 1)\,c}{\beta}\,l \qquad (4)$$



A

B

FIG. 15—OSCILLOGRAMS ILLUSTRATING OVERVOLTAGE EFFECT WITH STANDARD WAVE

(a) High-voltage bushing test:
- A. Applied wave
- B. Spark-over with 20 per cent overvoltage
- C. Spark-over with 40 per cent overvoltage

(b) Bushing test with slight overvoltages

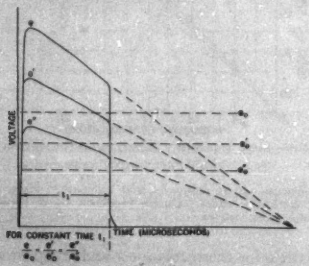



FIG. 16—OVERVOLTAGE SPARK-OVERS ON STANDARD WAVE AT CONSTANT TIME LAG

where $c$ varies between 1 and 2 and depends upon the "50 per cent sparking" breakdown point and $l$ is the length of the wave as defined above. When this lag is reached the full effect of the wave is utilized. This follows because the impulse voltage then approaches the 60-cycle value. This is illustrated as the 50 per cent sparking voltage in Figs. 17 and 18. When $\beta$ is known for 50 per cent spark-over on the full wave (Table II), $t$ may be calculated from (4). By substituting this value of $t$ and $\beta$ in (1), $a$ is found. The impulse ratio and sparking voltage for the given wave on

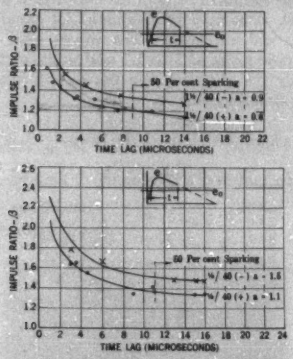



FIG. 17—IMPULSE RATIO-TIME LAG CURVES FOR OVERVOLTAGE SPARK-OVERS OF INSULATORS ON STANDARD WAVE

(Standard 5¾-in., 10-in. diameter insulators)

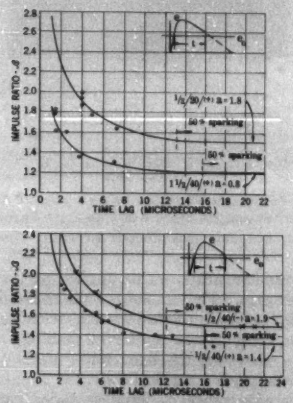



FIG. 18—IMPULSE RATIO-TIME LAG CURVES FOR OVERVOLTAGE SPARK-OVERS OF POINT-GAP ON STANDARD WAVE

overvoltages can then be calculated from (1) and (3).

The effects of various wavelengths and wave fronts for the full wave are given in Figs. 19 and 20. Fig. 21 shows the effect of varying front with constant length. These curves with constant length and varying front may be expressed by Equation (1) with $t$ = front of

wave. The (+) and (−) curves in Figs. 17 to 21 represent a range in values rather than a definite division, the (−) curve representing maximum (−) values and the (+) curves minimum (+) values. Frequently the average (+) and (−) values are not far apart.

The cathode ray oscillograph was used in making all

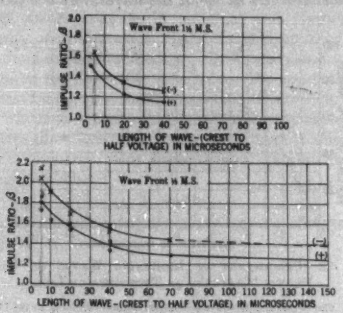



FIG. 19—IMPULSE RATIOS FOR FULL-WAVE INSULATORS SPARK-OVERS

(50 per cent sparking) with standard waves of constant front and varying lengths. (Standard 5½-in., 10-in. diameter insulators)
Example—$\beta$ = 1.8 for ½/5/(+)—To find impulse spark-over, multiply 60-cycle crest voltage by $\beta$.

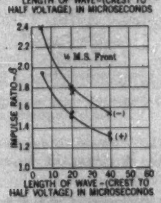



FIG. 20—IMPULSE RATIOS FOR FULL-WAVE POINT-GAP SPARK-OVERS (50 PER CENT SPARKING) WITH STANDARD WAVES OF CONSTANT FRONT AND VARYING LENGTH

tests. The sphere-gap was used for making calibration of the maximum of the full wave value used.

Values of $\alpha$ for different waves are given in Table I. Accurate values of $\beta$ for various waves and overvoltages can be calculated by inserting the proper value of $\alpha$ in the formula. The full wave spark-over voltages can be calculated for various waves from $\beta$ from Table II. Very

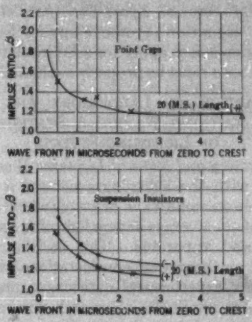



FIG. 21—IMPULSE RATIO-TIME CURVES OF POINT-GAP AND INSULATOR SPARK-OVER SHOWING EFFECT OF VARIATION OF WAVE FRONT WITH CONSTANT WAVELENGTH (IN THIS CASE 20 MICROSECONDS EFFECTIVE DURATION, *i. e.*, ABOVE HALF VOLTAGE)

TABLE I
$\alpha$ FOR VARIOUS WAVES

| Wave | Insulators | | Points | |
|---|---|---|---|---|
| | (+) | (−) | (+) | (−) |
| *Overvoltage* | | | | |
| ½/40 | 1.1 | 1.5 | 1.4 | 1.9 |
| 1½/40 | 0.6 | 0.9 | 0.8 | |
| *Rectangular* ½ microsecond front | 0.8 | .... | .... | .... |
| *Slanting* | 0.9 | 1.2 | 1.2 | 2.0 |
| | .... | .... | 1.5 | 2.2 |

(+) and (−) values represent a range

TABLE II
FULL WAVE SPARK-OVER
Impulse Ratio

| Wave | Insulators | | Points | |
|---|---|---|---|---|
| | (+) | (−) | (+) | (−) |
| ½/5 | 1.75 | 1.95 | 1.92 | 2.4 |
| 1 /5 | 1.50 | 1.65 | .... | .... |
| 1½/5 | 1.46 | 1.58 | .... | .... |
| 3 /5 | 1.28 | 1.34 | .... | .... |
| ¼/20 | .... | .... | .... | .... |
| ½/20 | 1.58 | 1.7 | 1.5 | 1.8 |
| 1 /20 | 1.33 | 1.40 | .... | .... |
| 1½/20 | 1.25 | 1.33 | .... | .... |
| 3 /20 | 1.15 | 1.20 | .... | .... |
| ½/40 | 1.40 | 1.50 | 1.33 | 1.55 |
| 1 /40 | 1.22 | 1.30 | .... | .... |
| 1½/40 | 1.18 | 1.28 | .... | .... |
| 3 /40 | 1.10 | 1.15 | .... | .... |

The (+) and (−) values of $\beta$ represent a range with minimum (+) values and maximum (−) values. Individual (+) values may be 5 per cent higher and (−) values 5 per cent lower than the curve. Frequently the average difference between (+) and (−) may be negligible. The average range between (+) and (−) for insulators in the table is 6½ per cent; for point-gaps it is somewhat higher.

extensive data on $a$ and $s$ have been obtained. As soon as these data are in form, the above tables will be revised and extended.

*4. Law of Impulse Spark-Over for Oil and Solid Insulation.* Equation (1) above applies for oil insulation and also seems to apply for solid insulation. However, the factor $a$ must be properly evaluated.

## IV. Comparison of Laboratory and Observed Natural Lightning Waves—A Statistical Study of Lightning Effects

*1. Laboratory and Natural Lightning Waves.* In the early work with the lightning generator it was necessary to decide on some wave or waves which would have the effects of the average severe lightning on insulators, insulation, and apparatus. This decision was necessarily based on theoretical considerations with the help of the meager experimental data on natural lightning that were then available. Research was made over a very wide range of wave-shapes with spark-over occurring on the fronts and tails. As tentative standards two waves were decided upon for general testing and comparison of insulators, and insulation—that is, the 5 and the 20 microsecond waves. These waves reach crest in ½ microsecond, decrease to half voltage in 5 and 20 microseconds, and to zero in 10 and 40 microseconds respectively.* Insulator spark-over curves obtained with these waves in the laboratory are given in Figs. 12 and 13. The crosses on Fig. 12 are points obtained by surge voltage recorder measurements of insulator spark-overs caused by natural lightning. These points fall in between the 5 and 20 microsecond curves. A further check is seen on the gap spark-over in Fig. 13. Other measurements on failures of insulators and insulation give impulse ratios of the order of 1.6 to 2. In obtaining the values in Figs. 12 and 13 the full wave was used by increasing the impulse voltage until spark-over occurred in 50 per cent of the applications.

TABLE III
PARALLEL SPARKING

| Insulator Units | Point-Gap Setting (Inches) | | | | | |
|---|---|---|---|---|---|---|
| Wave | ½/5 | | ½/20 | | 1½/40 | |
| | (+) | (−) | (+) | (−) | (+) | (−) |
| 4 | 20 | 22 | 23 | 22.7 | 23 | 21 |
| 8 | 43.5 | 44 | 45.2 | 46 | 47 | 46.5 |
| 12 | 64 | 70 | 70 | 71.2 | 70.2 | 69.2 |

Point gap set for equal sparking with parallel insulator.
Variation—plus or minus 5 per cent.

Data from some of the natural lightning waves measured by the cathode ray oscillograph are given in Fig. 22. The estimated front of the maximum voltage at the point of origin, and before the wave is free, as explained below, is given by the dotted line (*b*). It is this value that should determine the spark-over. Typical measured natural lightning waves are shown in Fig. 23 with the laboratory waves. These waves, in general, produce the same effects on lines and apparatus as the laboratory waves. *It is probable that insulator spark-overs frequently occur on the rising front of the wave as illustrated in Fig. 2.* If the waves were not chopped

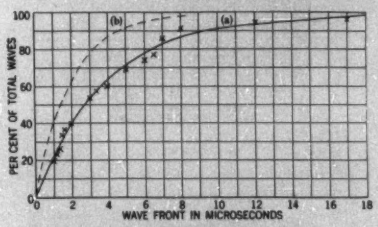



Fig. 22—Percentage of Lightning Waves of Various Fronts Measured on Transmission Lines

(a) Curve showing fronts of 35 highest natural lightning waves (voltage $V_1$) measured on Wallenpaupack-Siegfried Line in 1929
(b) Estimated equivalent fronts (voltage $V$) at points of origin of corresponding waves on curve *a*

the voltages would go much higher. Figs. 7 and 8 show how the impulse ratio varies with time on typical gap and line insulator arrangement.

Over one hundred oscillograms have been obtained of traveling voltage waves due to lightning on transmission lines. These waves had generally come a considerable distance and were thus greatly reduced in voltage, modified to some extent by attenuation, reflections, etc. In most cases they were evidently caused by storms

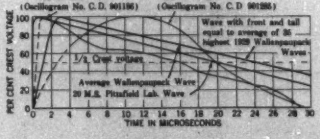



Fig. 23—Typical Natural Lightning Waves of Long and Short Fronts, and Average Shape as Recorded at Wallenpaupack in 1929

Pittsfield Standard 20-microsecond wave included for comparison

some distance away. It is interesting to examine these waves with the view of determining just what impulse spark-over voltages should be expected. The importance of this is seen when it is remembered that surge voltage recorder measurements indicated that lightning spark-over voltages were usually 1.8 or more times the 60-cycle voltage (see Figs. 12 and 13) although it is known that the impulse ratio varies widely with different waves and is dependent on conductor polarity. To

*Originally a ¼-microsecond front was used with a slightly higher voltage.

make this examination complete it is necessary to see what happens at the point of origin of the wave where the induced voltage $V$ is maximum.

The formation of induced voltage on lines is as as follows:[4]

The charging process of the cloud is relatively very slow. This permits the leakage from line to ground of the charge having the same potential as the cloud. A bound charge opposite in potential and varying in intensity with the cloud charge is held on the line. The cloud discharges at a very rapid rate releasing the charge on the line. *The voltage from line to ground increases rapidly to a maximum value.* Eventually two free traveling waves are formed and propagated in opposite directions with voltages less than maximum. If the discharge were instantaneous the maximum voltage would be:

$$V = g\,h$$

while the maximum voltage of the free traveling waves would be:

$$V_1 = \frac{g\,h}{2}$$

Since the discharge is not instantaneous these two voltages are:

$$V = g\,h\,\alpha \text{ (maximum actual voltage)}$$
$$V_1 = g\,h\,\alpha' \text{ (voltage of traveling wave)}$$

where $\alpha$ and $\alpha'$ depend upon the time it takes the cloud to discharge and the distribution of bound charge. If this time is over a few microseconds, $V$ and $V_1$ become quite small (see Fig. 24). From the above, insulator spark-overs should take place under the center of disturbance where the voltage is highest. They should thus be due to the voltage $V$, and not to the voltage $V_1$ measured by the oscillograph. Accordingly, the next step is to get an approximate idea of wave $V$ from $V_1$.

Calculations for a range of cloud sizes and rates of discharge show that $V$ reaches maximum in from one-half to one-third the time indicated by the front of the free traveling wave, and perhaps even less. Thus, voltage is applied at a more rapid rate for $V$ than $V_1$. Therefore the impulse ratio for spark-over on the front should be higher for $V$ than for $V_1$.

An examination of Fig. 22 shows that for the measured traveling waves 50 per cent reach crest voltage $V_1$ in less than 3 microseconds and 90 per cent in less than 8 microseconds. However, the rise in voltage $V$ at the origin should be at least twice as steep as $V_1$ the impulse ratio at the origin should thus correspond very approximately to the dotted curve in Fig. 22. This shows that 50 per cent reach crest in less than 1½ microseconds and 90 per cent reach crest in less than 4 microseconds. On Fig. 7 are plotted impulse ratio curves for spark-over on the rising front of a wave with time. This shows that for the waves measured the impulse ratio for $V$ should be higher than the average 1.55 for 90 per cent of the waves and over 1.9 for 50 per cent. These measurements thus seem to check the former impulse ratios obtained by surge voltage recorders of natural lightning in Figs. 12 and 13 and also justify the laboratory values of lightning voltage given in these figures. Of course, occasionally conditions may be right for breakdown to occur on the tail of the wave at a lower impulse ratio.

Fig. 24 shows that voltages high enough to cause spark-over by induction cannot occur unless the cloud discharge is quite rapid. For example, consider a line 30 ft. high and a cloud 2000 ft. long. For a discharge time of ten microseconds the maximum voltage $V = g\,h\,\alpha = 100 \times 30 \times 0.25$ (see Fig. 24) $= 750$ kv. With a 2000-ft. cloud and a 10-microsecond discharge the front would be in the order of 2 or 3 microseconds. The impulse ratio would be about 1.6. Thus $V$ would not be sufficient to cause spark-over on 7 insulators, the standard for a 110-kv. line. It would thus appear

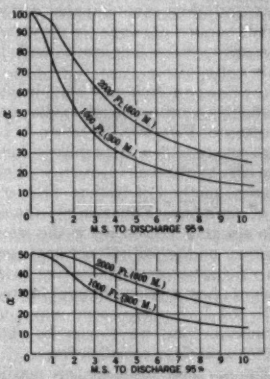



FIG. 24—REDUCTION FACTORS $\alpha$ AND $\alpha'$ FOR CLOUDS OF 1000- AND 2000-FT. LENGTHS

that voltage waves in Fig. 22, Curve (*b*) for a front of more than 3 microseconds (6 on the free wave) need not be considered *for high-voltage lines. For low-voltage lines* slower waves may reach sufficient voltage to cause spark-over at a lower impulse ratio. However, where the rate of cloud discharge is rapid, high induced voltages result. For example, assume a line 40 ft. high and a cloud 2000 ft. long discharging in 4 microseconds.

From Fig. 24, $\alpha = 0.53$

$V = 100 \times 0.53 \times 40 = 2120$ kv. This would give a wave with a front of about 2 microseconds at the source or 4 microseconds as measured when traveling free. The impulse ratio for the 2-microseconds front from Fig. 7 is about 1.8. With this impulse ratio the spark-over voltage is about 1900 kv. for 14 units from Fig. 10. Under these conditions the induced voltage is high enough to cause spark-over on a 220-kv. line.

This wave would correspond approximately to the average Wallenpaupack wave in Fig. 23. Induced spark-over voltages of a high impulse ratio would thus be expected for high-voltage lines and spark-overs at lower impulse ratios would be expected on lines insulated for voltages below 110 kv. Corresponding impulse ratios would also be expected for full wave and for "overvoltage" spark-over on the tail of the wave. For example, the average steep wave from Fig. 23 is 1/10 while the average for all high-voltage waves is 3/24. Overvoltages of from 0 to 50 per cent on these waves would give the highest impulse ratios observed.

It would thus appear that with reasonable assumptions as to length of bound charge (for example, 2000 ft.) and rate of cloud discharge, the average measured wave in Fig. 23 can be accounted for by induction and maximum voltage values of over 2000 kv. can be expected.

In case of direct strokes the wave would probably be still steeper and thus give impulse ratios over 1.8. Direct strokes become of relatively more importance as a cause of spark-overs as line insulation is increased or on the higher voltage lines.

While the above analysis can only be approximate, it is still probably accurate enough for its purpose.

A comparison of Figs. 10, 12, 13, and 14 shows that the standard waves of 5 and 20 microseconds can produce all the effects of breakdown on a rising front and offer a practical method of testing. Under equivalent conditions of time from Equation (1) the same spark-over results are thus obtained for the standard wave with breakdown on the tail (50 per cent sparking) and for uniformly rising waves with sparking on the front.

Fig. 14 shows how a range in impulse ratio varying from 2 (with the ½/5-microsecond wave) to 1.2 (with the 1½/40-microsecond wave) can be obtained with fixed waves for a check on coordination.

*2. Insulation.* The insulator or needle-gap is a useful means of expressing the strength of apparatus or insulation, especially when it is desired to compare test values obtained on waves of different shapes. By measuring the strength of insulation with insulators or needle-gaps the effect of wave variation is largely eliminated. See Fig. 14 where the point-gap is expressed in terms of insulator units.

*3. Statistical Study.* Fig. 25 is of particular interest since it is an attempt to arrive at the nature of lightning waves and voltages purely from a statistical study of outages. It is a plot of outages per hundred miles of line with the number of insulators per foot of line height. This method was used to put lines of different height and insulation on an equal basis. The points from lines in different parts of the country are shown on the curve. They were obtained on lines of varying height, number of insulators, with and without ground wires, etc., and are weighted and reduced to 100 thunder storm days per year. A word of explanation of Fig. 25 may be necessary. For example, referring to the curve with 0.4 insulator units per foot of conductor height, the expected outages would be 21 per 100 miles per year. If the conductors are 40 ft. high, the total insulator units per string would be 16. From Fig. 12 this would give a lightning spark-over voltage of 2200 kv. or a gradient to cause spark-over on 55 kv./ft. The expected outages would then be 21 per year per 100 miles of line in country where 100 storms occur per year. If the number of storms per year are 30 rather than 100 the expected outages would be $\frac{30}{100} \times 23 = 6.9$. With a

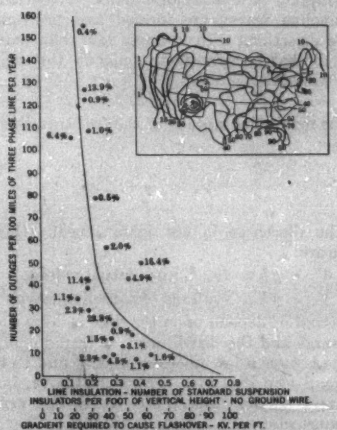



Fig. 25—Estimate of Probable Outages on Transmission Lines from a Statistical Study

(Reduced to standard basis by dividing insulators by height of conductor, correcting for ground wire effects, and reducing to 100 storms per year. Figures on points indicate percentage of total year-miles used in estimate)

This curve refers to a location having 100 thunderstorm days per year. For other locations take values from curve and apply to section under consideration by multiplying by percentage of 100 thunderstorm days per year as shown on the above map

ground wire reducing the voltage to 50 per cent the equivalent insulation is $\frac{0.4}{0.50} = 0.80$. The expected outages with the above insulation and 100 storms per year basis would be 5. While this curve is not yet as complete as would be desired it does give a good indication of what can be expected. Fig. 25 also indicates quite well, from the statistical standpoint, that the outages increase with the height of line, decrease with decreasing insulation, decrease with ground wires, and that a gradient of 100 kv./ft. is the maximum. To indicate this the gradients necessary to cause spark-over are shown on the curve. The outages should become very small when the gradient equals the maximum

lightning gradient provided the impulse ratio is about 1.9 as given in Fig. 12. This occurs for a gradient of 100 kv./ft. This value was originally arrived at on a different basis. These data also indicate that the lightning spark-over voltages of Fig. 12 are approximately correct. *Direct stroke outages are indicated when the line insulation is stronger than the maximum calculated induced lightning voltages.*

An example will be given of the use of the data in design of a line. Assume 60 ft. conductor height. At a gradient of 100 kv./ft., the maximum induced voltage, $V = 100 \times 60 = 6000$ kv. With a ground wire arranged to reduce the voltage to 50 per cent, $V = 6000 \times 0.50 = 3000$. Assume 20 insulators are used. From Fig. 12 the spark-over voltage of 20 units is 2700 kv. From Figs. 13 and 14 proper distance from conductor to tower can be obtained. Some outages should be expected because the insulator strength is less than the maximum voltage. By reducing the conductor height greater security could be obtained. It is now interesting to check in an entirely different manner by an entirely different method, the apparent ability of this line to resist lightning. In other words check it by experience gained in practise on similar lines. From Fig. 24 plot a curve for a 60-ft. line with different numbers of insulators and with and without ground wires for 30 storms a year. Plot the same for a 30-ft. line for comparison. It is seen that for the 60-ft. line with ground wire and 20 insulators the number of expected outages would be three or four. With a 30-ft. line and ground wires the maximum voltage would be $V = 30 \times 100 \times 0.50 = 1500$ kv. From Fig. 12 an insulator string of 12 units would have a strength greater than 1500 kv. Referring to the curve, the expected outages for such a line insulated with 12 units would be practically nil.

It is of interest to examine these curves from other angles.

It is seen that the expected outages would be 50 per 100 miles with 14 insulators and a 60-ft. conductor height. With a ground wire reducing the voltage to 50 per cent the expected outages would be 16.

By adding two insulators, a total of 16, the expected outages are 38 without and 12 with the ground wire arranged to reduce voltages to 50 per cent. With two ground wires and a reduction to 40 per cent the expected outages would be about 4. This corresponds to the usual 220-kv. line. With a properly located direct hit wire above the ground wire, and low resistance ground, it now appears feasible to eliminate direct stroke outages. For a 110-kv. line the usual insulation is 7 units. The expected outages would be 130 without a ground wire and 28 with two ground wires. Reducing the height to one-half has a marked effect. While such a curve could not give the exact number of outages for any one line any one year it should give approximate values over several years and be of great help in deciding the economic and technical value of various arrangements.

## V. Standard Wave—Coordination

*1. Standard Wave.* In general fundamental research on different types of gaps, insulators, insulation and different apparatus, such as lightning arresters, and transformers, various special effects must be considered. Careful research must be made with all types of waves. However, it would be of great convenience to have a standard wave particularly for the purpose of making a comparison of various types of insulators, bushings, and gaps. Such data are needed for coordination and to determine the ability to spark over without puncture. Such a wave should be easy to duplicate, should permit of many tests in a short time, and should produce the effects of severe lightning. The most severe lightning effects usually occur with high impulse ratios, particularly where solid insulations are present. This follows because the solid insulation of an insulating member is submitted to higher voltages for steeper impulses and the effect is cumulative. There is no reason to make impulse tests for an impulse ratio approximating unity because the effects are the same as at 60 cycles. A wave giving an impulse ratio of about 1.8 seems reasonable. This could be obtained for example by a uniformly rising wave reaching spark-over in about 2 microseconds or preferably by a standard wave (with 50 per cent sparking) of ½/5 or ½/20. The full fixed standard wave is by far the simplest method and is least subject to error. A greater range of effects could be obtained with a long and a short standard wave. Several impulse ratios could also be obtained by the full standard wave and by fixed wave overvoltage. The fixed full wave method with one or two standard waves is therefore recommended. For testing special types of apparatus it may sometimes be necessary to use a circuit giving proper energy relations of traveling waves on a line.

*2. Coordination.* Coordination means the adjustment of lightning breakdown voltage between the transformer or other apparatus and the adjacent line insulation so that if lightning voltages become high enough, line spark-over will occur and limit the incoming voltage waves sufficiently to prevent transformer or other apparatus failure. It is not intended to take the place of lightning arresters or other protective devices, but rather to act as a safe-guard against very heavy discharges and in case the arrester is out of service. If the arrester is operating satisfactorily it will prevent spark-over on the coordinated gap. The gap is thus also a good check on the condition of the arrester. Coordination may be effected either by the use of the standard insulation for ½ mile from the station or by a specified gap at the station and within 100 ft. of the apparatus. Coordination permits the use of extra insulation wherever desirable on other parts of the line. Since the coordinated section is relatively short the use of normal insulation on this portion usually has very little effect on the outages. If desirable, extra ground wires can be used over this section. The transformer bushing

is generally made stronger than the line insulation but weaker than the transformer insulation. Coordination has been in use on one 220-kv. line for several years. The coordinating gap has flashed over many times during this period without damage to the transformer.

In setting the coordinating gap or adjusting the line insulation it is important to know if coordination will hold over a wide range of transient wave-shapes. If the setting is made for the standard wave it will usually hold for all impulse conditions. (See Fig. 14 for point gap and insulators.) This follows unless the factor $a$ or $\beta$ in Equations (1), (2), (3), and (4) varies widely. The necessary margin for any arrangement of gaps or insulation can be readily determined from these equations. In order to make an experimental check, different high-voltage bushings were set up in parallel with insulators and then with a point gap, and tests made for full wave and overvoltages with the ½/5 and 1½/40 waves. Lags varying from less than one microsecond to over 40 microseconds, or impulse ratios for over 2 to 1.2, were thus obtained. The gap and insulator always protected the bushing as determined by spark-over values with the standard ½/5 wave. The values calculated from the equation also checked. An example of this type of test is given for insulators and point-gaps in Fig. 14.

## VI. Conclusions

1. The law of breakdown and time lag has been derived from experimental data and is expressed as follows:

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right) \quad \text{The impulse ratio} \tag{1}$$

$$t = \left(\frac{a}{\beta - 1}\right)^2 \quad \text{The time lag} \tag{2}$$

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right) \quad \text{The impulse breakdown voltage} \tag{3}$$

Where

$e_0$ = the minimum breakdown voltage—usually the 60-cycle crest value
$t$ = time lag in microseconds
$\beta$ = impulse ratio
$a$ = factor dependent on the electrode and insulating material

This law, which appears rational, states that a given amount of energy is required to break down insulation and that time and voltage are interdependent. It is quite in agreement with the work in the original paper[1] and applies to breakdown on rectangular waves, on slanting waves of uniformly rising voltage, or to overvoltages on standard waves. By means of the above formula the results for different waves can be calculated and correlated.

2. The three general types of waves, which are rectangular, uniformly rising front, and standard logarithmic, have characteristics and would give results as follows:

(a) A perfectly rectangular wave, because of its shape, would eliminate several variable factors in connection with the analyses of impulse spark-over results. However, due to circuit conditions, it is difficult to produce in practise a wave which more than approximates the rectangular form. With an approximate rectangular wave, practically the same variable factors that other wave forms cause are introduced. Also, this rectangular wave form would be very unlikely to occur in practise from natural lightning sources.

(b) Spark-over on the front of a wave probably is typical of many lightning flashovers in the field. The use of this form of impulse failure is feasible in laboratory studies. However, precise oscillographic records of every spark-over are necessary.

(c) The use of a standard laboratory wave of logarithmic front and tail permits securing impulse breakdown effects close to those associated with most natural lightning surges. By proper adjustment of wavelength and selection of breakdown point on the wave it is also possible to simulate the effect of a rectangular wave, sloping front, or any other wave form. An interesting mathematical relationship showing this equivalent effect can be deduced.

The fixed wave method simplifies the testing problem greatly as it necessitates merely a parallel sphere-gap for measurement purposes and requires no oscillographic records. Overvoltage tests on such waves increase the range. Since it also represents practical conditions, gives the most consistent results and can be made to give the effects of the others in insulator testing, it appears the best standard for comparison. Severe, steep wave-front effects can be obtained with the ½/5 wave, while a large range of results can be obtained with three waves of ½/5, ½/20, and 1½/40.

For testing very special apparatus the slanting front may sometimes be desirable with circuit arrangements to give proper energy relations.

3. Data are tabulated from which the impulse spark-over voltage for a wide condition of waves can be calculated. These data will be added to and corrected for greater accuracy as quickly as laboratory work permits.

4. The field investigation of lightning indicates that:

The average lightning wave, even with maximum voltages sufficient to cause spark-over on a 220-kv. line, can be accounted for by induction, with reasonable assumptions as to size of cloud and rate of discharge.

Spark-overs may be caused by either induced voltages or direct strokes. Direct strokes become of proportionally increasing importance as causes of outages when line insulation is increased.

Voltages giving impulse ratios of the order of 1.8

cause a large percentage of the spark-overs on high-voltage lines.

5. Waves giving low impulse ratios are not representative of average field conditions, and do not give severe enough effects for impulse testing.

6. Statistics compiled from lightning records gathered from widely scattered power systems substantiate the fact that the standard laboratory waves (½/5 and ½/20) discussed above give effects truly representative of average field conditions. These statistics also serve as a valuable basis for considering economically the line insulation necessary under different conditions.

7. It therefore seems quite proper to consider the above standard lightning wave as a rational basis upon which to compare insulator and insulation strengths in the general problem of coordinating line and apparatus insulation.

8. Coordination of system insulation on transmission lines has been used on important systems and its value is now recognized. The law of time lag given above permits the proper coordination under all conditions.

## VII. Acknowledgments

The author acknowledges the valuable assistance of Messrs. W. L. Lloyd, Jr., H. L. Rorden, J. C. Dowell, and L. G. Levoy in carrying out the laboratory work, and of Dr. J. T. Lusignan, Jr., and Mr. L. V. Bewley in formulating the data.

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## Discussion

For discussion of this paper see page 1496.

# Rationalization of Transmission Insulation Strength—II

## Need for, Present Status, and Necessary Developments for Carrying Through

BY PHILIP SPORN*

Member, A. I. E. E.

*Synopsis.—This paper, prepared with the cooperation of the members of the Insulator and Lightning Subcommittee, points out the present need for rationalizing transmission system strength on the basis of lightning voltage. The higher grade of service demanded of transmission systems today requires fewer interruptions. It is pointed out that for a four year period the line interruptions due to lightning on an extensive 132-kv. network average 75 per cent of all line outages.*

*Apparatus failures due to lightning, while not numerically great, can be materially reduced, if the system insulation is coordinated on the lightning basis.*

*Over-insulation of lines has been tried in some cases, particularly on wood pole lines, with varying degrees of success in reducing line outages. But this method of attacking the lightning problem does not consider the protection of station equipment where the most costly apparatus is subject to damage, and where apparatus damage may result in long service outage.*

*It is pointed out that additional knowledge is necessary on lightning strengths of insulation and apparatus to rationalize system voltage strengths on a lightning basis. This information is gradually being secured by various groups working on the problem.*

*To aid in solving the lightning problem it is proposed a set of standard test waves be adopted by which insulation and apparatus, if possible, may be tested. With this knowledge of the lightning insulation strength of apparatus it will be possible to design transmission systems more intelligently, as far as insulation is concerned, on a lightning basis in addition to the present 60-cycle basis.*

*On the basis of field data secured last year on wave-shapes of natural lightning, three standard test waves are proposed having voltage time characteristics similar to those actually observed.*

*Lightning voltage, it is pointed out, should be designated in units peculiar to lightning, and not in terms of 60-cycle voltage values.*

* * * * *

### I. Introduction

THIS paper is intended to represent the standpoint of the Insulator and Lightning Subcommittee in regard to rationalization. A standpoint representative of the committee as a whole, in so far as that is possible, is given. This does not mean, however, that in every respect it meets with the unanimous endorsement of every member of the Subcommittee; where divergencies of opinion exist the points of view expressed in the paper are those of the chairman and of a majority of the committee rather than of the committee as a whole. In particular is this true in regard to the question of standardization of a lightning wave. Several of the committee members believe strongly that a lightning test wave cannot be standardized at the present time; another group, however, feels equally convinced that a single or a group of waves can be standardized at the present time to great advantage and to the great benefit of all those interested in the advancement of the electrical insulation art, particularly as it affects the transmission system. The chairman of the subcommittee is among those favoring the adoption of a series of standard lightning test waves and the views with regard to this subject, expressed in this paper, can be taken as representative of his views and the majority of the subcommittee.

*Chief Electrical Engineer, American Gas & Elec Co., New York, N. Y.

Chairman Insulator and Lightning Subcommittee

Members: Philip Sporn, J. G. Hemstreet, W. W. Lewis, C. A. Jordan, J. H. Cox, Herman Halperin, I. W. Gross

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.*

### II. The Need for Rationalization

The general subject of rationalization of transmission system insulation strength, although perhaps known and practised for some time previous, was presented formally before the Institute in the Spring of 1928.[1] Subsequent events have demonstrated the importance of this phase of engineering and the need for its further development. A review of this development ought to be of help in obtaining a full idea of the significance of the problem.

In the paper already referred to,[1] it was pointed out that the principal high voltages which have to be insulated for are those due to lightning; in other words, the unsolved lightning problem is the one barrier to continuity of service. Further data, accumulated since then, have resulted in a further check of the correctness of this statement. For example, on the 132-kv. system of the subsidiaries of the American Gas and Electric Company the lightning outages in per cent of total outages have been as follows:

In 1926—81.6%
In 1927—77.2%
In 1928—68.2%
In 1929—75.7%

1. For references see Bibliography.



30-98

Data of the above type can leave no question of the predominance of lightning as the source of trouble; and a conclusion is reached that the insulation for lightning is the one factor that has to be particularly watched out for; in other words, that the lightning problem is the paramount insulation problem. Nor is there any doubt that at the present time lightning is only very little controlled. Yet in the face of all that, the power frequency (which in most cases means 60 cycles) is the frequency at which insulation strength is measured and in terms of which it is designed, built, sold, and installed. The logic of this is rather hard to defend; in fact one may doubt, and this has been expressed previously, that there is any logic in it.

The unhappy results of lack of rationalization continue to pile up. In a previous paper[1] there was cited a considerable number of failures on 132-kv. transformers; others have since developed. For example, there was a case on an extensive 132-kv. system on the property of one of the subsidiaries of the American Gas and Electric Company where a 10,000-kv-a. transformer that had been in service less than a year failed during a lightning storm at a substation where this transformer was tapped to the line. A surge recorder connected on each of the three phases of the circuit near the transformer showed a maximum crest voltage of 1050 kv. on two phases and 600 kv. on the third phase. The failure produced a short circuit between the transformer turns and coil sections at some distance from the line coils; the bushing in this case was entirely unharmed. A lightning arrester installed on the same bus and on which surge recorders were again connected showed current in the three phases of 96, 262, and 310 amperes respectively.

In another instance, during a lightning storm high voltage entered one phase of a 132-kv. transformer bank and jumped through the oil to the ground sleeve of the bushing. The transformer was put back into service and was apparently entirely satisfactory, but at the end of four hours tripped again. Subsequent examination showed that an arc had gone from the end to the middle of the winding by two paths, one through oil and barrier bolts to the tap changer and the other across the top of the coils. Two 132-kv. lightning arresters were connected to the incoming lines throughout this entire period; the arrester ground resistances were found to be five ohms in one case and one ohm in the second.

Again, a number of cases has since been experienced with failure of 132-kv. coupling capacitors, used for carrier current communication, these capacitors being in each case of the dry mica type. In each case the failure was during a lightning surge on the system. The electrostatic capacity of these capacitor groups was 0.001 microfarad. It is obvious that in the cases of these coupling condensers the electrostatic capacity of 0.001 microfarad which is an appreciable value, was not sufficiently high to act as a lowering medium for the surge, to render the capacitor self-protecting. Experience with failure of other important apparatus of the same nature is available; it cannot, of course, all be cited here.

There is another aspect of the generation and transmission problem which makes insulation rationalization very necessary and that is the development of high-voltage generation. With the higher generating voltages obtainable today the ideal always sought, but not often found, of distribution at generating voltages is again obtainable in many cases; but here again, the problem of insulation for high voltages, where feeders connected to overhead transmission systems are to be fed from these busses, is complicated by the problem of lightning strength of the generator windings.

Heretofore only a mild form of the problem had to be met. It is obvious that to take full advantage of the important advance in generator voltages the knowledge obtained on lightning insulation strength must be applied to the knowledge that has yielded the higher generator voltage. The introduction of a 1 to 1 transformer, for example, is not solving the problem; it is very definitely slurring it and running away from it.

The development of the idea of overinsulation of transmission lines is of rather recent occurrence and once again contributes to the chaos instead of solving the problem of rationalization of insulation. In the last few years there has been a very definite economic drive to obtain transmission line service with fewer outages. The types of load that have been taken on have in most cases demanded service continuity of the highest sort, and this has led to the raising of the insulation level to heights undreamed of a few years ago. Thus, we have had a recent 220 kv. development designed with eighteen 5¾ in. units for the transmission line. Again, the use of wood poles, wooden crossarms, and braces[2, 3] has spread over the last few years with the probability that their use will spread further in time to come. In many of these cases the use of wood has resulted in the setting up of insulation barriers that have permitted voltages of as high as 2,450,000 volts to be measured on moderate voltage transmission lines, with an indicated voltage in the order of 4,000,000 volts at the point of flashover.

Still another problem that adds to the gravity of the insulation situation has been the uncertainty of lightning arrester operation. The case of the 10,000-kv-a. transformer, where an arrester was installed very close to the transformer, which failed from a lightning impulse, has been cited. The transformers referred to in the earlier paper,[1] had in some cases lightning arresters installed, in other cases none, with apparently very little difference in behavior. In the case of the 132-kv. transformer where an internal bushing flashover occurred lightning arresters were installed near the transformer terminals. In another case where arrester performance was being measured voltages on the three phases of the arrester of 1300, 900, and 1000 kv. were

measured by the klydonograph and amperages of 500 and 650 measured on the phases corresponding to the first two voltages. Here it will be noticed that, within the limits of accuracy of the instrument employed, it was shown an arrester permitted the piling up of a voltage of 1300 kv. although it was discharging a considerable current. It is true of course that within the last year there have been developed new types of arresters,[4, 5] but after all, these arresters still have to prove themselves. It must not be forgotten that the electrolytic arrester, when it was developed, was confidently believed to be the ultimate in lightning protection.

In short, it may be said that while service on transmission systems has been in general pretty good it has been only that; on the other hand the crying need is for good and practically perfect service. There are still too many cases of trouble that interfere with this very necessary and ideal standard, and much blame for such trouble can undoubtedly be ascribed to the failure to properly rationalize system insulation strengths. The system not being designed or insulated to withstand the dangerous disruptive forces of lightning voltages, it is the fault of the *system* designer alone if these forces ultimately cause a failure in a portion of the system and raise all the havoc with service concomitant with such a failure.

## III. The Present Status of Rationalization

A first examination of the present status of rationalization gives the impression of a rather hopeless situation. Very little progress has been made since 1928. To date, therefore, the same chaotic situation with regard to data on insulation strength, particularly with regard to data on competitive equipment, exists as was pointed out previously. In fact, the more the situation is examined the more confusing it appears. Even the 60-cycle flashover value for standard suspension units *of the same spacing and of substantially the same design* as given by various manufacturers does not agree; differences of from 10 to 15 per cent are quite common.

As regards the lightning phase there is still apparent the same tendency to let well enough alone. The same idea that service is pretty good and that the situation need not be disturbed is found among many people who ought to take the situation more seriously, particularly when it is taken into account that such an attitude of mind invariably leads sooner or later to a disturbance of cyclonic character. There is still going on a haphazard adjustment or readjustment of insulation values. Points that are found apparently weak are strengthened without too much regard to the rest of the system. As an example of that, the use of wood to further increase the lightning flashover of the transmission line circuit can be cited.

The insulator and bushing manufacturers, it may be stated very definitely, have done little toward the problem of coordination in which they should be vitally interested. The entire problem has apparently been left to the transformer manufacturers (among these only a selected group has obviously been able to tackle the problem intelligently) and to large users of equipment.

And yet, if the situation is examined more closely, it does not appear quite so hopeless. For one thing, the importance of the transmission problem is greater than ever. Larger systems have been developed, and are continuing to be developed, and larger blocks of power are being transmitted and handled all the time. The effect of flashovers, therefore, in these larger systems is not only greater than ever but is also felt in many other directions. Not only is the destructive effect of an arc following a flashover greater with increased power of a system, but, as systems extending over hundreds of miles are put together, new disturbances arise as a result of flashovers. For example, the stability problem is one that has come to the forefront in the last few years.

Again there has been aroused a definite engineering interest in the problem and in its solution. Many organizations who would not have considered it except in the light of a very theoretical sort of study are now at work on the problem. In fact it is not rare at all, at the present time, to find designers of stations and substations who carefully go into the various phases of the problem and pay it as much attention as they formerly gave problems of line and station capacity, switching arrangement, etc. All this stirring of interest and concentration of many various engineering minds on the problem is bound to have a beneficial effect in the direction of bringing a satisfactory solution to the problem.

In the field of accomplishment, while positive and definite results are not obvious, there has nevertheless been achieved a considerable amount of progress. Manufacturers of apparatus, particularly of transformers, and among these again particularly the two largest manufacturers, have been studying the problem of lightning insulation and the problem of coordination and of rationalizing the entire insulation structure. There have actually been developed designs of transformers within the last two years and such transformers have been sold on a so-called self-protecting basis. This, of course, is rationalization, although only partial rationalization. It is highly desirable, and is significant of the progress that has been made; but the field to which it has been applied is altogether too narrow.

In the laboratory many fundamental researches have been undertaken as to the characteristics of various types of insulation under surge conditions. The work of Peek[6] and Torok[7] on the characteristics of insulation as affected by time and voltage is typical of this work. In the field a large number of investigations with artificial and with natural lightning has been carried through and particularly valuable data were obtained during the past year.[8]

Several committees of the Institute have taken the problem for their own and have done a considerable amount of work on it. Among these are the Trans-

former Subcommittee of the Electric Machinery Committee, the Insulator and Lightning Subcommittee of the Transmission Committee, and the Lightning Arrester Subcommittee of the Protective Devices Committee. Each of these has attempted in its way to contribute to the problem of rationalization of the transmission system insulation and each has made some progress, although none of the three has concluded its work. The fact, however, that the problem is being attacked from these three angles is significant and offers the hope that the solution, when it is finally reached, will be a broad one and will not be one satisfactory from one phase or from one angle of the situation only. In this connection, it may be very illuminating to describe the experience covering one important phase of the problem which was attacked by one committee and which, through the intervention of the activities of another committee, resulted in perhaps a different action being taken than would otherwise have occurred and in bringing about a situation more in conformity with the broad point of view necessary to maintain in problems of this type.

This situation involved a proposed addition to the Standards of the A. I. E. E. for transformers, induction regulators, and reactors. The Transformer Subcommittee of the Electric Machinery Committee had been considering the question of impulse strength of transformers. As a result of these discussions the subcommittee came to the conclusion that it would be desirable to recommend an addition to Section No. 13 of the Standards (dealing with transformers, induction regulators, and reactors) to embody recommendations on the relationship between transformer and line insulation strength. This relationship was to be given in the form of an appendix to the Standards, the principal paragraph of which is given below:

RECOMMENDATIONS ON RELATION OF TRANSFORMER INSULATION TO ADJACENT LINE INSULATION

(a) Transformers Receiving Standard Dielectric Tests—Para. 13-400 and 13-401.

Apparatus conforming with the standards of dielectric test should be so designed that their impulse strength against lightning is greater than the impulse flashover voltage to ground of non-shielded suspension type insulators having a 60-cycle r. m. s. dry flashover in accordance with Table I.*

TABLE I

| Rated circuit voltage | Transformer 60-cycle test voltage | Insulator 60-cycle dry flashover voltage |
|---|---|---|
| Kv. | Kv. r. m. s. | Kv. r. m. s. |
| 69 | 139 | 250 |
| 92 | 185 | 350 |
| 115 | 231 | 400 |
| 138 | 277 | 450 |
| 161 | 323 | 550 |
| 196 | 393 | 640 |
| 230 | 461 | 725 |

*Commercial methods for determining the impulse strength of transformer windings by acceptance test in the factory are not feasible. However, investigations in the laboratory show that the impulse strengths of transformer insulation and of standard line insulators or of air-gaps vary similarly with different forms of waves, also that the impulse ratio of strings of line insulators of different lengths is approximately constant for the same impulse wave. The forms of impulse waves actually occurring on transmission lines have not been fully determined. For these reasons, the impulse strength of transformer windings are expressed in terms of the 60-cycle dry flashover voltage of either line insulator or air-gaps.

The appendix included a long footnote defining the various methods of limiting lightning voltages on the portion of the circuit adjacent to the apparatus to the lightning flashover voltages of line insulators having the 60-cycle flashover voltages given in Table I.

This subcommittee was about ready to make its recommendations to the Machinery Committee when the Insulator and Lightning Subcommittee became interested in the problem and suggested that a matter of this type was of such vital interest to the transmission field, and of so great importance, that it would be desirable that the matter proposed be held in abeyance until such time as the problem could be gone into jointly between the two subcommittees.

After fully going into the situation, the Lightning Subcommittee decided that it would not be to the best interest of all concerned to have the proposed standard adopted, and it registered its opposition accordingly. In the course of a joint meeting between the two committees, where this entire question was threshed out, the Lightning Subcommittee pointed out the following specific objections to the proposed standard.

1. The material bearing on this subject is in a state of flux and should therefore not be put in standard form, under these conditions.

2. There is a strong feeling among engineers that operating practise should not be coordinated as a part of A. I. E. E. Standards.

3. While the proposed Standards do not propose to prescribe standard practise, it would in fact result in doing that. The data being obtained at the present time may quite likely result in standard practise changing considerably in the future.

4. Impulse strength should be expressed in appropriate units and not in secondary units, such as 60-cycle voltage. With the advance made in lightning research it ought to be possible to do that within the next two or three years.

5. The matter of coordination or rationalization of impulse strength of transformers and line insulation should not reach a stage of even tentative standards, but should be handled by papers presented before the Institute by interested parties having knowledge of the matter.

A subsequent canvass and discussion of this situation with the rest of the Transmission Committee resulted in a complete approval by its membership of the stand taken by the Lightning Committee. As a result, the proposed standard was not approved; the matter is instead being presented in the form of a symposium before the Institute, this paper being one of that group.

## IV. Necessary Developments for Carrying Through the Problem of Rationalization

The foregoing data have been presented with a view of showing the still chaotic condition of the present insulation situation and the various influences that are at work to bring some order out of the chaos. They show that

while the situation is still in a considerable state of fog and confusion, it is not entirely hopeless. The question arises as to what can be done to carry rationalization completely through.

A large number of items is needed. The most important of these are, however, the following:

1. *Knowledge as to Lightning Strength.* If, as is admitted, the major insulation problem is that under lightning conditions, then it is almost axiomatic that, before any definite progress can be made in design or coordination, the first thing necessary is the knowledge as to fundamental lightning strength of all links of insulation in the transmission chain. Expressing this strength in terms of any other unit, for example, in terms of the power frequency unit, is most certainly not satisfactory and will only result in delaying progress in the solution of the problem. It is not conceivable that for all classes of insulation the relationship between 60 cycles and lightning strength can remain the same for varying lightning voltages encountered. Nor will the lightning problem be placed on a stable and scientific foundation so long as a unit representative of insulation strength of a piece of apparatus under lightning conditions is shied at. The form which this lightning strength is to take is immaterial so long as the unit is one definitely expressive of lightning conditions. Whether this is to take shape in the form of volts and time or volts in terms of a standardized impulse wave is immaterial so long as a break is definitely made, and it is expressed in terms of its own rather than in 60-cycle or power frequency values.

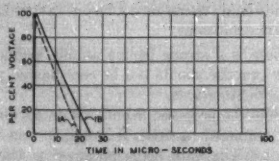


Fig. 1—Proposed Standard Impulse Test Wave

2. *Necessity for Standard Lightning Wave.* While, as pointed out above, the necessity of expressing lightning insulation strength in terms of a unit of its own is of prime importance and the form in which this is to be expressed is secondary, there is no question but that the establishing of a standard lightning wave will considerably accelerate the solution of the problem. Under present conditions data gathered by various investigators are not readily comparable. Some investigators have even cautioned that their data are not comparable with results obtained by others. The adoption of a standard test wave would automatically remove all these difficulties. The standard could be changed from year to year or as required until definite information is made available as to what could serve as a permanent standard.

It is admitted that a single wave would cover the situation rather unsatisfactorily; but it is not necessary to limit the standard to a single wave. It is possible, for example, to adopt three different waves and this is the proposal now made in this paper: That three waves referred to as 10-microsecond, 30-microsecond, and 90-microsecond waves* be adopted. That such an arrangement would represent a situation in fairly close conformity with the data as gathered to date can be seen from Figs. 1, 2, and 3. In each of the above three figures curve *A* represents one of the three proposed standards, Fig. 1, Curve 1-*A* showing the 10-microsecond standard, Fig. 2, Curve 2-*A*, the 30-microsecond standard, and Fig. 3, Curve 3-*A*, the 90-microsecond standard.

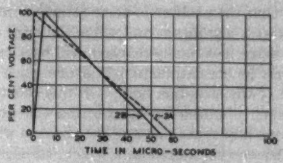


Fig. 2—Proposed Standard Impulse Test Wave

The *B* curves in Figs. 1, 2, and 3 are based on 15 natural lightning voltage waves obtained in the field during the 1929 lightning season.[9] The crest value of 12 of these waves varies from 500 kv. to 1260 kv. The voltage time characteristics of these 15 waves are as follows:

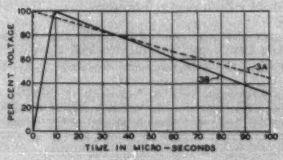


Fig. 3—Proposed Standard Impulse Test Wave

TABLE II

(TIME IN MICROSECONDS)

| | To Crest | Drop to 50% Crest |
|---|---|---|
| Maximum | 11 | 69 + |
| Minimum | 2.5 | 16. |
| Average | 6.3 | 30.2 |

The *B* curves, based on Table II have the following characteristics:

*It is proposed that all waves have a ¼-microsecond front; the time referred to in the designation of the waves may be considered as a special time constant and is the value in microseconds required for the wave to fall to 50 per cent of its crest value.

TABLE III
(TIME IN MICROSECONDS)

| | Curve | To Crest | Drop to 50% Crest |
|---|---|---|---|
| Maximum | 3-B | 10 | 75 |
| Minimum | 1-B | 1* | 15 |
| Average | 2-B | 5 | 30 |

*This value has been taken as less than one-half the observed value to allow for possible errors in determining wave fronts in the field, and further, to recognize the limitations of field observations where it is believed in many cases the lightning stroke did not occur close to the line.

It will be noted that in each case the proposed standard is a very fair approximation of the range in lightning wave-shape that it is intended to cover and it is believed that in the light of existing data, therefore, the three proposed standards, or slight modifications of them, can very definitely be undertaken. It is recognized that the adoption of standards as above would fall considerably short of the ideal standard, but the benefits to be obtained through the adoption of this temporary standard are so great as to decidedly make worth while its immediate adoption.

*3. Data as to Variation of Lightning Strength of Insulation.* The lightning strength of insulation and of the apparatus is dependent upon the type of wave that the apparatus is subject to, or put in another way, it is dependent not only upon voltage but upon the time of application. The specific data as to characteristics of all apparatus under these conditions are desirable. Here, however, it should be recognized that while specific data covering the volt time characteristics of apparatus can and will ultimately be obtained for all classes of material, the process is necessarily long and tedious.

It is admitted that data on apparatus insulation strength expressed in terms of a particular impulse wave, or in terms of a group of waves, will give, to say the least, a good approximation of the complete data referred to above, and would certainly give data more suitable than any available at the present time. Further, such data could be obtained rather quickly. It is necessary, however, if the gathering of such data is to be undertaken, to have a standard wave or a series of waves, such as the three outlined above definitely adopted.

*4. The Determination of Relative Frequency and Importance of the Direct and Induced Strokes.* There is at the present time a very divergent opinion as to relative frequency and importance of direct and induced strokes in high-tension circuits. Experimental data and opinion are about equally divided in assigning of paramount importance to the direct stroke or the induced stroke as a source of trouble. Such divergence does not exist with respect to low-tension lines, where it is admitted that the direct and induced strokes are perhaps equally important as a cause of trouble. But the diverse opinion with regard to high-tension circuits makes it imperative, more than ever, to obtain sufficient information to clarify the situation and find out the true state of affairs. It is obvious that the method of protection adopted may vary considerably and will depend to a great extent upon which type of disturbance protection is being provided for. This makes the necessity of authoritative data on that particular phase extremely important.

*5. Further Data on Shape of Natural Lightning Waves.* While a considerable amount of field data was obtained during the last year on the shape of natural lightning waves, these data are far from complete and far from being conclusive. Too many were obtained on waves at a considerable distance from the point of origin. While mathematical analysis can give a solution for the probable shape of the original lightning wave, if the distance from the point of disturbance is known, such data are of course difficult to obtain. A more satisfactory solution will be to obtain records of direct strokes. Such data when obtained can be immediately utilized in a revision of any standard for lightning waves that may be in existence at that time.

*6. More Extensive and Accurate Field Data on Performance of Lines and Apparatus.* It has been pointed out in this paper that a great deal of progress has been made over the past two years in the accumulation of laboratory data with artificial lightning and in collecting data in the field laboratories with natural lightning and also with artificial lightning. A third phase of investigation, which has also advanced considerably, has not been mentioned, but its importance is equal to each of the other two classes of investigations. That is the detailed record and analysis of actual operating experience with lines and apparatus under various conditions of lightning. The natural operating tendency to bury the dead has to be fought in this case, and each operating fault or trouble should be made to yield its share of knowledge to the solution of the problem. The keeping of case histories of this type is most certainly an important contribution to the solution of a problem as important as this. Considerable progress has been made, particularly in the last few years, in the keeping of such data and in its publication but there are still too many cases where a process of reasoning is indulged in to justify the withholding of such information. Nothing, of course, is accomplished by that except the postponement of the day when the complete solution of the problem will have been obtained. Particular emphasis ought to be laid on the recording and analysis of data relative to the lightning conditions and if possible to the data regarding intensity of the lightning storms encountered.

*7. Fundamental Data as to the Effects of Various Types of Station Designs and Apparatus on Incoming Lightning Waves.* While some data have been obtained on this phase of the problem, much more information of an authoritative nature is needed to determine definitely the effect on incoming waves of various types of structures, and terminal apparatus; also the effect of travel of an incoming wave through such apparatus, on the apparatus itself, and upon the con-

nected equipment. In particular is it necessary to have further data on the effect of bushings, cable terminals, insulated cable, and similar apparatus.

8. *The Segregation of Insulation Strength, Particularly Lightning Insulation Strength, from Operating or Nominal Voltage Rating.* It has been brought out again and again that insulation strength under lightning conditions differs for different materials that may have the same strength under power frequency or 60-cycle conditions, and yet it may be desirable that all these pieces of apparatus have the same or definitely related values of lightning strength. The logical procedure for obtaining this is to specify insulation strength and operating voltage independently. By doing this the ideal aimed at, namely of obtaining for each system the insulation strength needed for that particular system, would most certainly be advanced. This of course has already been previously proposed.[1]

9. *Authentic Data on 60-Cycle Flashover Values.* In many respects the situation with regard to 60-cycle data is indicative of the entire situation. While 60-cycle flashover data are not of paramount importance in the rationalization problem, it is a fact that operating voltages and the insulation characteristics at operating voltages cannot be entirely neglected. It certainly is not possible to entertain much hope of putting any order into the situation with regard to so complex a problem as lightning insulation if the problem of insulation value at 60-cycle values is in as confused a state as it is at the present time. It would seem that as a prelude to the rationalization of the entire problem of insulation, first, and without delay, a definite standard, sufficiently detailed and specific, be adopted for measuring 60-cycle values, so that measurements taken at any reliable laboratory will agree within the limits of accuracy of the measuring apparatus used with measurements taken at any other laboratory. This is far from the condition today.

## V. Conclusions

1. The higher standards of service reliability required of the electrical art, the increase in size of the generating stations, and therefore the growth in the amounts of power handled over transmission systems, have placed heavy and increasing responsibility on the design and performance of the high-tension transmission systems. Lightning being the cause of approximately 75 per cent of service interruptions on high-voltage transmission systems, it is the most important factor which must be brought under full control, in order to bring the service of these systems within the necessary requirements of the electrical art today.

2. There is evident at the present time, as in the past, a continuation of a practise of insulating one portion of a transmission system without too much regard to the rest of the system. Too often when service failures occur, the weak points are more highly insulated, with the transfer of trouble to another portion of the system.

3. The conditions outlined under 1 and 2 above show very forcefully the need of rationalizing system insulation strength on the basis of performance under lightning conditions.

4. Some steps in this direction have been made and numerous developments are under way which show that the gravity and importance of the problem are fully realized. Several committees of the Institute are working on the problem, and many fundamental researches are under way in the laboratories and in the field. Very little that is definite has as yet been accomplished.

5. It has been shown that a continuation of many of the fundamental lightning researches are now being carried out in the field and in the laboratory are highly essential to the carrying through of the problem of rationalization.

6. It has also been shown that one of the great obstacles to such a rationalization program is the failure to adopt some definite unit in which to express lightning insulation strength. To express it in terms of 60-cycle strength, when what is aimed at is rationalization on the basis of lightning insulation strength, seems illogical for several reasons:

(a) It is not known that the relationship between 60-cycle and lightning voltage is the same for all types of insulation generally used, even for one given type of lightning wave.

(b) The ratio of 60-cycle to lightning voltage breakdown of apparatus differs with the variations in design of a piece of apparatus even for a fixed lightning wave.

(c) There is at the present time a lack of agreement on the 60-cycle dry flashover values on insulators of equivalent design as determined by data obtained at different laboratories of recognized standing. It would therefore appear to be better and more desirable to standardize lightning insulation strength on the basis of a lightning wave of definite characteristics of its own rather than on a 60-cycle basis.

7. As a first step in this plan, a set of three standard impulse waves is proposed in terms of which all types of insulation are to be tested. All three waves considered are to have a ¼-microsecond front and are to attenuate to 50 per cent of crest value in 10, 30, and 90 microseconds respectively. The values and shapes chosen are very similar to, and are based on, wave-shapes of natural lightning obtained on actual transmission lines, and ought therefore to approximate actual conditions insulation and apparatus may have to withstand in the field. These shapes may have to be altered from time to time when, and as, additional field data show it to be necessary. It is recognized further that it may not be commercially feasible to apply these waves at the

present time to some types of apparatus with built-up insulation. It is believed, however, that the adoption of these test waves will hasten the time when such apparatus can be so tested; certainly it will make possible the determination of the lightning strength of various designs and accelerate the general problem of research of lightning strength of various types of apparatus, since it will make possible the comparison and checking of data obtained in different laboratories and by different observers.

8. It is recognized that electrical breakdown of insulation is a function of both voltage and time, and that this type of data should be obtained for all types of insulation and should ultimately be obtained for all types of apparatus. It is believed, however, that the obtaining of such data will take a great deal of time; but the problem cannot wait. The proposed system of standard waves will, however, make possible the obtaining of much data and these data are fundamental and necessary if an advance in rationalization is to be made.

9. The lightning strength and operating voltage of transmission systems are independent, as previously pointed out, and as once more emphasized here. The lightning strength will depend to a large extent upon the type of service which a system is called upon to deliver, and not upon its operating voltage. It is believed that a distinct advantage will result in rationalizing insulation of transmission systems by considering the lightning strength independent of the normal frequency operating voltage.

Special acknowledgment is due Mr. I. W. Gross, Secretary of the Lightning Committee, for the help given by him in the preparation of this paper.

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## Discussion

For discussion of this paper see page 1496.

# Recommendations on Balancing Transformer and Line Insulations On Basis of Impulse Voltage Strength*

BY V. M. MONTSINGER† and W. M. DANN‡
Fellow, A. I. E. E. Fellow, A. I. E. E.

***Synopsis.***—*The danger of over-insulating transmission lines without a corresponding increase in the insulation of connected apparatus is pointed out.*

*To avoid trouble from lightning reaching the apparatus, the Transformer Subcommittee of the Electrical Machinery Committee has prepared a set of proposed rules covering: (1) A practical method of defining the impulse strength of transformers, and (2) recommendation on coordinating the transformer and adjacent line insulation on the basis of impulse voltage strength.*

*It is pointed out that commercial methods for determining the impulse strength of transformer windings by acceptance test in the factory are not feasible. However, investigations in the laboratory show that the impulse strengths of transformer insulation and of standard line insulators or of air-gaps vary similarly with different forms of waves; also that the impulse ratio of strings of line insulators of different lengths is approximately constant for the same impulse waves. The forms of impulse waves actually occurring on transmission lines have not been fully determined. For these reasons the impulse strength of transformers is expressed in terms of the 60-cycle dry flashover voltage of non-shielded suspension type insulators.*

*If the transformer and line insulation are properly balanced with a given wave, it eliminates the necessity of having to consider the different shapes of waves encountered in practise.*

*Three methods are recommended for coordinating the transformer and line insulation, namely, (1) the use of an effective lightning arrester; (2) the use of a horn-gap; and (3) the maintenance of average line insulation for a limited distance from the station.*

* * * * *

## General

FOR a great many years it has been the prevailing practise in the United States to correlate the amount of insulation used in a transformer and the value of the dielectric test which it receives with the voltage of the circuit on which the transformer operates. So long as the level of line insulation was kept at a reasonable value, this method worked out very satisfactorily.

Lightning has been the chief source of the abnormal transient voltages which on account of interruptions to service caused by line flashovers give serious concern to operating engineers. As a result, in an effort to remedy this condition, transmission engineers have been adding more and more insulation to their lines. The need for a more rational basis for insulating high-voltage transmission systems was pointed out by Philip Sporn in 1928.[1]

Where lightning is not severe, increasing the line insulation for normal service conditions has not resulted unsatisfactorily, but it is obvious that if the practise is continued without regard to the insulation of apparatus, trouble will result, as it has in some cases, because the maximum lightning voltage reaching the apparatus is limited only by the height and insulation of the adjacent lines and by protective devices, and is in no way related to the circuit voltage except in so far as the insulation of the circuit may change with the voltage.

The need of new insulation standards on account of this practise of increasing the line insulation has long been recognized by interested manufacturers and operators, and may now be said to be a necessity. Failure to adopt such standards has been due chiefly to lack of general recognition and acceptance of their proper governing factors, together with the difficulties of verifying them in the completed apparatus. Commercial methods for demonstrating the impulse strengths of transformers by acceptance tests in the factory are still not feasible. To make such a test on a transformer might cause undetected injury which would later result in failure in service; on the other hand, sufficient field experience and experimental data are now available by which it is possible to set up certain standards for the coordination of line and apparatus insulation.

Research and experimental investigations carried on by both manufacturers and operators within the past few years have yielded a great deal of new information relating to the impulse voltage strength of transformers, the impulse voltage arc-over of line insulators as determined by the laboratory, and to the magnitude and character of lightning voltages occurring on transmission lines as determined in the field.

Realizing the need of a more rational method of insulating high-voltage transformers the Transformer Subcommittee of the Electrical Machinery Committee in 1927 undertook the preparation of a set of recommendations for defining the impulse-voltage strength of transformers and for balancing the transformer with the adjacent line insulation.

While these recommendations have been completed

*Sponsored by Transformer Subcommittee: V. M. Montsinger, Chairman, Raymond Bailey, W. H. Cooney, W. M. Dann, J. Allen Johnson, H. C. Louis, L. C. Nichols, J. F. Peters, Philip Sporn.

†Research Engineer, General Elec. Co., Pittsfield, Mass.

‡Asst. Engineering Manager, Westinghouse Elec. & Mfg. Co., Sharon, Pa.

1. For numbered references see Bibliography.

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and are used by the manufacturers for expressing the impulse strength of transformers, they have not yet been recognized by the Institute for coordination purposes.

Before attempting to get any action by the Institute, it was agreed that the Transformer Subcommittee and the Lightning Subcommittee of the Transmission Committee sponsor the symposium of papers being presented at this session. It is hoped that as a result of all these papers, a definite set of rules can be agreed upon which will be acceptable to all concerned.

The purpose of this paper is to give the recommendations prepared by the Transformer Subcommittee together with a discussion of some of the more important phases of the subject matter.

## Proposed Rules

The proposal is divided into two distinct parts—Part I dealing with a method of defining the impulse strength of transformers, and Part II giving recommendations on coordinating the transformer and adjacent line insulation.

## PART I

### Impulse Voltage Strength of Transformer Insulation

*(a)—Transformers Receiving Standard Dielectric Tests, as Specified in Par. 13-400, A. I. E. E. Standards No. 13.*

Apparatus conforming with the standards of dielectric test should be so designed that their impulse strength against lightning is greater than the impulse flashover voltage to earth of non-shielded suspension type insulators having a 60-cycle r. m. s. dry flashover in accordance with Table I.*

TABLE I

| Rated circuit voltage | Transformer 60-cycle test voltage | Insulator 60-cycle dry flashover voltage | Corresponding† No. of insulator disks spaced 5¾ in. apart |
|---|---|---|---|
| Kv. | Kv. r. m. s. | Kv. r. m. s. | |
| 69 | 139 | 250 | 4 |
| 92 | 185 | 350 | 6 |
| 115 | 231 | 400 | 7 |
| 138 | 277 | 450 | 8 |
| 161 | 323 | 550 | 10 |
| 196 | 393 | 640 | 12 |
| 230 | 461 | 725 | 14 |
| | 510† | 810† | 16 |
| | 570† | 895† | 18 |
| | 625† | 980† | 20 |

*(b)—Transformers Receiving Higher Than Standard Test.*

If the 60-cycle dry flashover of the adjacent line insulation is greater than the value given in Table I, and is not locally limited to that value, transformers having a dielectric test corresponding to the actual adjacent line insulation should be used.

*(c)—Transformers Receiving Lower Than Standard Test, as Specified in Par. 13-402 (n), A. I. E. E. Standards No. 13.*

Transformers used with solidly earthed neutral and having the reduced insulation test of 2.73 times line to neutral voltage should have an impulse strength equal to that of a standard transformer for the next lower circuit voltage.

*Commercial methods for determining the impulse strength of transformer windings by acceptance test in the factory are not feasible. However, investigations in the laboratory show that the impulse strengths of transformer insulation and of standard line insulators or of air-gaps vary similarly with different forms of waves; also that the impulse ratio of strings of line insulators of different lengths is approximately constant for the same impulse waves. The forms of impulse waves actually occurring on transmission lines have not been fully determined. For these reasons, the impulse strength of transformer windings is expressed in terms of the 60-cycle dry flashover voltage of line insulators.

†These do not appear in the rules as proposed, but are given here merely for reference purposes.

## PART II

### Recommendations for Coordinating Transformer Insulation with Line Insulation in the Field

Limitation of lightning voltages, on the portion of the circuit adjacent to the apparatus, to the lightning flashover voltages of line insulation having the 60-cycle flashover voltages given in Table I may be accomplished by the use of one or more of the following methods:

*Method No. 1.*—An effective and properly applied lightning arrester connected to the circuit within 100 circuit feet (30 meters) of the terminals of the apparatus.

Method No. 1 furnishes the most effective protection, but in the absence of Standards for Lightning Arresters and their installation, Method Nos. 2 or 3 should always be used in combination with Method No. 1. If the impulse strength of the supporting insulation of the arrester conforms to the impulse strength of the gap with settings as given in Table II, then no additional parallel gap is necessary.

*Method No. 2.*—A suitable safety gap connected between each conductor of the circuit and earth within 100 circuit feet (30 meters) of the terminals of the apparatus with gap setting not in excess of the flashover voltage given in Table II.

TABLE II

| Rated circuit voltage | Transformer—60-cycle test voltage | Gap—60-cycle dry flashover voltage |
|---|---|---|
| Kv. r. m. s. | Kv. r. m. s. | Kv. r. m. s. |
| 69 | 139 | 185 |
| 92 | 185 | 240 |
| 115 | 231 | 300 |
| 138 | 277 | 355 |
| 161 | 323 | 410 |
| 196 | 393 | 500 |
| 230 | 461 | 585 |

These values apply to either arcing horns or rings attached to insulator strings or to points mounted separately. If rings are used, in order to avoid affecting the impulse ratio the gap should not be greater than 80 per cent of the length of the supporting insulator string.

*Method No. 3.*—Limitation of the line insulation to earth from points within 100 circuit feet (30 meters) of the terminals of the apparatus to points approximately ½ mi. (1 kilometer) therefrom, to values not in excess of the flashover voltage given in Table I.

## Available Data on the Impulse Strength of Transformers

The available data on the impulse strength of transformers may be divided into two general classes, namely, those obtained in the laboratory and those obtained under service conditions.

The natures of the two classes of data are, of course, quite different because in the laboratory a transformer can be tested to destruction, while the data obtained under service conditions have been in the form of "records" covering many years of service. These records show that when connected to transmission lines having certain insulation, transformers receiving a certain dielectric test have successfully withstood lightning voltages. The conclusion is that the impulse voltage strength of the transformers is satisfactory when coupled with line insulation having a certain impulse

*Ratio of impulse to 60-cycle crest voltage arc-over.

arc-over voltage. For example, if transformers receiving a 60-cycle dielectric test of 231 kv. have been operating successfully for many years on a 115-kv. circuit exposed to severe lightning conditions, and the line is insulated with seven 10-in. (25.4-cm.) disks spaced 5¾ in. (14.6 cm.) apart, the flashover value of these line insulators may be used as a "yard stick," indicating the impulse voltage strength of the transformer. This, of course, does not give a numerical measurement of the impulse breakdown strength, but affords a convenient measure of satisfactory impulse strength.

Laboratory tests have proved to be of great benefit in determining the impulse arc-over voltage of insulator strings using various shapes of waves, in obtaining the impulse breakdown of insulating materials such as oil, solids, oil and solids in series as used in transformers, and of complete transformer windings. These tests have brought out the following points:

1. The impulse ratio* of various types of transformer windings is fairly constant for a given wave. The significance of this is that the low-frequency dielectric strength from windings to earth gives a rough measure of the impulse strength (from windings to earth).

2. The impulse ratio of the flashover of insulator strings of different lengths, and of point-gaps of various spacings in air is practically constant for a given wave.

3. The impulse strength of windings which are fully insulated in accordance with the A. I. E. E. Standards (*i. e.*, windings insulated for a test of twice line to line voltage plus 1000 volts) is satisfactory when used with average line insulation used in the United States.

## Selection of Line Insulator Disks

Voltage arc-over values of 10-in. (25.4-cm.) insulator disks spaced 5¾ in. (14.6 cm.) between units, have been selected as the standard for expressing the impulse strength of transformers for circuit voltages of 69 kv. and above. Table I shows the general average number of 10-in. (25.4-cm.) disks used on the leading transmission lines in the United States[3] before the practise of over-insulating began.

## Yard Stick Used to Express Impulse Voltage Strength of Transformers

Since the impulse voltage strength of transformers as herein defined bears a certain definite relation to the arc-over of standard suspension insulator disks when subjected to various shapes of waves, under both dry and wet atmospheric conditions, it is possible to express the impulse voltage strength of the transformers in terms of disks. It could be specified by definite numbers of disks but disks sometimes vary slightly in length of spacing. Since both the 60-cycle and impulse flashover voltage of insulator strings is, within reasonable limits of lengths, proportional to the total length of the string made up of disks having different spacings, it seemed that the most dependable way of specifying an insulator string that represents a definite measure of impulse voltage is by its 60-cycle arc-over value. It was decided, therefore, to use the 60-cycle *dry* flashover values for "yard-stick" purposes. This results in a very simple and convenient way of arriving at the desired results.

The dry 60-cycle arc-over values of 4¾-in., 5⅛-in., 5¾-in., and 6½-in. spaced disks are given in Table III for reference purposes.

TABLE III

| Unit No. | 60-Cycle Dry Arc-Over Kv. r. m. s. | | | |
|---|---|---|---|---|
| | 4¾ In.† | 5 ⅛ In. | 5 ¾ In. | 6½ In. |
| 1* | (78) | (78) | 78 | (78) |
| 2 | 120 | 125 | 140 | 155 |
| 3 | 165 | 175 | 195 | 215 |
| 4 | 215 | 225 | 250 | 280 |
| 5 | 260 | 275 | 300 | 340 |
| 6 | 300 | 320 | 350 | 395 |
| 7 | 345 | 365 | 400 | 450 |
| 8 | 385 | 410 | 450 | 505 |
| 9 | 425 | 455 | 500 | 555 |
| 10 | 470 | 500 | 550 | 610 |
| 11 | 505 | 540 | 595 | 660 |
| 12 | 540 | 580 | 640 | 710 |
| 13 | 580 | 615 | 680 | 755 |
| 14 | 615 | 660 | 725 | 805 |
| 15 | 655 | 700 | 770 | 855 |
| 16 | 690 | 735 | 810 | 900 |
| 17 | 725 | 770 | 850 | 945 |
| 18 | 760 | 810 | 895 | 995 |
| 19 | 800 | 850 | 940 | 1040 |
| 20 | 835 | 890 | 980 | 1085 |

*Flashover of single unit taken as same for each size.
†Spacing between units.

The tabulation in Table I simply expresses the impulse strength of a standard transformer insulated in accordance with the American Institute Standards of Dielectric Test; it places no restriction whatever on the line insulation but rather it suggests suitable transformer insulation for any given adjacent line insulation. For instance, if it is desired to over-insulate the line next to the substation, Paragraph (b) indicates to what extent the transformers should be over-insulated. If, for example, a 230-kv. transformer is to operate on a circuit insulated with 18 instead of the standard number of fourteen 10-in. disks per string, the transformer should be given an insulation test of $461 \times \frac{895}{725} = 570$ kv.

On the other hand, if transformers of the reduced insulation class (built for operation with solidly and permanently grounded neutral and receiving an induced voltage test of 2.73 times line-to-neutral voltage) are used in accordance with the A. I. E. E. Standards, the adjacent line insulation should be reduced in the ratio of $\frac{2.73}{3.46}$. This reduction by coincidence corresponds approximately to the reduction in the adjacent line insulation for the next lower rated circuit voltage.

*Ratio of impulse to 60-cycle crest voltage breakdown.

## Recommendations for Balancing the Transformer and Transmission Line Insulation

So far, the method of expressing the impulse strength of transformers only has been discussed. It is quite important, however, that steps be taken by the purchaser to carry out the principle of balancing the transformer and the line insulation. If this is done, then the main part of the transmission line may be over-insulated without increasing the size and cost of the transformer.

Three methods are recommended: namely, (1) the use of an effective lightning arrester, (2) the use of a horn-gap, and (3) the maintenance of average line insulation for a limited distance from the station.

### Method 1—Lightning Arresters

The requirement that Method (2) or (3) should always be used in combination with Method (1) is included because quite often the lightning arrester is temporarily disconnected for inspection, overhauling, maintenance, etc., and it is desirable to have something to act as a last line of defense.

### Method 2—Horn-Gap

Quite often it is more convenient to use a gap to limit impulse voltages rather than maintaining average line insulation for a distance of one-half mile. This gap is sometimes in the form of spoons, or blunt points, mounted separately from the insulator string. Also, quite often the gap is formed by fastening guard-rings or arcing horns to each end of an insulator string using the insulators as a method of support. All these gaps as well as needle-gaps have practically the same 60-cycle and impulse arc-over characteristics for the same settings.

The gap impulse arc-over values are roughly 10 per cent less than the insulator impulse arc-over values. The reason for this is that except for a direct stroke of lightning at the transformer bank, the half-mile of reduced line insulation should provide better protection than a single gap having the same impulse voltage arc-over, because a wave coming in over the half-mile of normal line insulation will usually be attenuated more than 10 per cent by the time it reaches the station. By this is meant that if a wave comes along whose maximum value is just under the arc-over of the first insulator string, or if it arcs over the first insulation string, by the time it reaches the transformer one-half mile away, its maximum value has decreased at least 10 per cent below the value it had when passing the first insulator. Then, too, the one-half mile of normal line has several earthed points whereas a gap has only one. This should contribute to a little better protection.

It will be noted that the 60-cycle dry flashover values given in Table II are less than the 60-cycle dry flashover voltages of line insulators given in Table I by more than 10 per cent. This is because the impulse ratio of gaps is from 20 to 25 per cent greater than the impulse ratio of suspension insulator strings. Hence, for a gap to have say a 10 per cent less impulse arc-over the 60-cycle arc-over must be from 30 to 35 per cent less than that of an insulator string.

### Method 3

The 60-cycle flashover voltage values given in Table I represent even numbers of disks spaced 5¾ in. (14.6 cm.) apart. Consequently, these voltage steps are not in all cases proportional to the circuit voltage steps. The 60-cycle values which correspond in steps to the circuit voltages ignoring whether or not they represent even numbers of disks, would be about as shown in Table IV.

TABLE IV

| Rated circuit kv. | Trans. 60-cycle test voltage—kv. r. m. s. | Insulator 60-cycle dry flashover—kv. r. m. s. |
|---|---|---|
| 69 | 139 | 250 |
| 92 | 185 | 315 |
| 115 | 231 | 385 |
| 138 | 277 | 450 |
| 161 | 323 | 520 |
| 196 | 393 | 625 |
| 230 | 461 | 725 |

The length of the insulator strings corresponding to these voltages would be as given in Table V.

TABLE V

| Circuit kv. | Length of insulator string | |
|---|---|---|
| | Inches | cm. |
| 69 | 23 | 57.5 |
| 92 | 31 | 78.8 |
| 115 | 39 | 99.0 |
| 138 | 46 | 117 |
| 161 | 55 | 140 |
| 196 | 68 | 173 |
| 230 | 80 | 203 |

From the above it will be noted that the length of the string in inches is roughly one-third the rated circuit voltage.

Where insulator disks have a spacing different from 5¾ in. (14.6 cm.), it is felt that values corresponding to the above, or as near as can be obtained with even numbers of disks, would be the more correct values to use rather than those given in Table I.

## Nature of the Recommendations in Part II

These recommendations on balancing the transformer and line insulation are intended to be strictly advisory; they are given simply as a guide for the application of transformers on high-voltage transmission systems, considered from the standpoint of lightning voltages.

## Bibliography

1. *Rationalization of Transmission System Insulation Strength*, Philip Sporn, A. I. E. E. Quarterly Trans., Oct. 1928, p. 998.

2. "Surge vs. Impulse Tests for Transformers," *Electrical Wld.*, June 22, 1929, by V. M. Montsinger and J. F. Peters.

3. *Relation Between Transmission Line Insulation and Transformer Insulation*, by W. W. Lewis, A. I. E. E. Quarterly Trans., Oct. 1928, p. 992.

4. *Lightning*, by F. W. Peek, Jr., A. I. E. E. Quarterly Trans., 1929, p. 436.

5. *Surge Characteristics of Insulators and Gaps*, J. J. Torok, A. I. E. E. Jl., 1930, p. 276.

## Discussion

For discussion of this paper see page 1496.

# Coordination of Insulation as a Design Problem

BY G. D. FLOYD*
Member, A. I. E. E.

*Synopsis.—The factors having influence on insulation design of transmission line and station are briefly reviewed, and it is pointed out that the progress of the art does not yet allow of close design of the insulation structure for insulation strength.*

*The prominent part played by the lightning arrester is stressed, and the fact that it has a marked effect on the coordination of station insulation.*

*Examples of a typical 110-kv. station where no coordination was made, and of a 220-kv. station where a deliberate coordination was attempted, are given, as well as the experience obtained with each.*

## Introduction

INSULATION design, both for the transmission line and for the various members of the station insulation, has reached its present status largely through experience. The behavior of insulation, when subjected to electric stress, is probably less understood, even today, than any other electrical phenomenon, and as a consequence it has been necessary to apply the acid test of operation in order to determine the suitability of insulation design for the service intended. The almost total lack of knowledge of the magnitude and character of the over potentials appearing on a system has only added to the difficulty of rational design.

Overhead transmission at voltages of 110 kv. and above and for distances of the order of 100 miles and greater has been general for a number of years, and the service given by these systems has been, generally speaking, quite good from an insulation standpoint, considering the lack of knowledge of the behavior of insulation. Where weakness has developed, that part of the insulation structure has been strengthened, and therefore, unconsciously perhaps, a rational coordination of the various members of the insulation structure to the stresses, has resulted.

Several factors appear to have had an influence on the present condition of affairs. In the first place, there has been the desire for increased service security, and consequently attempts to make important lines lightning proof. The result, in many cases has been increase in the line insulation without corresponding increase in station insulation, so that the coordination accomplished through experience has been all upset, —sometimes with disastrous results.

A second factor has been the recent intensive study of the behavior of insulation when subjected to surges, and the parallel study of the magnitude and character of surges appearing upon transmission lines. The data obtained are by no means complete, and conclusions are often contradictory, but the general result has been to make possible, for the transmission line itself at least, a design which can make the line practically lightning proof, if desired. The data for bus supports and station inductive apparatus are not nearly so complete, so that the tendency naturally is, to design the line insulation to give a lightning-proof line, and to assume that the station insulation is satisfactory, in the absence of data to the contrary.

A third factor calling for close study of insulation requirements is the recent increase in practical system voltage to 220 kv. The natural tendency here has been to keep down capital cost of transformation by solidly grounding the 220-kv. neutral and using graded insulation on the transformer. The only justification for the higher system voltage is a decrease in over-all transmission cost, so that any means of accomplishing this with safety is desirable. On the other hand, the amount of power per circuit carried on these high-voltage lines has made it imperative that the line insulation be sufficient to keep outages from flashover to the lowest possible number. These tendencies are in opposite directions, so that some means of coordination must be arrived at. The most direct method would appear to be to increase the transformer insulation strength, but other means are available, some of which are given in detail later.

## Factors Governing Design

*A. Transmission Line.* The overhead transmission line is subject either to lightning, switching surges, and surges due to arcing grounds, or to the latter two only. The magnitude of the maximum lightning surge has been quite definitely established to be several times that of the switching surge, so that a line which has ample insulation to withstand lightning surges can usually be considered as safe against all surges that may occur of whatever nature.

The magnitude of the lightning surge is proportional to the average height of conductor above ground if the surge is induced, and the voltage is higher, if no ground wire is used, for the same average height of conductor. The maximum surge potential that the line may assume is also limited to the insulation strength of the insulators for the surge in question. This in itself, is a variable quantity, due to the variation in impulse ratio of the insulators. This applies whether the surge is a so-called direct hit, or an induced surge.

The insulation strength of the string along its length has been determined with some degree of accuracy by laboratory tests, and varies greatly with the duration of the surge, increasing as the duration decreases. The insulator string is therefore, to some extent, self-protecting, as the surges of highest magnitude are usually also of short duration. Fig. 1 shows this clearly; also the effect of grading rings.

*Testing Engineer, Hydro-Electric Power Commission of Ontario, Toronto, Ont., Can.

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Minimum insulation strength is not always developed along the insulator string, and arcs sometimes strike from the line end of the string to the tower. The present tendency towards increasing the insulation on existing lines will increase this possibility, and it should be kept in mind when increase in insulation of the line is contemplated.

Table I has been compiled from data on 110-kv. and

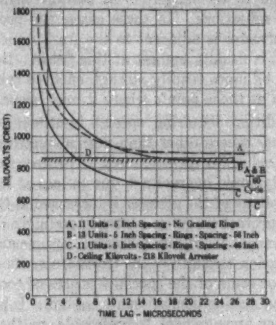


FIG. 1—KILOVOLT FLASHOVER-DURATION CURVES FOR SPILLWAY GAP

220-kv. lines of the Hydro-Electric Power Commission of Ontario, and shows the estimated insulation strength of the lines, at commercial frequency.

TABLE I

| Line | Average height of top conductor | No. of insulator units of 5 inch spacing | 60 Cycle flashover | |
|---|---|---|---|---|
| | | | Dry | Wet |
| | feet | | kv. | r. m. s. |
| Pelham-St. Thomas steel tower | 58 | 9 | 470 | 340 |
| St. Thomas-Windsor steel tower | 50 | 8 | 420 | 310 |
| Niagara-Dundas steel tower | 47 | 8 | 420 | 310 |
| St. Thomas-St. Clair wood pole | 29* | 7 | | |
| Thunder Bay wood pole | 33 | 7 | | |
| Thunder Bay steel tower | 54 | 8 | 420 | 310 |
| Ottawa-Smith Falls wood pole | 28* | 7 | | |
| Paugan-Leaside steel tower | 37* | 18 | 785 | 608 |

*Flat configuration. Paugan-Leaside line has two ground wires, all others one ground wire.

The lightning outages on approximately 1000 circuit miles of 110-kv. line equipped with suspension insulators per 100 miles per year are as follows:

1926—2.96
1927—1.25
1928—1.53
1929—2.65

The corresponding figure for the 230 miles of 220-kv. line from Paugan Falls to Toronto for one year of operation (1929) is 1.75.

When the majority of the 110-kv. lines were placed in service, nothing was known regarding the magnitude of lightning voltages to be expected, or of the impulse insulation strength of the insulators, yet these lines have been relatively immune from flashover due to lightning in districts having 25 to 30 storms per year. The outages average less than two per 100 miles per year for all 110-kv. lines, and the line insulation has never been increased.

The 220-kv. line has only been operating one lightning season, and there have been four outages, the cause of which could not be traced. Due to the fact that thunder storm areas were known to be in the vicinity of the line at the time the line flashed over, the outage has been considered as due to lightning. The insulation requirements for this line had been very carefully reviewed before specifying 18 units with 5-inch spacing. From the data available at the time, it appeared that this line should be very nearly immune from flashover due to lightning, but that to make it lightning proof appeared possible only by greatly increasing the insulation. The increase in cost would not be justified by the relatively small increase in service security.

This point cannot be stressed too strongly. It seems certain that with the present types of lines, one or two flashovers per year are bound to occur, in lightning areas, no matter what the design. The cost of towers, as well as of insulation, will increase rapidly if the number of insulator units required to make the line 100 per cent proof are specified. The increase in cost cannot be justified, unless in some very special cases of important tie lines of short length. It would appear to be better to concentrate on means whereby the line may be cleared rapidly, before the power arc can do material damage, and accept the momentary interruption. This may not involve a total interruption in many cases, because of the increasing degree of interconnection of power sources, and the fact that power demands have increased to such an extent that a number of high voltage lines are necessary to serve most districts where service security is of paramount importance.

The transmission scheme suggested in another paper[1] read at this convention can be coordinated easily as to insulation, if the scheme is found practicable from other considerations. With the arrangement suggested, it is possible to accept flashovers on any one high-voltage circuit. If these are cleared instantaneously, as seems to be easily done, so that no conductor or insulator damage occurs, there is no loss of service or increase in maintenance cost. Over insulation of lines is not necessary, and coordination of insulation, other than that normally required heretofore, is not required.

*B. Station Insulation.* Some measure of coordination of insulation strength among the various members of the station insulation structure is desirable, regardless of whether there is necessity for coordination of the station insulation with line insulation. If flashover is to occur, it is always better that the overstress be relieved at a point where least damage will result. The difficulty is that it is practically impossible to design the various members so that failure will occur for all

1. For references see Bibliography.

types of surges and all conditions at a given location, unless the insulation is so greatly weakened that there is danger of flashover for surges that would be harmless otherwise. It is not sufficient to design so that the oncoming wave will encounter slightly higher insulation as it progresses into the station because possible reflections at points of discontinuity make it necessary to have the insulation greatly stronger at such points. For example, unless the bushing at the line side of an open circuit breaker had at least twice the flashover value of the coordinated line insulation approaching the station, a surge which would just pass this insulation would be likely to cause flashover at the bushing. The assumption is made that the coordinated insulation is depended upon to restrict surges to a value harmless to the station insulation.

Great progress has been made in the last few years in knowledge of the behavior of station insulation when subjected to surges. As a result, the maximum surge voltage which station apparatus may be subjected to without injury will no doubt soon be known, but at present this information is far from being complete. It appears certain that for a few years at least, designers must rely on the sum total of experience supplemented by such reliable information on insulation strength of apparatus as becomes available. This does not mean that coordination of insulation cannot be attempted at the present time, but it does mean that with the data available, too much reliance must not be placed on coordination to give results that will always be effective.

## Effect of Lightning Arrester

Fortunately, the same investigations that made possible increased knowledge of insulation strength to surges, also placed the operation of the valve type lightning arrester out of the realm of speculation. It is now possible to state with some definiteness to what value the maximum surge voltage will be limited, with a given arrester. It is, therefore, possible, in the general case, to design the station insulation so that its impulse flashover will be greater than the ceiling voltage of the arrester installed. The term ceiling voltage is defined as the maximum crest voltage at arrester location permitted by the arrester for all types and magnitudes of surges. The impulse strength of bus insulation and to a lesser extent, of high-voltage bushings, is known with some degree of accuracy, but in the absence of such data, a fair approximation can be made on the basis of the 60-cycle insulation strength.

The impulse strength of transformers is still a point regarding which very little is known definitely. Experience with transformers on the lower voltage lines which are protected by lightning arresters, indicates that the arrester having a protective ratio of 3.5 or better will protect the transformer which is designed for standard insulation test against 90 per cent of lightning surges to which it is subjected.[3] It may be concluded that the transformer impulse strength is therefore in the order of at least 2.5 to 3.0 times crest value of system voltage to ground. The coordination of station insulation therefore resolves itself into designing the various parts to have greater strength than the arrester ceiling voltage.

A number of exceptions to the above general condition are evident. In the case of outdoor stations the length of bus may be such that an arrester, if located at the line entrance, may allow surges to pass, of sufficient magnitude to be dangerous to station insulation because of reflections. In these cases, the proper place for the arrester is adjacent to the transformers, as the reflection is usually highest at this point. Bus insulation can be more readily strengthened to take care of reflection at those points where it may occur.

A condition requiring special treatment occurs in those cases where other than normal number of units are required in the arrester stack to protect the arrester against dynamic overvoltage due to loss of load. The ceiling voltage of the arrester is increased in these cases and the protection given is correspondingly decreased. If the increase in ceiling voltage is appreciable, either the insulation strength of the transformer should be increased, or some of the special features of coordination of line and station insulation attempted. It is felt that the former arrangement is preferable, as the latter is still of too uncertain a nature to be depended upon, especially for stations of large capacity.

A third case is one which applies most particularly to some 220-kv. systems, where advantage was taken of a solidly grounded neutral to specify graded insulation. In these cases, it would be expected that an arrester with the normal protective ratio might not be quite good enough to protect the transformer against all surges. Coordination of line and station insulation may then be used as a last resort, or a spillway or protective gap installed, but drastic reduction in insulation strength on the line adjacent to the station appears to be necessary with its attendant difficulties due to line outages.

Two typical cases are tabulated below for stations of the Hydro-Electric Power Commission. The first, given in Table II, is for a 110-kv. outdoor step-down station, protected by lightning arresters, in which no attempt was made to coordinate line and station insulation, other than by specifying for the station, bus insulation which was known to be satisfactory from previous experience in other stations. It may be stated that no failure of transformer insulation due to lightning has occurred and only two or three flashovers of porcelain in any 110-kv. station of the commission. With one exception, lightning arresters have been installed at such stations and an insulation test of twice maximum rated voltage for the transformers has been specified. None of these transformers have graded insulation.

The second case is that of the 220-kv. line entrance and station bus insulation for Toronto-Leaside transformer station. Two banks of transformers were installed in this station in 1928, and as no satisfactory

TABLE II

110-KV. INSULATION. HAMILTON TRANSFORMER STATION

| Item | Insulation units | Flashover 60 cycle | |
|---|---|---|---|
| | | Dry | Wet |
| Lightning arrester. Oxide film. Total cells 1168. 3 phase stacks and ground stack. Cells per stack—292 | | kv. | r. m. s. |
| Line and bus disconnects | 2 unit pillar | 329 | 220 |
| Circuit breakers—Line | 110 kv. bushing | 345 | 300 |
| —Transformer | 132 kv. bushing | 400 | 345 |
| —Transformer | 110 kv. bushing | 345 | 300 |
| Transformer | 110 kv. bushing | 345 | 300 |
| Strain bus | 10 suspension units 5 inch spacing | 515 | 385 |

lightning arresters were available at that time, a deliberate attempt was made to coordinate the line entrance and station insulation with the transformer insulation. The transformers had the 220-kv. winding insulation graded, and the standard A. I. E. E. induced test of 2.73 times system voltage to ground or 350 kv. was specified. There are four groups of high-voltage coils and as an additional precaution, the line group of coils was provided with insulation equivalent to that for a transformer designed for 440-kv. test voltage.

The various items of the insulation structure are given in Table III

TABLE III

| Item | Insulation units | 60 Cycle flashover | |
|---|---|---|---|
| | | Dry | Wet |
| Line from station to point 2 miles out, with 4 ground wires | 14 five-inch, ungraded suspension disks | kv. 665 | r. m. s. 520 |
| Disconnecting switch | 6 unit pillar | 645 | 560 |
| Supported bus | 6 unit pillar | 645 | 560 |
| Suspension bus | 20-5 inch, ungraded suspension disks | 850 | 670 |
| Oil breaker bushing | Oil filled | 585 | 420 |
| Transformer bushing | Condenser—not less than | 550 | 465 |

In spite of this attempt at coordination, an apparatus insulation failure occurred during a severe lightning storm early in 1929. No evidence of lightning flashover on the reduced line insulation was found.

After the failure, a spillway gap was installed adjacent to the transformers having 13 five-inch disks, and arrangements were made to have an equivalent gap tested in the laboratory, both with and without grading rings. Although a number of storms have occurred since installation of the spillway gap, no flashover of the gap has occurred. However, a continuous record was kept during the lightning season with a klydonograph recorder, and no record of any surge of magnitude sufficient to cause flashover of the gap was obtained.

Lightning arresters are now being installed adjacent to these transformer banks, having an estimated ceiling voltage of 870-kv. crest. The relation of this ceiling voltage to the flashover voltage of the spillway gap is shown in Fig. 1.

One other instance of an attempt at insulation coordination is of interest. A number of 110-kv. potential transformers purchased by the commission in 1924, were built to a specification which required that on test, the voltage be applied to the low voltage winding and raised until flashover occurred on the high-voltage bushing.

These transformers have given satisfactory service, but there is no evidence that they would not have given equally as good performance if the above feature had been left out of the specification.

## Summary

The trend of insulation coordination has been indicated and summarized; this trend appears to be somewhat as follows:

1. Knowledge of insulation required for both line and station apparatus has been acquired largely as a matter of experience, and a coordinated system has resulted.
2. Increased line insulation has come about as a result of:
   (a) Recent investigations into behavior of lines and line insulation when subjected to surges.
   (b) Better knowledge of magnitude and character of lightning surges.
   (c) Desire to decrease the number of line outages, especially on important circuits, with relatively high loading.
3. Knowledge of the behavior of station insulation is still such as to allow only very general approximations to be made. The situation is complicated by the very intricate nature of voltage reflections which may occur at points of discontinuity.
4. Station insulation has not been increased because the amount of increase necessary could not be accurately specified, and also because of the difficulty of modifying existing stations to the new insulation design.
5. If the valve type lightning arrester is used, it is a determining factor in station insulation requirements.

## Acknowledgment

The facilities of the High-Voltage Laboratory of the Westinghouse Electric and Manufacturing Company at Trafford were used to obtain the data shown in Fig. 1. It is a pleasure to record the cooperation of engineers of this and other organizations in studies of our insulation problems.

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4. *Rationalization of Transmission System Insulation Strength*, Philip Sporn, Trans. A. I. E. E., Oct. 1928, page 998.

## Discussion

For discussion of this paper see page 1496.

# Standards of Insulation and Protection for Transformers

BY J. ALLEN JOHNSON[1]
Fellow, A. I. E. E.

and

EDWIN S. BUNDY[2]
Associate, A. I. E. E.

*Synopsis.—This paper presents the reasons and the evidence which have influenced the authors to favor the proposed Recommendations on Relation of Transformer Insulation to Adjacent Line Insulation set forth in a companion paper by Messrs. Montsinger and Dann.*

*The paper first outlines the principal considerations which govern the determination of transmission line insulation on the one hand and transformer insulation on the other, and concludes that the line insulation is a service problem requiring a unique solution whereas the transformer insulation is a manufacturing problem requiring a standardized solution. True co-ordination of the one with the other therefore seems impossible, indicating the need for protective measures at the point of contact.*

*Considerations affecting the selection and characteristics of such protective measures are discussed briefly and the reasons outlined for believing that, at present, service experience is a better criterion than research tests upon which to decide such selection.*

*Twenty-five years' service experience on the system now controlled by the Buffalo, Niagara and Eastern Power Corporation, with protective gaps similar to those recommended as one of the proposed protective measures, is described and the conclusion drawn that the use of such gaps under suitable conditions constitutes a satisfactory protective measure.*

* * * * *

THIS general subject was first brought to the attention of the Institute in a formal way by two papers[3,4] presented in 1928.

Following the presentation of these two papers, the question was referred to the Transformer Subcommittee of the Electrical Machinery Committee. After long consideration this subcommittee formulated for insertion into the Institute Standards for transformers a proposal defining the conditions, with respect to surge voltages, under which standard transformers might safely be operated. The proposed provisions are included in the companion paper by Messrs. Montsinger and Dann.

The problem has been precipitated by the trend toward higher standards of transmission line insulation than prevailed at the time the present standards for transformer insulation strength were adopted, and takes the form of a question whether transformer insulation strength should be increased, or transformer protection standardized.

The purpose of this paper is to record some of the considerations which influenced the writers, one of whom is a member of the Transformer Subcommittee, to favor the proposed method of dealing with this situation. These considerations relate, first, to certain factors which appear to govern the rational choice of line and transformer insulation strength, and second, to operating experience with a system of protection similar to one of those proposed. No claim is made for originality, but it has seemed worth while to record the argument in order to help clarify the situation and crystallize opinion.

## Considerations Governing Selection of Line Insulation

It is now universally recognized, of course, that long transmission lines must be insulated against lightning rather than merely for the operating voltage if they are to render acceptable service from the standpoint of continuity. Just how strong the insulation should be is a unique economic problem in each particular case, governed by a number of factors.

In a territory subject to a given statistical number of lightning storms per year producing a given number of discharges per unit of area, the number of outages occurring on a given transmission line will be a function of two factors which may be broadly and briefly stated as (1) strength and (2) length. The number of interruptions per year on a given line, other things being equal, will be in proportion to an inverse function of its insulation strength and a direct function of its length. We have become accustomed during the past few years to sum up the insulation performance of a transmission line in terms of flashovers per mile per year, but unfortunately the standard of service to customers dependent upon the continuity of the line, which is the basic determining factor, depends not upon the number of interruptions *per mile* per year, but upon the *total* number of interruptions per year. Thus it follows that if equal service is to be rendered by lines of unequal length, the insulation strength must be varied in inverse proportion to the length of the line. A ten mile 66-kv. line insulated with four standard 10-in. disks will almost certainly give more continuous service than a hundred mile line insulated with eight disks.

Thus it is apparent that length is one factor entering

1. Chief Electrical Engineer, Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.

2. Electrical and Operating Engineer, Niagara, Lockport & Ontario Power Co., Buffalo, N. Y.

3. *Relation Between Transmission Line Insulation and Transformer Insulation*, W. W. Lewis, A. I. E. E. Trans., Vol. 47, Oct. 1928, p. 992.

4. *Rationalization of Transmission System Insulation Strength*, Philip Sporn, A. I. E. E. Trans., Vol. 47, Oct. 1928, p. 998.

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30-114

the rational design of transmission line insulation for a given service requirement.

Another factor which bears on the question is whether it is the only line supplying the load or whether there are other lines supplying the same load either from the same source or from different sources. It is obvious that for a given quality of service to the customer, a single supply must be better insulated than a properly relayed multiple supply.

Another set of factors involved is the frequency and severity of storms in the territory traversed by the line. A line traversing territories differing in these respects may have its insulation varied accordingly. Of similar import is the profile of the right of way or of the line itself. A high river crossing for instance, is often more heavily insulated than the remainder of the same line.

Still another factor is that of earth conditions, which may affect not only the level of the conducting plane with relation to the transmission wires, but also the resistance of the tower foundations to earth, both of which may, in appropriate circumstances, affect the frequency of flashover of a given insulation.

The presence or absence of ground wires and other protective devices is still another factor of importance.

The above are believed to be the principal factors controlling the rational design of line insulation and it will be observed that they all relate to the particular circumstances surrounding each individual problem.

## Considerations Governing the Selection of Transformer Insulation

In the first place, it is obvious that transformers connected to overhead transmission circuits must be built to withstand lightning surges in some degree. The only question is as to the degree of strength which they should possess. There are three alternatives: (1) the transformers may be built to withstand the maximum surges which they can receive from any line, or (2) the transformers may be built "special" for each installation to withstand the maximum surges which can be received from the actual transmission lines, or (3) the transformers may be built to withstand surges of a definite maximum amount and protected against surges of a higher value.

Under the first alternative it would be necessary to build all transformers to withstand direct strokes of lightning. It seems obvious that if this were possible at all its cost would be quite uneconomic and entirely out of the question.

Under the second alternative since practically every transformer built would have different conditions to meet they would all be different, and standardization of transformers would, of course, have to be abandoned. Moreover, conditions might change with time and transformers originally installed to supply short lightly insulated lines, for instance, might later be called upon to supply long heavily insulated lines, for which they would not be adequate. That this alternative would result in chaos and would be entirely unworkable is too obvious to require further discussion.

We are therefore forced to the adoption of the third alternative, namely, the standardization of transformer insulation to withstand surges of limited magnitude. This also involves the problem of protecting the transformer against surges of greater magnitude than it is designed to withstand. Both of these problems, it should be observed, are questions of standardization.

To sum up, it is evident that the transformer is a manufacturing problem and calls for a standardized solution, whereas the line is a service problem and demands an individual solution. Co-ordination between the two, therefore, appears quite impossible.

There are two ways in which the strength of the transformer insulation might be fixed. One way would be to determine the characteristics and magnitude of the lightning surges to which transformers are subjected, devise ways of reproducing such surges in the laboratory in order to learn the surge resisting properties of insulation, and then use these data to design transformers to withstand such surges. Another way would be to build transformers and put them in service where they are subjected to the actual lightning surges and learn by experience. This method is perhaps less scientific, but lightning surges and insulating materials, and our knowledge of them being what they are, it seems likely that this method would result at least as well and possibly better than the more scientific method. As a matter of fact, this is the method which has been largely followed in the past and has resulted in our present transformers

The next question is whether the present standards for transformer insulation are satisfactory or whether new standards possibly more closely related to the higher average strength of modern transmission line insulation should be adopted. Since many millions of kv-a. of transformers built under present standard specifications are already giving satisfactory service there would seem little point in now establishing a new standard at a different level, especially as protection against surges of greater magnitude than the transformers would be designed to withstand would always be necessary, regardless of the actual level of insulation strength chosen as standard.

## Protection of Transformer Against Excessive Lightning Surges

If this conclusion is accepted, the problem still remains of protecting the transformer against surges too severe for it to withstand. Again there are two ways in which we can proceed. The first alternative is to specify exactly the magnitude and characteristics of the maximum surges which the transformer will withstand, leaving the user to determine as best he can the required protection. This alternative demands intricate scientific knowledge of natural surges and of the behavior of insulation, which is not now and may never be completely available.

The second alternative is to standardize the characteristics of protective devices. Such devices may be much simpler and their characteristics much more easily determined and more closely controlled than those of the transformer and therefore may lend themselves much more readily to standardization with respect to surge voltage characteristics. Such devices may be separate pieces of equipment, or may be a part of the transformer.

Such protective devices may be selected not only with reference to the characteristics of the transformers but also with respect to the requirements of the service. For instance, if the service requirements should make it necessary that the transformer be protected against surges without interruption of the circuit, then a protective device of one character may be indicated. If on the other hand, the service requirements should be such as to permit an interruption of the circuit to protect the transformer, then a somewhat different and possibly less costly device may be justified.

Having come this far, one more question remains, namely: Is the protection of standard transformers against lightning surges a proper subject for Institute standardization? It seems to the writer that it is. Certainly it is if the protective device is made a part of the transformer. In any case the surges to which a transformer is subjected are a part of its environment in the same sense that the elevation, ambient temperature, weather exposure, and circuit current and voltage conditions are parts of its environment. The Institute Standards do not hesitate to specify the limiting conditions, in these other respects, to which the transformer is adapted, and there would seem to be no reason why they should not also specify the limiting conditions as to lightning surges.

If this is conceded, then again we are faced with the choice of either the scientific or the practical procedure. Again we find that the scientific procedure involves knowledge which is not available, whereas the practical procedure can be based on simple laboratory tests and on experience which can be demonstrated to have given satisfactory results.

The remainder of this paper is a brief account of the development on the system of the Buffalo, Niagara and Eastern Power Corporation of a simple protective scheme which is now generally used on this system and has behind it a record of some twenty years or more of satisfactory operating experience. This experience demonstrates that such devices will give adequate protection to transformers without themselves causing unnecessary interruptions.

## Experience with Protective Gaps

When the first 60-kv. transmission line was constructed across the western half of New York State between Niagara Falls and Syracuse in 1905 and 1906, it was necessary to work out some scheme for the protection of the terminal apparatus against lightning and switching surges.

The original arrangement designed by R. D. Mershon consisted of three horn gaps on each phase wire. These horn gaps with different settings were mounted on single poles with the phase wire carried across the top as shown in Fig. 1. On pole *C*, or the one nearest the station, the gap was set to flash over at a value of 45,000 volts to ground and the ground current passed through an open fuse wire of No. 20 B & S copper 15 ft. in length mounted between insulators on the side of the pole. On pole *B* the intermediate gap was set to flash over at 67,000 volts to ground. The current in this path to ground passed through a series of carbon resistance rods mounted on the side of the pole on 33-kv. insulators. The resistance in the ground lead was designed to be 20,000 ohms. On pole *A*, or the one nearest to the line, the gap was set to flash over at 115,000 volts to ground and the ground current passed through a resistance of 100 ohms made up of carbon rods and mounted in the same manner as on pole *B*.

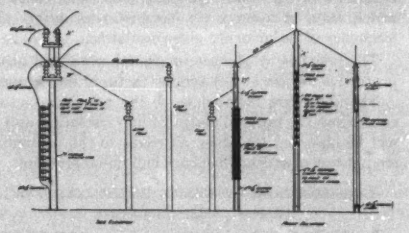

Fig. 1—Original Lightning Protection Equipment of Niagara, Lockport and Ontario Power Company—Installed 1905

At the time of construction some structures located in particularly exposed locations were equipped with gaps to ground on each phase wire. These were arranged by mounting a cap of cast iron on the pin type insulator supporting the line. This cap was drilled to take one horn of the gap, and the other horn made of a curved angle iron, was attached to the grounded part of the structure itself. The purpose of the grounded gaps on the line structures was, of course, to prevent damage to the insulators at these exposed points. Interruptions were necessarily experienced when a flashover occurred but when flashovers occurred on these structures, the lines could be cut back in service.

Trouble was experienced with the carbon resistance rods on the original station gaps and the design was changed in 1909, using heavy carborundum rods. These rods were 3⅛ in. in diameter and 7 ft. 6 in. long and were mounted on insulators on the side of the pole. Three rods in parallel were used as a resistance for each gap as shown in Fig. 2.

Experiments were made during 1909 with concrete

resistances made up of a series of concrete blocks. These seemed to work about as well as the carborundum rod resistances and installations of both types were made and put in operation.

In 1920 the design of station horn gaps was changed to

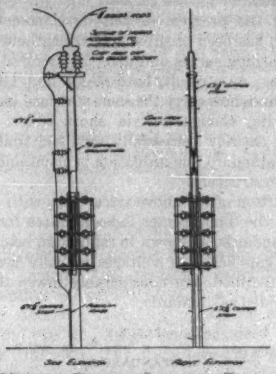

Fig. 2—Modified Form of Lightning Protection Used by Niagara, Lockport and Ontario Power Company—Installed 1909

make a much simpler and smaller structure. At this time the gaps for the three phases were mounted on one structure and the resistance grounds eliminated. The construction adopted was as shown in Fig. 3 and in

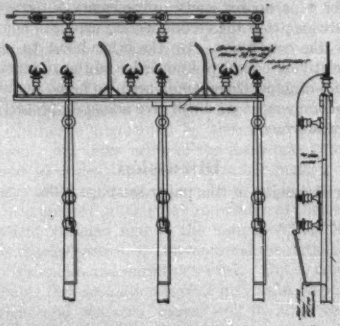

Fig. 3—Present Form of 60-Kv. Station Lightning Protection Used by Niagara, Lockport and Ontario Power Company—Adopted 1920

Fuse gap 7 in.; 75-kv. 60-cycle flashover. Ground gap 10 in.; 100-kv. 60-cycle flashover

general, this type of construction is in service today. The insulator supporting the line wire is equipped with two horns as shown. Another insulator mounted adjacent to the line insulator supports the horn making up the fused or smaller gap and this horn is connected through a disconnecting switch and expulsion fuse to ground. The fuse tube used is made up of a 1½-in. O. D. micarta tube with a ¾-in. bore 6 ft., 6 in. long bound with torpedo twine. The fuse wire used is No. 26 B & S copper. The dead ground gap is made up of a bent angle mounted on the structure itself and thoroughly grounded. On the 60-kv. system the fused gap is normally set at 7 in. and the dead ground gap set

Fig. 4—John L. Harper Station of The Niagara Falls Power Company Showing Safety Gaps on 60-Kv. Structure

at 10 in., corresponding to 60-cycle flashover values of approximately 75,000 and 100,000 volts.

The type of construction shown in Fig. 3 has been built in several forms: mounted on both wood and steel poles, with two and three poles for the supporting structures, with standard pin type and post type insulators, and with a hinged fuse tube eliminating the disconnecting switches. At the newer and larger 60-kv. stations, the dead grounded gaps are mounted on the top of the structure as shown in Figs. 4 and 5.

On the 110-kv. system the same general type of con-

Fig. 5—Norman R. Gibson Station of The Niagara Falls Power Company Showing Safety Gaps on the 60-Kv. Structure

struction has been used, except that the spacing and insulation have been increased. On the main 110-kv. structures, which are made up of latticed beams and columns, the gaps have been mounted on top of the main structure as shown in Fig. 6. In this case the fuses are mounted near the ground on a separate beam and are hinged so that no auxiliary disconnecting switches are needed.

The gaps on the 110-kv. system are set at 13 in. and

18 in. corresponding to 60-cycle flashover values of approximately 150,000 and 250,000 volts.

The proper gap settings have been determined largely by experience. On the 60-kv. system operating at 25 cycles, the switching surges are not severe and only slight changes have been made since the first gaps were put in service. On the 110-kv. system the first gaps were installed in 1925 when the entire system consisted of two parallel lines 40 miles in length. The gaps were first set at 11 and 14 in., but it was found that switching under some conditions would cause the fused gaps to arc. The gaps were then increased in length to 12 and

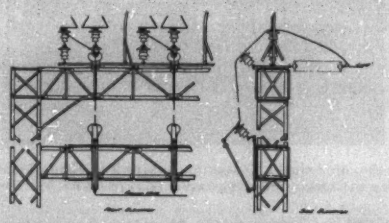

Fig. 6—Present Form of 110-Kv. Station Lightning Protection Used by Niagara, Lockport and Ontario Power Company

Fuse gap 13 in.; 150-kv. 60-cycle flashover. Ground gap 18 in.; 250-kv. 60-cycle flashover

15 in. and no trouble was experienced until the system became more extensive and the length of circuits switched at one point became greater. It was finally found that with settings of 13 and 18 in., no trouble resulted from switching and the records show that no failures of equipment connected to the 110-kv. system have occurred.

On both the 60-kv. and 110-kv. systems the operation of the horn gaps has been very successful in protecting the terminal equipment since there have been practically no failures during lightning storms. There have been many cases where the fused gaps arced over, blowing the fuses without arcing across the wider settings of the dead grounded gaps. In most cases when the dead grounded gaps have arced over, the breakers controlling the line have tripped, but since practically all main stations or points of delivery are supplied over two or more circuits, interruptions have not followed.

During the progress of this development the line insulation has been progressively strengthened to withstand lightning surges and give the required character of service. As a result, both 60-kv. and 110-kv. long distance lines now carry the same standard insulation of seven units, though certain short 60-kv. lines are operating entirely successfully with four units. In all cases the standard line insulation is maintained right to the station structure.

Comparison of the above safety gaps with those proposed by the Transformer Subcommittee for insertion in the Standards, as shown in tabulation below, reveals that the gap flashover voltages actually used on the system described, are considerably lower than those recommended as standards.

TABLE I

COMPARISON OF B. N. & E. PRACTISE WITH PROPOSED STANDARDS

60-Cycle Dry Flashover Voltages

| Nominal line kv. | Proposed standard gaps kv. | B. N. & E. system flashover kv. | | |
|---|---|---|---|---|
| | | Line insulation | Fused gaps | Ground gap |
| 69 | 185 | 255 (4 units) | 75 | 100 |
| 69 | 185 | 400 (7 units) | 75 | 100 |
| 115 | 300 | 400 (7 units) | 150 | 250 |

Since the evidence of actual operation shows that the smaller gaps do not cause unnecessary interruptions, it is obvious that the recommended gaps will not do so under like conditions. On the other hand, in view of the relatively complete knowledge of the surge characteristics of gaps, there would seem to be no doubt that the recommended gaps will give adequate protection to the transformers.

## Discussion

For discussion of this paper see page 1496.

# Essential Factors in the Coordination of Line, Station and Apparatus Insulation

A. E. SILVER[1] and H. L. MELVIN[2]
Fellow, A. I. E. E. Member, A. I. E. E.

*Synopsis.—Generated, switching, and lightning surge voltages all influence the design and application of insulation. The first two might logically be taken as the bases for determining the minimum insulation levels at stations; also, for lines where lightning is not encountered. Since lightning voltages affect service primarily through their influence on lines, the insulation strengths suitable for the lines may bear little relation to the insulation strengths of the stations.*

*Several lightning insulation levels are proposed for the coordination of line, station, and apparatus insulation; the basic or lowest level (determined by consideration of generated and switching surge voltages), being established by the line insulation or spillway gaps at the line station entrances, when the line is at a higher level; the busses and connections would constitute the next higher level; the apparatus bushings next; and finally, the apparatus internals.*

*More complete data on the nature of transient voltages as they originate and are modified by the circuit, and the performance of insulation with these voltages applied, are required before insulation can be coordinated with assurance. During the interim it should be possible to accomplish substantial improvement to service by applying to specific cases as they arise, the knowledge and data already available and being gathered, along the general lines proposed in the paper.*

## I. Introduction

THE insulation of electric circuits has been prominent among the problems commanding the attention of investigators, manufacturers, and operators since the beginning of electric service. In light of the new knowledge being acquired concerning transient voltages as they are imposed upon insulation, the performance of insulation and its application to power systems are now receiving renewed consideration.

It should be distinctly borne in mind that the term "Insulation," wherever used subsequently in this paper, is confined strictly to features of insulation surface strength and does not treat of those qualities of materials and design which control efficiency of manufacture, dielectric strength against puncture, and life; insulation satisfactory in these respects is assumed. It should also be understood that in applying the ideas proposed, economics and similar considerations must be taken into account.

Present practise for line, substation, and apparatus insulation has grown up largely through actual operating experience augmented by theoretical conceptions, research, and tests using in the main test voltages of 25 and 60 cycles, together with rather meager data on transient over-voltages. Due, however, in large part to the incomplete fundamental knowledge of the nature of transient voltages and of the corresponding performance characteristics of conventional insulations, many inconsistencies and variations exist. But it now seems probable that insulation layout may soon be placed on efficient and economic bases, well in advance of its somewhat haphazard present state.

Three general types of voltages are encountered by power system insulations, namely; normal frequency generated voltages; switching and system disturbance transient over-voltages; and lightning voltages. Insulating for generated voltage is quite well understood; insulating for switching surges is not a serious problem; but lightning is still uncontrolled, and no practicable amount of insulation seems adequate in itself to sustain the more severe lightning voltages.

Since station equipment and terminal connections are concentrated and need represent only an extremely limited direct exposure to the influence of lightning, switching surges, or those transients arising within the circuits, may logically be taken as determining minimum or basic insulation levels. On the other hand, lightning voltages which bear no relation to generated voltages usually originate on, and influence service, by affecting the performance of lines, so that in lightning territories the line insulation may be determined from the consideration of lightning. Suitable insulation strengths for lines and for terminal equipment, therefore, may not bear any direct relation, one to the other. The two, however, must be coupled in an effective manner.

It is too early to predict conclusions as to the finally applied results from the present intensive lightning investigations, but it is easy to conceive of quite radical modifications being made in the design and application of insulation during the next few years. For this reason, caution may well be observed in the establishing of standards of insulation practise and methods of testing; rather, the task of obtaining fundamental data should be stressed and the new knowledge, as fast as it becomes available, be applied in the most constructive manner possible.

The following, therefore, is intended to treat of the more essential factors as they now appear, pertaining to the selection, application, and coordination of power system insulation.

## II. Insulating for Generated Voltages

Over-voltages from generators are imposed upon insulation due to line regulation, overspeed, over-

1. Electrical Engineer, Electric Bond and Share Company.
2. Assistant Electrical Engineer, Electric Bond and Share Company.

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30-99

excitation, and faults on ungrounded systems. The maximum probable generated voltage, and the condition of the surface of the insulation due to weather and contamination may, in some cases, but not generally, determine the minimum amounts of insulation required for apparatus, stations, transmission and distribution lines. Under some conditions outdoors,—such as near cement mills, chemical plants, paper mills, or along seacoasts,—unusual amounts of insulation may be required and in extreme cases, it may not be economically practicable to provide sufficient porcelain leakage surface to overcome contamination, thus making necessary the alternative of periodically cleaning the insulators.

In arriving at the insulation requirements for generated voltages, insulator deterioration and loss of insulation due to physical damage, either from extraneous causes or flashovers, are factors to be considered. The former, however, is not the serious problem that it was several years ago when it was common practise to install several more insulator units in the strain position than in suspension, because of the more rapid depreciation of the former. Now, one, or possibly two, additional units are advisable to increase the insulation strength of the strain string above the normal insulation to give a margin against flashover at the more vital insulator units. Extraneous causes, such as malicious damage, animals and birds, are frequently an important factor in selecting the amounts of insulation and clearances, particularly in the lower voltage classes.

Another important consideration in the selection of the type, (and possibly the amount of insulation), is radio interference, as it has become essential that power circuits be adapted to successful radio coordination.

Only under unusual conditions would it be expected that generated voltages would determine the amounts of insulation which are satisfactory in actual service, as such voltages are considerably lower than switching surges. When insulator contamination is the controlling or a major factor, operating experience and tests simulating the particular conditions encountered seem to be the best guides in selecting the amounts of insulation.

## III. Insulating for Switching and System Disturbance Surges

Recent investigations and theoretical considerations indicate that over-voltages may originate within the circuit having maximum values of five to six times the normal circuit crest voltage to ground. The nature of these surges and their magnitudes have not been fully determined though they appear to have the characteristics of damped high-frequency oscillations. The performance of conventional types of line insulators and apparatus insulation has not been sufficiently investigated to be positive regarding their failure strengths with these types of voltages applied. From the information available, however, it seems reasonable to assume that these voltages are of sufficiently long duration to take on some of the characteristics of 60-cycle voltages so far as failure values are concerned. It may even be possible that because of the marked changes in distribution of stresses in the insulation with frequency, and the fact that these surges may be superimposed upon the normal frequency voltage, conventional insulations will fail at lower values for some types of switching surges than for 60-cycle voltages. If this reasoning is correct, the minimum strengths of insulation required to sustain switching surges would be five or six times normal generated voltage to ground with the insulation in its normal operating condition. Experience would appear to indicate, however, that if lightning voltages are eliminated from consideration, insulation having 60-cycle wet flashover values considerably lower than this has performed successfully. Whether this has been due to diversity whereby the maximum switching surge has not occurred with the insulation in its worst condition, or because of assigning an incorrect cause of flashover, cannot be stated. It is not an uncommon experience to have a line trip immediately upon being energized and then stay in on the second or third trial. For such cases it has usually been assumed that the fault which caused the original interruption still existed but it may have actually been the switching surge causing flashover of the damaged or even the unimpaired line insulation. Also, many interruptions are listed as "cause unknown" or "faulty relay action," some of which might have actually been caused by these internal transients.

More complete and careful investigation along the lines of determining the nature of switching surges and the characteristics of insulation under these voltages would seem essential. The influence of present trends toward higher speed switching on the magnitudes of switching surges should also be taken into consideration. These data are of prime importance, because the maximum values of transient over-voltages originating within the circuit may logically be used as the basis for establishing insulation levels for stations and station equipment.

## IV. Insulating for Lightning Voltages

Lightning voltages attain higher values than any of the other voltages which insulation is called upon to support. The problem of insulating lines and equipment to give the best, or even acceptable, service is at the present time in a speculative state. The magnitudes and nature of lightning voltages have been only partially determined, though investigations in progress bid fair to accomplish this within the next few years. In general, records obtained to date have been measurements of the insulating strengths of various types and amounts of insulation under lightning surges, and of the characteristics of lightning voltage waves as they appear

traveling on lines. There seems little prospect of completely solving the problem until more fundamental data are obtained and there has been opportunity to confirm them by experimental application.

On the assumption that both induced and direct lightning strokes affect line performance, there would seem to be at least three methods of attack for their control: first, the diversion of direct strokes before contact with the conductors and provision of sufficient insulation to support the maximum induced voltages; second, similar to the first, except for the combination of conventional overhead ground wires and less insulation for the induced voltages; and third, provision of means of discharging the lightning appearing on the conductors without generated current follow up. In addition to these are the present compromise methods for minimizing the number of flashovers and their influence on service, including provision of effective amounts of insulation in combination with conventional overhead ground wires, increase of the lightning insulation strengths, and improvement in switching and relaying. Since lightning magnitudes bear no relation to the operating voltages of the exposed circuits, insulation strengths to restrain lightning will be quite independent of normal circuit voltage.

An analysis of present practise will show wide variations in insulation strengths of lines to lightning voltages even for those operating in comparable territories. To a large extent, these can be accounted for, by the repeated attempts of engineers to improve performance by applying greater and greater amounts of insulation, or the utilization of wood, either intentionally or accidentally, in the quest of satisfactory lightning insulation for the lines. These conditions illustrate present and possible future variations in line insulation practise. They further indicate that present practise cannot be averaged or taken as a criterion of what the final solutions may be for the line insulation problem.

If maximum generated and switching surge voltages are used as the bases for determining the amounts of insulation for lines and terminal equipment, their insulation strengths should be similar. On the other hand, if lightning control is the basis for the line insulation strength, and switching surges for terminal equipment, no particular relation may exist between line and station insulation levels. However, the two must be brought together in a manner to avoid any injurious reaction of either on the other.

## V. Coordination of Line, Station and Apparatus Insulation Strengths

Since it is not practicable from present knowledge completely to safeguard service against lightning voltages, it would seem essential as an interim procedure, that the component strengths of the insulation along the circuit be so selected and coordinated that voltages, which do exceed the extablished insulation levels will find relief by spilling at chosen locations where no damage will result or it will be minimized.

Viewed from the standpoint of service,—to accomplish this for the substation and terminal facilities, four insulation levels, each having a suitable margin over the next lower, are proposed, as follows:

The basic, or lowest insulation level would be the line entrance to the station, the insulation strength of this level being set at a value having a safety margin above the maximum switching or similar surge. When differing from the line insulation level, this line entrance section would be equipped as a free spillway, capable of repeatedly discharging excess surges of any kind without damage, whether originating within or without the station.

The next higher insulation level, or second defense, would be the busses and bus connections.

The next higher insulation level, or third defense, would be apparatus bushings.

The highest insulation level would be the internal insulation of apparatus, thus placing this most expensive and most difficult to repair portion of plant in the position of maximum security against over-voltage, and rendering each item of apparatus self-protecting in itself.

For stations where the integrity of the main busses is of major importance, on account of inability to take them out of service for inspection and repairs, or their failure seriously affecting service, these busses might well be placed in the highest insulation level.

With the foregoing voltage levels throughout the station separated by proper intervals, it is believed that excess voltages of any nature encountered at the station will find relief at the spillway sections at the line entrances. It is assumed that direct strokes of lightning to the power conductors within a station will be avoided by utilizing the supporting structures, perhaps reinforced by grounded overhead cables, as diverters.

For the line, the source of lightning surges and seat of lightning flashovers, the insulation level would be determined by the conditions specific to each individual situation, and set at any requisite value quite independent of the levels established in the stations and terminals to which the line connects. In localities without lightning, the general insulation level of the line might be the same as that of the spillway section at the line entrance to the station.

Fig. 1 represents these insulation level relations diagrammatically.

To determine what the insulation levels should be, also the intervals between levels, will require much more data than are now available. These include the nature of surge voltages with their reflections, attenuation, absorption, modifications in magnitude and character due to changes in the electrical constants of the circuit, the characteristics of insulation with these voltages applied, as well as operating experience.

Proper intervals between the levels will be considerably influenced by physical arrangement; for example, in the case of extensive switchyards, it might be possible that negative intervals would be ample for incoming surges; but this would hardly be the case for lightning voltages originating at the terminals. On the other hand, in simple stations of relatively small dimensions and with no branch circuits, large intervals may be necessary.

Even though definite values for these intervals between insulation levels cannot be intelligently assigned at this time, nevertheless, pending more dependable knowledge of the problem, approximately 10 per cent between the spillway at the station entrance and the bus and 5 per cent between bus and apparatus bushings are proposed for trial to advance the experience on this point. These intervals represent the minimum separations between the impulse sparkover curves for the various insulators and spillway gaps, determined by the application of a range of waves giving impulse ratios extending from the higher values

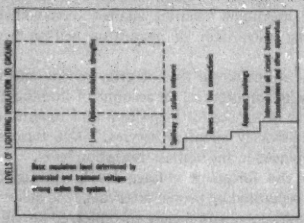



FIG. 1—DIAGRAMMATIC ILLUSTRATION OF RELATIVE LIGHTNING INSULATION STRENGTHS

to approximately unit, or between volt-time curves covering a similar range.

It must be recognized that the foregoing proposals are not free from conjecture. However, meager experience with installations where the insulation has been so coordinated from the limited data on insulation characteristics available gives promise of quite satisfactory results. At least it may be stated in general that, where insulation flashovers due to lightning voltages have been experienced, they have occurred at points which, upon analysis, appear to be weak. These weak points are frequently at locations where failures are most injurious.

It may not always be practicable to obtain the desired grading of insulation levels by selections from present standard insulators; also, if contamination is a controlling factor, the amounts of insulation capable of supporting the low-frequency voltages may have impulse insulation strengths higher than desired for apparatus safety. In these cases, relief gaps might be employed at one or more levels.

As in the past, manufacturers of insulators and manufacturers of bushings may be depended upon to recognize their important position in this problem and to be alert to progress in this branch of the art. They will be able to contribute much in the way of molding their scheduled standards to facilitate the selection of suitably related types and sizes for satisfactory coordination.

Variations from this basic plan of insulation coordination must be expected. For example, for economic and practical reasons, some types of apparatus may have inherently low insulation strengths to lightning voltages as encountered in suitably insulated stations. In such cases there may be an additional problem of providing protection specific to, and supplementing, the insulation of the apparatus.

So long as lightning voltages of magnitudes beyond practicable control must be dealt with, occasional discharges at the spillway gaps as proposed must be accepted; but these should occur without injury to station apparatus and insulation. However, with these gaps spilling freely in air, service interruptions will result. There is then a strong need for a simple and efficient barrier to normal frequency follow-up current to place in these gaps without impeding the unrestricted discharge of the lightning surge, even though its origin be at the spillway. Such devices are not as yet available.

## VI. DATA REQUIRED FOR THE COORDINATION OF INSULATION

More complete fundamental knowledge of the nature of transient over-voltages originating within the circuit, and especially of lightning voltages at their origin upon circuits, is essential in order that the characteristics of insulation under these voltages may be fully investigated. This work is progressing, though it must be realized that it is a large task and time will be required for the development of instruments and technique, as well as for the actual accumulation of the data.

In the laboratory, complete volt—time characteristics of the various types and sizes of insulation must be obtained, both clean and as influenced by weather conditions, for the full range of wave shapes encountered from 60-cycle to the steepest lightning impulse. Systematic and uniform methods for this insulation calibration such as methods of voltage measurements, humidity, barometric pressure and temperature, must be developed and applied. Finally these characteristic data should be a part of the manufacturer's catalogued information on insulators and bushings.

Volt—time characteristics of air clearances, such as may obtain between conductors and grounded parts of structures and those which may be used for spillway gaps, are also a necessary part of the data.

New knowledge obtained from lightning research work as it progresses may materially modify present ideas, and extend the scope of investigations and tests.

Even before these researches have been completed, data as they become available, can doubtless be applied to advantage in improving insulation designs and practise. Operating experience from such improved designs, and from existing installations, will be of demonstrating value.

These further investigations of lightning and other extraneous surge voltages encountered in power circuits as at present, can best be carried on cooperatively between the operators of the power systems and the manufacturers equipped with suitable research facilities. On the other hand, as in the past, the facilities of the high-voltage laboratories must be looked to for the insulation calibration work.

During the interim, until more complete insulation characteristic data are available, limited use of the conventional 10-in. diameter suspension insulator as an insulation strength yardstick may be expedient. However, as a standard of reference it is an undesirably crude device since the characteristics of various types of insulation evidently do not remain in similar relation over the range of transient voltages met with in practise. Length of air-gap might be a more suitable substitute for the insulator string as an interim reference standard.

Very substantial results have already been accomplished in the investigation of insulation characteristics. Testing facilities are well established. Many data have been obtained and although somewhat scattering and incomplete, can be used to advantage. Notable among these contributions are: the early work of F. W. Peek, Jr., the results of which were published in Franklin Institute papers, this work being supplemented and extended from time to time, and summarized in his paper on *Lightning*, A. I. E. E. TRANS., Vol. 48, April 1929, p. 436; the investigations by K. B. McEachron on the volt—time characteristics of insulation, also article by E. J. Wade and G. S. Smith on the subject of "Time Lag of Insulators," *Electrical World*, Aug. 18, 1928, p. 309; and the comprehensive work of C. L. Fortescue and J. J. Torok, the general results of which are included in the paper by J. J. Torok on *Surge Characteristics of Insulators and Gaps* published in abridged form in JOURNAL of the A. I. E. E., April 1930, p. 276.

This latter paper, giving volt—time curves for certain types and amounts of insulation, is of particular value as the data are in the form believed to be most useful for the purposes of insulation coordination.

## CONCLUSIONS

In the interest of protection to service, closer limitation of voltage stresses on apparatus, economy, and much better coordination of insulation strengths for the component parts of an electric power system is needed. To accomplish this efficiently, the development of a far more comprehensive knowledge of the characteristics of the voltages encountered, and of the insulations for their restraint, is essential. However, in the meantime, considerable improvement can be realized by a more thoughtful application of the knowledge gained to date.

The strength of the insulation system must be designed to cope with three classes of excess voltages; viz., generated over-voltages, transients from switching, faults, etc., and lightning. It is proposed that the station or terminal insulation be laid out to a basic level for supporting normal frequency and switching surges, and that in territories where lightning is not prevalent, the line insulation be established at the same level. However, where lightning occurs, the insulation level for the line should be laid out for the specific conditions encountered and it may be considerably above the level of the station. This makes it necessary that the line insulation level be coupled to the station at the line entrance in a manner to dependably discharge any lightning voltage propagated from the more highly insulated line, in excess of what can be supported by the basic insulation level of the station.

To accomplish this relation, it is proposed that the basic insulation level be established by an excess voltage spillway located at each line entrance to the station, and capable of discharging freely and repeatedly without damage. For the case where the line is insulated at a higher level, service would be improved should this spillway be equipped with a barrier to 60-cycle current without sacrificing its ability to freely discharge lightning surges.

Furthermore, for the increased security of the busses and apparatus, in keeping with their greater respective values and importance, successively higher insulation levels within the station are proposed for the bus work, apparatus bushings, and apparatus internals except in cases where, for economical and practical reasons, it may be necessary to supplement the insulation of certain types of apparatus with suitable protective devices.

For present cases, in determining quantitatively the required insulating strengths, and selecting suitable insulators and bushings from the available assortments, considerable data on impulse characteristics are already available in A. I. E. E. papers and elsewhere. However, these lack much of being complete and balanced, and as rapidly as possible must be greatly extended and coordinated by further research and calibration work.

Volt—time characteristics are considered to offer a practical method of rating insulators of various types to permit of successfully comparing and applying them in a coordinated insulation system.

The entire project is distinctly in the development and research stage, and the authors believe more progress and experience should be accomplished before recognized standardization can be undertaken to advantage of such features as lightning test waves, the characteristics of insulation and insulation levels for lines and stations.

## Discussion

### RATIONALIZATION OF STATION INSULATING STRUCTURES

(Fortescue)

### THE EFFECT OF TRANSIENT VOLTAGES AND DIELECTRICS—IV

(Peek, Jr.)

### RATIONALIZATION OF TRANSMISSION INSULATION STRENGTH—II

(Sporn)

### RECOMMENDATIONS ON BALANCING TRANSFORMER AND LINE INSULATIONS

(Montsinger and Dann)

### COORDINATION OF INSULATION AS A DESIGN PROBLEM

(Floyd)

### STANDARDS OF INSULATION AND PROTECTION FOR TRANSFORMERS

(Johnson and Bundy)

### ESSENTIAL FACTORS IN THE COORDINATION OF LINE, STATION AND APPARATUS INSULATION

(Silver and Melvin)

**A. O. Austin:** In the standardization of an impulse wave it would seem that there are two conditions of wave form that should receive attention. For the transmission system where flashovers mean interruptions the wave with a long tail or slow rate of decay gives the best information for judging the value of line insulation. This is particularly true for station insulation.

However, in order to simulate the condition of a chopped wave in connection with the comparative performance of arresters, voltage limiting gaps, and composite insulation assemblies, a short tail wave or one with a very high crest should also be used. Even here the wave with steep front and long tail, but with a high crest may be preferable as results comparable to the short wave will be obtained and in addition the relative performance with the long tail wave may be readily determined without changing the wave. This requires comparative tests or oscillograms. Where the short wave only is used for the same work, crest values may be obtained but there is a question as to what the performance would be under less favorable conditions.

Other factors besides wave form should be considered in standardizing lightning sparkover tests. For example, tests in the Barberton laboratory show that gap resistances (as affected by the number and length of intermediate gaps), impedances in the impulse circuit, and the capacitance of test leads are very important factors. Where the gap resistance or impedance together with leads of small capacitance come into play the sparkover of the insulator may be arrested, so that complete breakdown does not take place. In fact oscillograms show that an insulator may start to fail and then recover under these conditions only to sparkover later. Voltage measurements secured under these conditions would be very confusing.

While standardization should be very beneficial it is necessary to consider a number of factors in the test circuits before the results of different laboratories can be compared on a numerical basis. Ignoring these will lead to misinformation in the same way that the use of the chopped wave or the very short wave has for line insulation study. At this stage of the art it should be possible to cover a wide range of waves, each particular type being chosen to conform with characteristics of the insulation and service conditions.

As temperature, pressure, humidity, polarity, wind, and the electrostatic field of the test set-up, are other factors in addition to the wave form, it would seem that very close agreements of tests made even in the same laboratory may vary materially from time to time. For this reason comparable parallel tests are to be preferred, together with methods which permit as short a period of time as possible between tests.

Balancing the insulation of line, station and apparatus has always received much attention on some transmission systems. While at first glance it might appear that a chaotic situation exists in present practise, it is well to look first at several factors other than the relative impulse strength of the different elements. For example it has been known for some time that the time lag for solid and liquid insulation is usually much greater than for air. This had been made use of on many systems in order to reduce the interruptions from flashovers.

Although theoretically possible, the difficulty of balancing insulating members within 10 or 15 per cent is greater than it seems. Insulator strings and bus insulators are usually of such size that an allowance for depreciation of 10 to 20 per cent is made. This combined with the allowance for smoke and dirt will give a high insulation level, possibly well over 50 per cent of that required when the insulators are clean and new. It is a recognition of these factors that has led to the apparent lack of balance in many cases.

A slight change in a transformer design may greatly increase its ability to withstand transients. It would therefore seem that the goal should be to provide ample insulation in line and station as the best results can be obtained by strengthening the weak rather than weakening the strong. A voltage limiting device such as a fused gap or arrester can be used to protect the weak in the meantime. If line and bus insulation is limited it may not be possible to increase it later.

Among other factors which have been given careful consideration is the absorbing capacitance of the station, the small probability of a direct stroke in the vicinity of the station, and the ease of protection against direct stroke for the station.

The desire to limit the voltage on station and equipment has been given much attention in the past and it is to be hoped that the present attention given to the problem will result in material improvement both as to performance and cost. However, limiting the voltage by an arc which will cause an interruption, is hardly the answer desired, although it may be a valuable method for the time being.

**S. Murray Jones:** Fig. 8 of Mr. Fortescue's paper indicates that it is desirable to reduce transmission line insulation gradually, starting some distance away from stations. Although this practise has been used by some operating companies, it is, in our opinion, inviting more trouble rather than reducing it. In case of either a direct or an induced stroke, it is always desirable to have the maximum possible insulation. Therefore, it would seem desirable to maintain the line insulation at a uniform level up to the station, using either lightning arresters or voltage limiting gaps, or both, to protect the station apparatus.

Mr. Sporn, in his paper, states that the insulator manufacturers are apparently not in agreement on the 60 cycle flashover values given out for substantially the same type and design of units, to say nothing of the values given for impulse flashovers. The differences in impulse flashover values are obvious to most of us, but there should be no dissimilarity in the 60 cycle values. These differences which occur may be explained by variations in wave form or differences in temperature and humidity at which the insulators have been tested, or both. Mr. Austin has always endeavored to take these factors into consideration in figures which have been given out from our Barberton Laboratory. In fact, he has been using humidity correction factors for over 15 years. As is well known, insulator strings have characteristics when tested under different conditions of humidity, similar to that of the needle gap and it is for this reason that Mr. Austin has preferred to use the needle gap as a means of calibration for determining 60 cycle insulator sparkover voltages.

It would certainly be desirable at the present time to standardize on impulse test waves if such standardization would result in comparable figures being obtained from the different

laboratories for tests on the same types of insulation. We do not believe that standardizing on test waves would accomplish the desired purpose since, in our opinion, several other and perhaps more important factors must be included in the standardization.

The method of potentiometer coupling for determining impulse wave shapes is perhaps the most important factor to which more study must be given in an attempt to obtain a true oscillogram of the phenomena occurring at the test piece. Other factors which must be considered and included in any standardization of impulse testing are, polarity of the test wave, the method of mounting the test piece, the length and size of the test leads, the location of the potentiometer and cathode ray oscillograph, and the temperature and humidity at which the tests are taken. There may also be other important factors which must be taken into consideration before comparable results can be procured from the different testing laboratories from tests obtained on similar apparatus. Until the majority of these factors can be included in any insulator impulse test standards, we are of the opinion that it will be preferable not to attempt to standardize on wave shapes.

### Effect of Shape of the Voltage Wave on the Distribution of Dielectric Stresses Within Winding

**K. K. Palueff:** Since the principle of coordination suggests that the transformer should be protected by gaps without a series resistance, it is of importance to understand the effect of a short ("chopped") wave on the distribution of dielectric stress within an ordinary transformer winding.

The relations between the shape of the incident wave and the corresponding stresses within the transformer winding were established rather completely in the papers presented by the author during the last year and a half. For this reason, the present discussion will be limited to the conclusions arrived at in these papers.

The entire insulation structure of a transformer winding can be divided into three categories: turn insulation, coil insulation, and major insulation, *i. e.*, insulation between a given winding and ground and other windings. All these categories are equally vital.

The following can be stated, as general laws:

1. The closer the two elements of a given winding, the higher is the frequency of oscillation capable of producing equally dangerous dielectric stress.

2. Free transformer oscillation consists of some eleven harmonics.

3. To produce a free oscillation of not less than one-half of the amplitude that would be produced by a long wave with rectangular front, of the frequency of any of these harmonics, the front or tail of the incident wave must not be longer than about 50 per cent of the period of the harmonics.

4. However, even if the front or the tail of the wave is sufficiently steep, to allow the amplitude of this oscillation to reach at least one-half of the amplitude that would be produced by a long wave with rectangular front, the length of the wave must be not less than a quarter of the period of the harmonic.

5. The oscillation at the frequency of any given harmonic (and of all higher harmonics), cannot be produced by a wave having both front and tail longer than the period of the harmonic, regardless of the length of the wave.

6. If the length of the wave with steep front and tail is equal to an odd number of half-periods of a given harmonic, the amplitude of this harmonic will be twice that produced by a long wave with the same front but with a slanted tail.

Taking as a standard for comparison, stresses created in a winding by an extremely long wave with rectangular front, the following conclusions can be arrived at from the above:

a. For turn insulation the waves with "exceedingly steep" front or tail (from, say, 0.25 to 4 microseconds, depending on transformer constants) are the most dangerous. Depending on the length of the wave, the stresses may be doubled if both the front and the tail of the wave are "exceedingly steep."

b. For the coil to coil insulation, the waves with either *exceedingly steep* or *very steep* (some 10 microseconds), front or tail, are the most dangerous. Depending on the length of the wave, the stress may be practically doubled, if both the front and the tail of the wave are sufficiently steep.

c. For the major insulation the waves having the front or tail *exceedingly steep* or *very steep* or just *steep* (not much longer than 50 microseconds) are the most dangerous. Depending on the length of the wave, the stresses in some parts of major insulation may be materially increased, if both the front and the tail of the wave are sufficiently steep.

d. An incident wave with both front and tail not shorter than the period of the fundamental harmonic of the transformer will produce a practically uniform voltage distribution throughout the winding during the entire transient, regardless of the length of the wave.

e. Up to the present, no protective devices have been developed which would limit the voltage of the incoming wave to an absolutely negligible value. Therefore, an ideal protective device should be considered one which lowers the crest of the incident wave to a safe value and also modifies the shape of the wave so that the lengths of its front and of its tail become not shorter than the period of the fundamental neutral frequency of the apparatus to be protected.

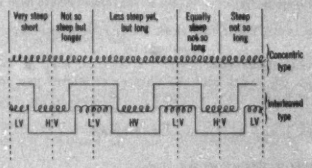



Fig. 1—Zones of High Voltage to Ground Produced in Concentric and Interleaved Windings by Lightning Waves of Various Shapes

Minimum requirements for steepness and length of the waves

f. A device that would modify the shape of the incident wave as just described, but would not reduce its crest value, would materially relieve stresses between turns and coils, but would allow the greater part of the major insulation to be over-stressed.

g. A device that would reduce appreciably the amplitude of the crest of the wave but would not properly modify its shape, would correspondingly relieve the stress on major insulation, but stresses on coil and turn insulation would not be reduced in the same proportion.

A gap without resistance in series, chops the incoming wave very abruptly. Thus, as a rule, short waves with steep front and tail are allowed to be impressed on the transformer. These waves, under circumstances mentioned above, may produce practically the same stresses between coils and particularly between turns, as waves of the same front, but with slanted tail, and with the crest twice as high.

All this applies to all ordinary transformers, (or any other inductive apparatus) of core and shell types.

In the non-resonating transformers, the stresses in turn, coil and major insulations are uniformly distributed for any shape of incident wave.

All the above emphasizes the necessity of coordination of line and transformer insulations.

To permit such a coordination, it is essential to have data on impulse volt-time characteristics of bushings, suspension insulators, pedestal insulators, etc. To permit the drawing of a volt-time curve with engineering accuracy, three arcover test

points appeared to be sufficient: one obtained with very steep and short wave, another with a wave not so steep, but much longer, (say, 30-50 microseconds) and a third with 60 cycles.

It is obvious that it would be far more desirable if different experimenters agreed on exact shape of the preferred two impulse waves. This would give a common ground for comparison of various insulating members of transmission systems.

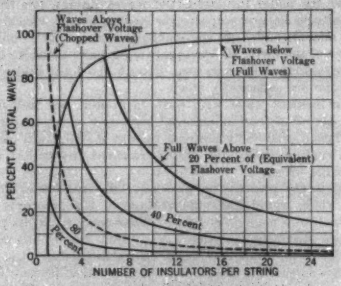



Fig. 2—Relation Between Number and Amplitude of Lightning Waves on Transmission Lines

All waves below flashover voltage of one insulator have been neglected

### The Relation Between Line Insulations and Number of Arcovers

From statistical data it appears that, for a given height of conductor, its length and the number of storms per year, the number of flashovers is inversely proportional to the number of insulators, *i. e.*, $f = \frac{k}{n}$ or $f\,n = k$ where

$f$ —number of flashovers per year
$n$ —number of insulators
$k$ —constant depending on the length of lines, the height of conductor, the number of storms per year and the number of ground wires

For 100 miles of line, 40 storms per year, one ground wire and 40 ft. height of the conductor: $K = 46$.

For any conductor with one ground wire, the relation seems to satisfy the following formula:

$$f = A\,\frac{h^2}{n}\,S\,l\,10^{-6}$$

where
$f$ —number of flashovers per year
$h$ —height of conductor in feet
$l$ —length of the transmission line
$A$—constant (7.2 for one ground wire, 6.5 for two ground wires)
$S$—number of storms per year
$n$ —number of insulators (5¾ in.)

On account of great varieties in lightning characteristics of different transmission systems, it cannot be expected that an accurate general law could be developed. Therefore, the above formula should not be looked upon as an exact law, but rather as an approximate expression of the tendency due to the various factors mentioned.

I applied the above formula to data given for a 220-kv. system by Mr. Floyd in his present paper, and found $f = 1.48$ for 15.7 of 5¾ in. insulators (equivalent to (18) 5 in. insulators). The service record gives 1.75.

I could not check the formula against Mr. Floyd's data on the 110-kv. system, as the length of individual lines is not given and no mention is made of whether the hardware on wood pole lines was grounded or insulated.

If the above formula is at all correct, then the lightning waves that appear on lines with different numbers of insulators can be segregated as shown on Fig. 2.

### Service Experience with Coordination of Insulation

Since coordination of line and transformer insulation has already been put in practise by a number of operating companies, it is of interest to review some of the results.

In 1926 a 220-kv. transformer failed. The transformer was built for 346 kv., (2.73) induced voltage test with major insulation not graded, with coil and turn insulation as in a fully insulated transformer. The line insulation consisted of disks with 60 cycle arcover of 725 kv. The proposed rule of coordination in such a case would require the transformer to be tested at 461 kv. The cause of the failure is therefore obvious. It had been predicted, but in those days very few believed in the possibility of 1,800,000 volts on 220-kv. lines.

After the transformers were repaired, the line insulation near the station was reduced to correspond to transformer insulation. Since then the transformers have been examined at regular intervals and no sign of damage was found, in spite of the fact that a great many lightning arcovers have been recorded near the stations.

Mr. Floyd, in his present paper, discusses his experience with coordinated insulation on his 220-kv. system. He states that the transformers were of interleaved design with high voltage winding consisting of four groups with major insulation graded on the basis of 2.73 times normal test (346 kv.), but with line group insulated for 440 kv. This gives the following strength for various groups: line 440 kv., second 260 kv., third 173 kv. and fourth or ground 86 kv.

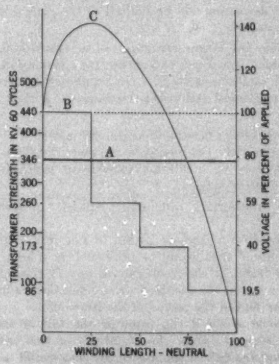



Fig. 3

A—Major Insulation of Transformer Which Failed in 1926
B—Major Insulation of Mr. Floyd's Transformer
C—Maximum Voltage to Ground that Could be Produced in Transformer B by Non-Oscillatory Single Lightning Wave

Furthermore, it is stated that line insulation for two miles next to the station had four ground wires and a 60-cycle arcover of 665 kv., which corresponds to a 422-kv. transformer test (Fig. 3 illustrates the relation between line and transformer insulation for the 220-kv. transformers mentioned).

In spite of the fact that line insulation was some 5 per cent lower than the rule of coordination requires, the transformer failed during lightning.

The study of the phenomenon indicates that, on the one hand, the grading of major insulation is not justified by the distribution of voltage throughout the winding caused by a lightning wave (Curve *C*, Fig. 3), on the other hand, to make reduced line insulation protect the station, the tower footing resistance must not be of excessive value. I should appreciate it, if Mr. Floyd would tell us just how high the tower footing resistance of the line near the station is, and whether, with his knowledge of all the details of the system characteristics, he could suggest some other reasons that made the coordination of insulation ineffective as a means of protection.

**J. H. Cox:** Mr. Sporn has discussed to considerable length the need for rationalization of transmission system insulation in order to effect greater reliability of service and has pointed out some desirable methods by which this scheme might be advanced. He further states that the situation appears somewhat chaotic at the present time but I must disagree with his statement that very little has been accomplished.

There can be no question but that great strides have been made in the past few years regarding the nature of lightning and the impulse characteristics of insulation, and that the situation is a great deal more clear now than in the past. For instance, at the present time fairly complete and accurate impulse ratio time lag curves for porcelain line insulation and air gaps exist along with much data regarding the nature of lightning impulses to which lines are subjected. With these data, line insulation and air gaps can now be intelligently applied on a rational basis.

Mr. Sporn has put up a strong plea for the adoption of a standard impulse wave for testing purposes. Although, since Mr. Sporn's paper was written the situation has been considerably altered, the paper is part of the permanent record and I would like to give an outline, as I see it, of the opinion of what Mr. Sporn has called, the minority.

In general there is no question but that standards should not be adopted until definite lines have been established with considerable accuracy. It is also impossible at the present time to define with any degree of accuracy the impulse characteristics of fibrous and composite insulation. An excellent example of the prior need for accurate definition is the suspension insulator. It has long been known that the impulse characteristic of any insulation is a function of voltage and time. Up until two or three years ago practically nothing was known about the quantitative values of these factors. At the present time complete curves have been determined for the impulse characteristics of porcelain insulation, so this is now on a definite basis. Had a standard wave or series of waves been adopted prior to the actual determination of the curves it would have meant nothing and might have been misleading in a serious degree. At the present time, since the curves have been determined such standard waves are not necessary.

Transformer and other more complicated insulating structures are only now in the process of being studied. The distribution of impulse voltage throughout transformers has been determined, but the impulse strength of the insulating members is still practically unknown. A great amount of work remains to be done on this problem and until this is done it is wasted effort to attempt to define these characteristics on the basis of standard waves misleading ourselves thereby into thinking that something is being defined which actually cannot be explained at the present time.

Mr. Sporn admits that any wave adopted at the present time would necessarily be a tentative standard requiring revision from time to time. Such a procedure would greatly delay the program of investigating the fundamentals since it would seriously handicap the available laboratories. For instance, after the adoption of a standard, work in the laboratories would for a time be confined to the determination of the characteristics of various insulating members in connection with the particular waves chosen. Subsequently a similar amount of work would be required each time the standards changed. It is obvious that with the available equipment now being used full time to determine the fundamentals of the problem, this determination would be handicapped.

Mr. Sporn's argument for a standard wave seems to me particularly inconsistent. In the early part of his paper he discussed the efforts of the Transformer Committee to formulate a standard method of coordinating station apparatus and gives some strong arguments against such standardization before the necessary factors are determined. Immediately following this argument he puts up a plea for standardization of test waves which so far as I can see present the same arguments. To quote from an article by Mr. Sporn which appeared in a recent issue of the *Electrical World*:

> "There have appeared, it is true, tendencies, particularly among manufacturers, to codify some of the changes in practices in this regard, but fortunately this tendency has been averted so that the entire problem is free to continue and develop itself along natural lines."

It is realized that the need for definition is great and that the time may be long before the necessary data are obtained but the facts of the case should be looked at squarely. The adoption of a standard wave at the present time would merely be the expression of the desire to fill a need rather than the accomplishment of any real results. As it is the work is progressing in an orderly fashion towards the rational solution and the real need is for greater support of the test program. The attempt to formulate definitions and standards at the present time is a side stepping of the actual problem.

To summarize, as I see it, the following points outline the objections to the adoption of standard impulse waves:

1. In general it is unsound practise to standardize on a test where this test must be based on inadequate and unproved data and there is an element of danger in forming a standard which is admittedly tentative and will require changing in the near future.

2. Even though tentative, such a standard is misleading and creates a false sense of security since one is inclined to believe that apparatus tested by an A. I. E. E. standard is adequately tested and representative of what the apparatus should withstand in practise.

3. The particular incentive in the present case for setting up a standard test seems to be to provide a comparison between different makes of apparatus, but a standard of comparison which is not based on a sound foundation may be unjust and lead to indications which are the reverse from facts.

4. After a standard has been set up competition forces a manufacturer to build apparatus to meet a standard test and tends to make him overlook the factor of service requirements which has been the predominant factor in the previous design practise.

5. In general the premature adoption of a standard tends to relax and divert efforts, and to postpone the ultimate final solution.

None of this should be interpreted as an objection to the selection of a couple of preferred waves, say a short wave and a long wave, to be used in the determination of a couple of points on the volt-time curve of such insulation for which the volt-time curves have been determined, but they should not be adopted as standards in the present state of the act.

I have one comment on Mr. Peek's paper. Mr. Peek admits that the use of the cathode-ray oscillograph in impulse tests yields more accurate and complete results but he makes a plea for the greater use of the sphere gap on the grounds that it is more convenient and permits more rapid testing, and is good enough for many purposes. It has been our experience that with up-to-date equipment and a high grade of personnel, tests with the more adequate oscillograph can actually be made as rapidly as with the sphere gap.

With the oscillograph each shot tells its story while with the sphere gap it takes a number of shots to obtain a setting. The difference in testing time about equals the time of analysis of the films. This being the case I see no reason for being satisfied with anything less than the best possible records.

**M. M. Samuels:** At the Northeastern District No. 1 Meeting at New Haven, May 9-12, 1928, Mr. Philip Sporn presented a paper on *Rationalization of Transmission System Insulation Strength*. To the best of my knowledge that paper was the first systematic presentation of the various problems involved. Had that paper been used by others as a guide for further study and discussion, we would be much closer to the solution of the problem than we are today.

Many papers have since been presented and a great deal of discussion has taken place, but most of the discussions not only did not result in definite answers, but they did not even bring out more definite questions than those which were raised in Mr. Sporn's first paper. Even the numerous papers presented here do not indicate any logical subdivision of definite questions. To my mind the uncertainty is principally caused not so much by the inability to answer the questions, but in the confusion of the questions themselves. That a question correctly stated is already partly answered is still an acknowledged fact. Before dividing up the various problems into definite individual questions, it would seem that three *groups* of questions can now be crystallized from the various discussions:

*Group A.* Shall one part of a system have lower insulation than another part of the same system, and if so what part and how much lower?

*B.* What shall the insulation rating of each part be?

*C.* What definite commercial test method shall be used to determine whether or not a piece of equipment has the specified insulation value?

While it is quite proper to study groups *B* and *C*, it is at once obvious that no definite answers can be obtained for them until the questions of group *A* have been disposed of. On the other hand, as was brought out in the paper by Messrs. Johnson and Dann and also indicated in Mr. Sporn's paper, while some may say that the questions of group *A* refer to operation and are not a fit subject for the Institute, it is true that since *B* and *C* are matters of standardization and are precisely within the scope of the Institute, and since they cannot be answered without disposing of *A*, group *A* thus also falls within the range of Institute discussion.

In an article which I prepared for the *Electrical World* before I knew that these various papers would be presented, and which was published in the issue of June 14th of that paper, I attempted to crystallize definite *sub-questions for Group A*, which I repeat here:

1. What shall be the flashover value of transformer bushings in relation to the insulation of transmission lines which are connected to the same bus?
2. What shall be the relation of the insulation of the transformer itself to that of its bushing?
3. What shall be the insulation value of a breaker bushing in relation to that of the transformer bushing?
4. What shall be the insulation value of an insulator on a bus to that of the bushings on transformers and breakers?
5. What relation shall there be between the insulation value of an insulator on a disconnect or a branch in relation to that of the bus or the bushings?
6. What part shall be assigned to the lightning arrester in this discussion?
7. When shall the line insulation close to a station be made lower than the line insulation on the rest of the line?

I also took courage and attempted to answer these questions in my own way, and also to briefly summarize these answers: My answer to No. 1 agrees with the recommendations of Messrs. Johnson and Dann, that it would be hopeless to establish any relationship between transmission line insulation and stations insulation.

To No. 2 it is my opinion that operating companies will continue to insist that transformers be so designed that the bushing flashover, before the transformer insulation fails. To Nos. 3, 4, and 5 I recommend that the insulation values for all bushings and insulators of the same voltage be standardized to be practically the same, and my answer to No. 6 is that the lightning arrester should be considered a reliable protection, and that an arrester be used for each large transformer. As regards No. 7, it is my opinion that the idea of reducing the insulation of the line close to a station is based on a very pessimistic conception of the arrester. I have more faith in arresters, and believe that the very vigorous work done on lightning investigation by Mr. Sporn and others will bring out even more reliable arresters. I do not consider my answers as anything more than suggestions, but I beg to lay great stress on the proper subdivision of the questions and to submit it for the consideration of the Committee to canvass the questions in some such form, perhaps working up an even more elaborate subdivision for group *A* and a similar subdivision for groups *B* and *C*.

But most important of all I want to emphasize the fact that the questions of Group *A* are questions of *relativity only*, and have nothing whatever to do with definite insulation ratings, types of insulators or bushings, testing methods or any particular voltage range. They are practical questions, and a canvass of practical men should bring definite answers to them.

**H. L. Wallau:** The papers presented indicate a general agreement among all authors that coordination is not only desirable but necessary. No one suggests a maximum insulation limit for the line, per se, provided that suitable means for reducing this limit, if necessary, are furnished at points where equipment might be jeoparidzed by incoming transients of a magnitude in excess of the value which the equipment installed could safely withstand.

With regard to transformer windings, the Transformer Subcommittee takes the stand that their impulse ratio "is fairly constant for a given wave" and by inference is fairly constant for all waves. Sporn categorically challenges this statement and its inferences and also the Subcommittee's similar statement with reference to insulator strings. Fortescue (Fig. 7) shows large differences in flash-over values of insulator strings tested by General Electric and Westinghouse engineers with waves which are presumably similar.

For a ten-unit string, Peek's 20 microsecond wave gives a flash-over of about 1350 kv. while the Trafford 20 microsecond wave gives about 70 per cent of this. Even the 60 cycle crest data for this type string differs, the Trafford tests giving a value 100 kv. above the Pittsfield tests.

In the face of these inconsistencies, Sporn's proposal to measure impulse strength by means of impulse voltages cannot seem but entirely rational and his proposal to standardize these waves, in close agreement with our present knowledge of natural lightning waves, merits careful consideration.

The Transformer Subcommittee's proposal embodies experience to date and attempts to express that experience by means of a general statement that the transformers shall be designed for impulse strengths in excess of those corresponding to a series of insulator strings, and this strength is expressed in terms of 60 cycle r. m. s. voltages. Whether this excess strength is to be 1/10 per cent or 1000 per cent is not specified, and the foot-note blandly informs us that it could not be proven in any event.

Why cumber Standard No. 13 with this proposal? Is it not wiser for the manufacturers to continue to build transformers as they are and for operators to put into effect the recommendations contained in Part II of the proposal, meanwhile both groups trying to reach a sensible agreement as to the number and characteristics of impulse waves to be standardized upon, the number of impulses from each standardized wave to which

a transformer should be subjected and the value of crest voltage for each type of wave in terms of the circuit voltage on which the transformer is to be operated?

Before these criteria can be determined (after the standard waves have been agreed upon), it will take considerable test data to determine the safe limits to be set up, but we will be progressing in the right direction and knowledge will gradually eliminate guesswork.

**W. W. Lewis:** In connection with the discussion of a preferred test wave or waves, it has been suggested that such wave should have some relation to the waves observed on transmission systems which were caused by natural lightning. For this reason an investigation was made by Mr. W. B. Jordan under

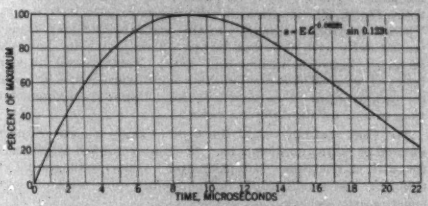



Fig. 4—Typical Oscillatory Lighthning Wave

Based on 15 oscillograms

the direction of the writer using as a basis all of the data presented at the lightning symposium given at the winter convention of the A. I. E. E. in January 1930 in the papers by Messrs. Cox and Beck, George and Eaton, Sporn and Lloyd, and Smeloff and Price.

The waves were divided in two classes, oscillatory and uni-

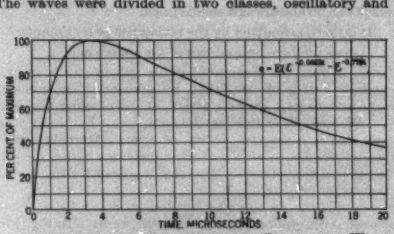



Fig. 5—Typical Unidirectional Lightning Wave

Based on 33 oscillograms

directional. It was assumed that these two classes could be represented by the type equations

$$e = E\,\epsilon^{-kt} \sin p\,t \qquad \text{Oscillatory}$$

$$\text{and} \quad e = E\,(\epsilon^{-\alpha t} - \epsilon^{-\beta t}) \qquad \text{Unidirectional}$$

The constants $k$, $p$, $\alpha$ and $\beta$ could be determined from the time to reach maximum, $t_m$, and the time to fall to 50 per cent of maximum on the tail of the wave, $t_1$. Both of these times are given in the data in the papers.

For a ratio of $t_1$ to $t_m$ less than 8/3 and greater than 5/3, the wave was oscillatory and for a ratio greater than 8/3 the wave was unidirectional. For a ratio less than 5/3 the formulas did not apply.

Certain of the waves given were rejected on account of insufficient data or being outside the limits of the formula, and finally there remained 15 waves of the oscillatory type and 33 waves of the unidirectional type. The constants were calculated for each wave and the logarithmic mean taken for each type of wave. These mean values were substituted in the original equations to give the average wave of each type. The final equations of the mean waves were as follows:

$$e = E\,\epsilon^{-0.0622t} \sin 0.123\,t \qquad \text{Oscillatory}$$

$$\text{and} \quad e = E\,(\epsilon^{-0.0663t} - \epsilon^{-0.776t}) \qquad \text{Unidirectional}$$

where $t$ is measured in microseconds.

The mean oscillatory and unidirectional waves derived from these equations are plotted in Figs. 4 and 5.

In Mr. Austin's discussion he refers to the effect of humidity on the arc-over voltage of insulators and gaps and states that it will be seen that humidity has about the same effect upon the arcing voltage of a needle gap as it has upon the arcing voltage of an insulator. He concludes that where no correction is applied to the flashover of the insulator the needle gap will tend to give more consistent results than a sphere gap, even though the flashover of the latter was not affected by humidity.

This conclusion is based on the assumption that reliable data are available showing the effect of humidity on the flashover of a needle gap with a fixed spacing or on the voltage required to flash over gaps of varying spacings at a constant humidity. The further assumption is made that the variation of humidity for a fixed spacing follows a curve parallel to the curve of insulator flashover with varying humidity. Data as to these points are not available and accepted by the industry. The A. I. E. E. Rules do not sanction the use of a needle gap for voltages over 50 kv. The sphere gap, however, is sanctioned for voltages up to 800 kv. effective. It is generally assumed that the sphere gap flashover is not affected by humidity. It would seem better, therefore, in measuring the flashover of insulator strings which vary with humidity to use as a measuring device a gap which is not so affected and which is authorized by the A. I. E. E. Rules, rather than to use a gap which varies with humidity and other causes and which is not authorized by the A. I. E. E.

In the paper by Messrs. Silver and Melvin, a scheme of coordination is proposed in which the lightning arrester finds no place. In this scheme rather close margins are proposed between the setting of the spillway gap and the insulation of the bus, etc. The flashover of such a spillway gap may impose serious gradients on the insulation of adjacent apparatus, especially transformers. The writer is of the opinion that either the margin between the flashover of the spillway gap and station insulation must be very greatly increased or the lightning arrester must be brought into the picture. The lightning arrester will allow a higher setting of the spillway gap and at the same time prevent this gap from flashing over except on rare occasions.

**Robert Treat:** I desire to commend the basic idea expressed by Messrs. Johnson and Bundy that there need not and should not be too much coordination between the transmission line insulation on the one hand and the substation and transformer insulation on the other.

It seems to me that too many of the papers presented at this session either ignore the lightning arrester completely as a part of this picture or they treat it as an unreliable device which must have a very high degree of backup.

It is true that in former years lightning arresters were of somewhat questionable value owing to several factors:

1. It was impossible to determine with any degree of precision the protective value of an arrester.

2. Because of this difficulty lightning arresters were often improperly selected and applied.

3. Because the lightning arrester's value was questionable it was often relegated to a location which suited the convenience of the substation designer after he had completed the layout of his major apparatus.

4. The importance of an adequate ground has been really appreciated only recently.

For these reasons it is probable that many arresters have been installed in the past which gave little if any protection and as a natural result transformers and other apparatus presumably protected by an arrester, have failed. These failures have provided those who question the value of an arrester with data to support their position.

Within the last few years this situation has seen a decided change. With the advent of the cathode ray oscillograph and the lightning generator as practical tools for testing, the performance of a lightning arrester can be checked and predicted with a high degree of precision. Data are now available for the proper selection, application, location and grounding of lightning arresters in order to permit them to afford maximum protection to apparatus. Lightning arresters are now commercially available which afford a high degree of protection.

No matter how much coordinating may be done between line, substation, bushing, and transformer insulation it is perfectly clear that unless the entire insulation level is placed above the strength necessary to resist the maximum voltages which can be encountered, insulation breakdowns are to be expected. In the face of the present efforts of power companies to give better and better service, it is important in most cases that insulation breakdowns should not permit dynamic current to follow. It becomes necessary, therefore, either to have a very high insulation level throughout the whole system, or to provide spillways which do not permit dynamic current to follow the lighting current. There are relatively few devices which fulfill this condition. One of these is the gap in series with a fuse. This device, however, is not entirely satisfactory from all standpoints because once it has operated, the protection is destroyed unless a multiplicity of devices are put in parallel or some mechanism is used such as the Nicholson arc suppressor for automatically replacing fuses after they have blown. Another such device is the lightning arrester which is especially designed to perform that function.

In much of the talk concerning coordination of insulation the spread between the maximum voltage permitted by the protective insulation on the one hand and the voltage which the transformer can stand on the other, is very small—in the order of 5 to 15 per cent—and is less than the probable uncertainties in our knowledge of what these voltages actually are. The lightning arrester on the other hand will in most cases at least limit the voltage to 50 or 60 per cent of the apparatus insulation strength, and thereby provide a margin which should be adequate even for our present lack of precision in impulse strength values.

Although these facts are generally admitted there is still some disposition to regard the lightning arrester as insufficient because it may have been disconnected for inspection or maintenance, or for various other reasons it may not be on the job when needed and, therefore, backup is necessary. It is a question whether the hazard to service from this condition is as great as some commentators appear to believe. If it is, however, there is ample precedent in other fields particularly in the oil circuit breaker field for employing more than one arrester so that if one is out of commission, others will be available to maintain the protection. In such a case the margin of 40 or 50 per cent between the voltage applied to apparatus and the voltage which it can stand would never have to be reduced to the small value of 5, 10, or 15 per cent. In this connection it may be pointed out that there are types of arresters on the market today which are not only better but less expensive than ever before.

If the lightning arrester is as unreliable a device as it seems to be regarded in certain quarters, perhaps in the interest of honesty and straight-shooting we should discontinue its manufacture as we did that of the choke coil when we had determined by test that it was of little value as a protective device. On the other hand since the same group of experimenters who studied the choke coil have shown that the lightning arrester is of definite value as a protective device it should be given the credit to which it is entitled.

**F. D. Fielder and P. H. McAuley:** Mr. Peek has done much work on the surge breakdown of air. He is to be commended greatly for studying the effect of various wave fronts and attempting to derive empirical formulas to conform to the results. However, in doing so, he has used some data which we are unable to check in the Trafford Laboratory using what we consider to be very rigorous methods. It is stated that it may be assumed that a given amount of energy is required to break a given gap and the equations follow from this assumption. Nevertheless, the data show considerably higher flashover voltages and impulse ratios for the short fronts with other conditions the same. For instance, in Table II of the paper, the impulse ratios for $\frac{1}{2}/20$, $1\frac{1}{2}/20$ and $3/20$ waves progressively decrease. The same statement applies to the waves with 5 and 40 microsecond tails with different fronts. This seems to show a discrepancy between theory and data. Furthermore, it is not believed possible that one equation could express the relationships for various kinds of waves where the voltages are different functions of time for the different waves.

Mr. Peek has not stated the type of surge generator and the method of taking oscillograms. We use a modified Marx generator with a resistance potentiometer to the oscillograph. We calibrate the oscillograph independently and merely use the sphere gap as a check.

Very often these two independent methods of measurement fail to check on the first trial even at the minimum sparkover point of the insulation under test. But, in every case, it has always been possible to obtain a check within 2 per cent by smoothing out the applied voltage wave. We suspect that a very highly damped oscillation may appear at the point where the wave reaches its crest. This is of such a nature that it acts as follows:

1. It has little or no effect on breakdown in non-homogeneous fields such as insulators and needle gaps.
2. It is not transmitted by the resistance potentiometer.
3. It does produce breakdown of the sphere gap.

Hence, it must be eliminated if the sphere gap is to be used successfully. It is obvious that, by calibrating the oscillograph with the sphere gap, there is a risk of introducing considerable error. We are not criticizing the sphere gap but merely stating that we find it a possible source of error. Moreover, we have found that the above source of error increases with the steepness of the applied wave front. This may account for the discrepancies pointed out above.

We would like to ask the author on what basis the wave front time is determined from the oscillograms. In Fig. 4 of the paper the front is given as one-half microsecond, but according to classical definition, the time to crest would be over two microseconds.

In connection with the adoption of a standard wave, we feel that much remains to be done in securing fundamental data. It is perhaps to be regretted that in our early work we used the term "rectangular wave" to illustrate our methods of analyses. Actually our test wave has always been approximately $1\frac{1}{2}/40$ positive, using Mr. Peek's designation. It is rectangular only by comparison with a 5 microsecond wave. But the front is short enough and the tail is long enough that, for the range of time lag values usually considered, it produces essentially the same results that a rectangular wave would be expected to give. In testing we cover the full range of the "full wave" and "overvoltage" methods to secure a complete time lag curve. As a matter of fact, it is felt that the longer the tail of the wave the better, because the most pessimistic values are thereby obtained. Furthermore, for purposes of co-ordination, data obtained in this way are all inclusive of the waves recorded on lines and not

limited in application to a certain percentage of natural lightning waves like the short or 5 microsecond wave data.

Mr. Sporn has called attention to the variations in 60 cycle flashover values given out by the various manufacturers. This situation has caused us considerable concern for some time. In the Trafford Laboratory we use a 100 cm. brass sphere gap for measurement and compare the insulators under test directly with the gap by bracketing in parallel. The voltage rises at an average rate of 11,500 volts r. m. s. per second. Another group using an aluminum gap and a higher rate of rise report lower flashover values. The same calibration curves and correction factors are used in each laboratory. Hence, it is evident that the cause of the discrepancy is not readily detected. However, steps are now under way to investigate the situation thoroughly and it is expected that, in the near future, more general agreement will be attained. In this connection, it is felt that the effect of humidity cannot be neglected and possibly is responsible for a large part of the differences. Unfortunately, this is a difficult problem to study at high voltages.

**J. J. Torok:** Mr. Peek, in his paper, has covered a very wide field which includes both theoretical and laboratory viewpoints. From our work, which is parallel in nature, we have arrived at somewhat different conclusions. In this early work it soon became apparent that the breakdown or sparkover was a phenomenon involving two factors, namely, voltage and time. In order to segregate these elements and find the absolute significance of each in regard to breakdown, a wave had to be chosen which would hold one or the other constant. Such a wave must of necessity be rectangular in shape. In using such a wave, its shape is not changed throughout the testing cycle, only its magnitude is varied. First a low voltage is applied and the time element determined from oscillograms. Then the voltage is raised and another measurement made. This process is continued until the characteristics of the breakdown in terms of time and voltage are found for all practical purposes. Truly an ideal method, for it fulfills all requirements. Of course, the physical and economic limitations of the laboratory equipment were such that an absolute flat topped wave could not be obtained, but the deviation is so small as to be negligible in performance. This wave was designated as the Trafford Wave.

The technique of the laboratory staff has with intensive study and requirements reached such a point that the most desirable data can be obtained with the cathode-ray oscillograph in the same period of time as was required with the sphere gap alone.

Subsequent to our work on flashover, Mr. Cox entered into a correspondence with Professor Ryan on the mathematical analysis of flashover time. Together they worked out a fairly satisfactory solution based on the laws of thermal ionization and streamer propagation. However, Mr. Cox, considered these calculations of theoretical interest but of little practical value because of the independent variables which could not be predetermined for an unknown condition.

To obtain a true prospective of the entire lightning field, we had to obtain considerable information in the field which klydonograph data did not give. The oscillograms obtained in the field were classified into two groups, first those which caused line insulation flashover and, second those which did not. The first group, because of distortion by flashover, could not be used for determination of the nature of the wave. The second group of data, however, were useful in this connection. Most of them were of 50-150 microseconds duration. This indicated that either the cloud discharge area was from 10-30 miles in extent or that the cloud discharged in 50 to 150 microseconds. It is well known from meteorological data that the discharge area is of the order of one-half to one mile in extent. The discharge being of such long duration, we found from Bewley's work as well as Mr. Peek's curves, that the maximum induced voltage cannot exceed 100 to 150 kv. on a 50-ft. line.

In further correlating our field and laboratory data with theory, we have found that any given wave shape of the second group will not cause flashover at any fixed impulse ratio but that the factor of magnitude is vitally interlinked, so that any impulse ratio ranging from one and upwards, might result. Incidentally in the work it soon became apparent that the change of wave shape on a line was caused by corona or tap off lines and that the wave upon formation was of exactly the same shape as it was later when it was in motion.

Carrying this conception to transmission lines, we are led to believe that with greater quantities of insulation and a given wave, the flashover will take place in a period of time much longer than if the insulation were reduced. This means that the impulse ratio would be much lower on a 220-kv. line than on a 110-kv. line.

**C. L. Fortescue:** The results of observations made during the past two years have forced Westinghouse engineers to conclude that induced surges due to lightning strokes were of no consequence on high voltage lines and that it was necessary to look to direct strokes as the cause of transmission line outages due to lightning. The first evidence of the fact that the induced surge was not an important factor arose during the lightning investigation at our Tennessee station in 1928. The lightning storms were of frequent occurrence in close proximity to the line and in spite of the fact that strokes to earth took place at distances varying from one-fourth to one mile there was no indication of any surge on the cathode ray oscillograph. The calibration of this instrument in the Tennessee test was such that any surge potential exceeding line voltage would have given a record on the photographic film. Later on in 1929 the same results were experienced in all our field stations: on the 220-kv. line of the Public Service Electric & Gas Company at Stillwater, New Jersey, our station on the Turner-Logan Line of the American Gas & Electric Company in West Virginia, and our station at Frankfort, Illinois, on the lines of the Public Service Company of Northern Illinois.

Although the scientific evidence of the observations of the past two years is quite convincing, at the same time, in order to establish the proposition that induced surges are not an important factor in producing outages on high voltage transmission lines, a theory of induced surges which will account for these observed facts seems necessary. The basis for the classic theory of induced surges is founded on the erroneous assumption that the cloud is a conductor and therefore can discharge to earth in a very short time. The fallacy of this has been exposed by a number of prominent scientists. Sir James Thompson, Sir Ernest Rutherford and others have shown that the conductivity of air depends upon the number of free electrons present. Townshend and others have shown that the sparkover in air also depends upon the number of free electrons present and it has also been shown that an ionizing agent such as ultra-violet rays will affect the apparent strength of air. A number of early investigators have shown that in an atmosphere highly saturated with water vapor when a cloud is formed the free electrons are absorbed by the particles of vapor such that their mobility is lost and thereby the conductivity of the cloud is reduced. This is also further borne out by the fact that high humidity increases the sparkover voltage of insulators and needle gaps though its effect on sphere gaps is very slight. It is therefore an established fact that the atmosphere in the interior of a cloud, far from being a conductor, is a very good insulator.

Another fact that the protagonists of the classic theory of induced strokes have lost sight of is that in order to discharge a cloud instantly the whole charge would have to be concentrated in a very small volume, and assuming that a channel had been provided from cloud to earth, this charge would have to move over this path to earth as a concentrated charge. Since it requires a concentrated charge of twenty coulombs a mile above the earth to produce a potential gradient of 50,000 volts

per ft. the actual potential of this charge concentrated in a small volume would be enormous, very many times greater than the value that a number of scientific observers have estimated as the potential of the cloud to earth. If, on the other hand, the assumption is made that the cloud is a good conductor of spherical form one mile in diameter and that this charge is distributed through this conductor (which would be physically impossible), it will require five microseconds for the more remote portions of the charge to reach the point of discharge. Therefore, a minimum limit for the complete discharge would necessarily be at least seven microseconds.

When we consider the possible rate of discharge on the basis of the actual characteristics of the cloud the rate at which this can take place seems to be comparatively slow. In the first place the mobility of the charged particles of water forming the cloud is so low that discharge cannot take place in a reasonable time through motion of these charged particles. The only way in which a volume of cloud can be discharged is by ionization within the cloud itself. This process within the atmosphere of the cloud is much slower than in ordinary air on account of the small number of free electrons present. The rate of progress of the streamers within the cloud will therefore be no greater than one-twentieth the velocity of light and probably considerably slower than this. The mechanism of discharge would be probably as follows: As the streamer to earth forms, the portion of the charge in the cloud immediately adjacent to the streamer will go into the formation of the streamer and thereby a high gradient will be set up in the portion of the cloud in the immediate neighborhood of the streamer. The streamers will therefore begin to form outward from this portion of the cloud into the body of the cloud; as they progress an increased portion of the cloud charge is tapped and carried into the streamer forming to earth. When the streamer reaches earth the gradient in the cloud is increased on account of the greater demand for current to support the ionized channel to earth so that the rate of progress of the streamers into the body of the cloud is increased. After a while a point will be reached where the further progress in the formation of streamers in the body of the cloud will not supply the amount of current necessary to sustain the lightning channel to earth and the lightning stroke will cease. Considered on this basis it will be plainly evident that to discharge a volume of the cloud a mile in diameter would require at least 100 microseconds. If this volume contained 20 coulombs the average rate of discharge would be 200,000 amperes.

A very interesting up to date treatment of the discharge from cloud to cloud and from cloud to earth is given by Dr. G. C. Simpson in his Twentieth Kelvin Lecture entitled "Lightning," delivered before the Royal Institution, April 25, 1929. For a more detailed treatment of the subject the reader is referred to this lecture. In this article Dr. Simpson makes the following statement: "A very important factor in connection with a lightning discharge is the time element. Wilson has not determined this, but we have recent measurements by Norinder and Matthias and, if we may accept the opinion that atmospherics are due to lightning discharges, we have the large mass of data collected by Watson Watt. All these determinations agree in making the average duration of a lightning discharge greater than 0.001 second. A discharge of twenty coulombs in 0.001 second gives a mean current of 20,000 amperes—a value agreeing well with the direct observations of current made by Matthias. This mean value must, however, be greatly exceeded for short periods during the course of a discharge, and we may well expect instantaneous values of the order of 100,000 amperes." I think it probable that in a very severe lightning stroke the maximum rate of discharge may reach a value of 200,000 amperes but, if according to the classic theory, a complete discharge of the cloud will take place in two microseconds, the rate of discharge would have to be of the order of 10,000,000 amperes which is obviously an impossible value and even if the upper value of five microseconds mentioned by some of the protagonists of the classic theory were true the current would have to be of the order of four million amperes. It does not seem likely that such observers as Norinder, Matthias and other scientists who have measured the value of current in the lightning discharge by various means should be so far out in the order of the measurements that they have made. Let us now consider the value of the induced surge due to a lightning stroke in the close vicinity of a long transmission line.

It will be assumed that the discharge takes place between cloud and earth and that a uniformly charged spherical volume of the cloud whose center is a height $H$ above the line is completely discharged, the total quantity being $Q$. Then if the discharge takes place instantly, the potential induced on a line of height $h$ above ground at a point $x$ distant from the point on the line vertical below the center of the sphere may be obtained on the basis that the release of the bound charge will give rise to the same potential as that which would be induced on a similar line that was insulated from earth. We may assume that if $h$ is small compared with $H$ the gradient from $h$ to earth will be uniform and vertical and the value of the gradient at $x$ will be

$$\frac{2\,Q\,H}{(H^2+x^2)^{3/2}}.$$

The induced potential on the wire will be

$$\frac{2\,Q\,H\,h}{(H^2+x^2)^{3/2}}.$$

The discharge of the cloud over the lightning path is, however, comparatively slow. If we assume that this discharge takes place at a uniform rate $i$, the amount discharged during the time $d\,t$ is

$$i\,d\,t = \delta\,Q.$$

We may, therefore, take for the released potential at any point $x$ due to the increment $d\,Q = i\,d\,t$.

$$\delta\,V = \frac{2\,i\,H\,h}{(H^2+x^2)^{3/2}}\,d\,t.$$

This increment of potential divides into a positively and negatively traveling surge expressed by

$$H\,h\left[\frac{1}{\{H^2+(x+\alpha\,t)^2\}^{3/2}}+\frac{1}{\{H^2+(x-\alpha\,t)^2\}^{3/2}}\right]i\,d\,t$$

The increment contributed to the potential of the surge at the point $x$ at time $T$ due to the increment of potential released at time $t < T$ is given by

$$H\,h\left[\frac{1}{[H^2+\{(x+\alpha\,T)-\alpha\,t\}^2]^{3/2}}+\frac{1}{[H^2+\{(x-\alpha\,T)+\alpha\,t\}^2]^{3/2}}\right]i\,d\,t$$

The total potential of the surge at time $T$ is therefore

$$H\,h\int_0^T\left[\frac{1}{[H^2+\{(x+\alpha\,T)-\alpha\,t\}^2]^{3/2}}+\frac{1}{[H^2+\{(x-\alpha\,T)+\alpha\,t\}^2]^{3/2}}\right]i\,d\,t$$

$$H^2+\{(x+\alpha\,T)-\alpha\,t\}^2=H^2+(x+\alpha\,T)^2-2\,\alpha(x+\alpha\,T)t+\alpha^2\,t^2$$

$$H^2+\{(x-\alpha\,T)+\alpha\,t\}^2=H^2+(x-\alpha\,T)^2+2\,\alpha(x-\alpha\,T)t+\alpha^2\,t^2$$

The integrals of the two terms in the bracket are

$$\text{First Term}\left[\frac{\alpha^2+-\alpha\,(x+\alpha\,T)}{\alpha^2\,H^2\,\sqrt{H^2+\{(x+\alpha\,T)-\alpha\,t\}^2}}\right]_0^T$$

$$\text{Second Term}\left[\frac{\alpha^2\,t+\alpha\,(x-\alpha\,T)^2}{\alpha^2\,H^2\,\sqrt{H^2+\{(x-\alpha\,T)+\alpha\,t\}^2}}\right]_0^T$$

Taking the limits we have

$$\text{First Term} = \frac{x + \alpha T}{\alpha H^2 \sqrt{H^2 + (x + \alpha T)^2}} - \frac{x}{\alpha H^2 \sqrt{H^2 + x^2}}$$

$$\text{Second Term} = \frac{x}{\alpha H^2 \sqrt{H^2 + x^2}} - \frac{(x - \alpha T)}{\alpha H^2 \sqrt{H^2 + (x - \alpha T)^2}}$$

The complete solution is therefore

$$\frac{i h}{\alpha H} \left\{ \frac{x + \alpha T}{\sqrt{H^2 + (x + \alpha T)^2}} - \frac{x - \alpha T}{\sqrt{H^2 + (x - \alpha T)^2}} \right\}$$

For $x = 0$ we have potential at end of time $T$.

$$V_T = \frac{2 i T h}{H \sqrt{H^2 + \alpha^2 T^2}}$$

$$\frac{d V_T}{d t} = \frac{2 i h H^2}{H (H^2 + \alpha^2 T^2) \sqrt{H^2 + \alpha^2 T^2}}$$

The value of $V_T$ will reach its maximum when

$$\frac{d V_T}{d t} = 0.$$

This gives

$$H^2 + \alpha^2 T^2 = \infty$$

or

$$\alpha T = \infty \text{ and } Q = 20 \text{ coulombs.}$$

This simply states that assuming a constant rate of discharge $V_T$ will keep on increasing so long as the discharge lasts and will cease to increase when the discharge stops.

If $i = 200{,}000$ then the maximum will be reached in 100 microseconds. We infer that the important data is the average rate of discharge of the cloud during the first few microseconds since the rate of building up is most rapid during this time. We will not be justified in ignoring the discharge rate during the formation of the streamer from cloud to earth, as the space charge formed along the discharge channel probably accounts for a very substantial part of the total discharge from the cloud, but the results obtained on the assumption that the cloud discharge reaches its average value instantaneously will have the advantage of being conservative.

For a discharge a distance $d$ from the line we may substitute for $H^2$, $(H^2 + d^2)$ and for $V_T$ the expression will be for the point $x = 0$

$$V_T = \frac{2 i T h}{\sqrt{H^2 + d^2} \sqrt{H^2 + d^2 + \alpha^2 T^2}}$$

$$V_T = \frac{2 i T h}{H \sqrt{H^2 + \alpha^2 T^2}} \, x \, 9 \, x \, 10^{11} \text{ volts.}$$

Where the cloud discharge is distant $d$ from the line, the maximum value of the surge at the point $x = 0$ is

$$V_T = \frac{2 i T h}{\sqrt{H^2 + d^2} \sqrt{H^2 + d^2 + \alpha^2 T^2}} \, x \, 9 \, x \, 10^{11}$$

Where the value of $H h d$ are given in centimeters and $\alpha$ is given in centimeters per second. To obtain $V$ in volts when $i$ is given in amperes the factor $9 \, x \, 10^{11}$ is included in the equations given above.

Let us now consider some numerical examples. Assume a spherical portion of a cloud which is uniformly charged and whose center is 5000 ft. above the earth to be discharged by a stroke of lightning and let the height of a line in close proximity to the discharge path be 50 ft. What will be the maximum voltage induced? Here $\frac{h}{H} = \frac{1}{100}$, and if we assume a current $i = 200{,}000$ we obtain

$$V_{max.} = 120{,}000 \text{ volts.}$$

If the line is one mile from the point of discharge

$$V_{max.} = 85{,}000 \text{ volts.}$$

Thus it will be seen that the values obtained by taking into account the slow rate of discharge of the cloud, adequately explain the fact that at numerous observation stations no value of induced surge due to lightning stroke has been observed which will cause the cathode beam to move off the target of the Norinder cathode ray oscillograph when the width of this target is such as to preclude the line voltage from appearing on the film. It seems appropriate also to remark that if, as a result of the lightning stroke, surges corresponding to gradients of 50,000 volts per ft. appear on the transmission line the difference in induced effect of a stroke right adjacent to the line, and one a mile or two miles away is not very great, the former induces a value 71 per cent of the value due to the stroke in close proximity to the line and the latter 45 per cent. If, therefore, values of induced stroke corresponding to a gradient of 50,000 volts per ft. were produced, strokes one mile away would give values corresponding to a gradient of 35½ volts per ft., or two miles away a corresponding gradient of 22½ volts per ft. These values are so large that it would be impossible for a lightning storm in the neighborhood of a line to fail to give indications on the cathode ray oscillograph. In fact each thunderstorm lasting for an hour would give perhaps as many as 100 records varying in magnitude from a few hundred thousand volts up to millions of volts. This does not correspond with the results backed by observations.

To complete the argument it must be shown also that the probability of direct strokes to line rather than to earth must be such as to account for the average number of surges of magnitude higher than the above value estimated as due to induction which has been observed by cathode ray oscillographs and klydonographs. Let us consider a cloud some 2000 ft. above the level of the earth, moving over a transmission line, then if the ground wires on the transmission line are some 90 ft. above the surface of the earth we will find that if we take a 2000-ft. radius with each ground wire as center and strike an arc intersecting the surface of the cloud, these points struck from every point on the two ground wires over which the cloud is passing will bound an area of the cloud in the form of a broad band 600 ft. wide on either side of the tower. Within this band every stroke which forms will hit the tower or ground wire rather than the earth. If the cloud extends for two miles on either side of the center line of the transmission line, this band in the cloud will comprise approximately 6 per cent of the total area of the cloud. If it is assumed that the strokes originate equally from every portion of the cloud and there are an average of three strokes a minute, in one hour there will be a total of 180 strokes from cloud towards earth of which 10 or 11 will probably strike the ground wires. This proportion of direct strokes corresponds very well with the results of actual observations on transmission lines by utility engineers as well as with the results that have been obtained by means of the klydonograph and the cathode ray oscillograph.

The other evidence in support of the theory advanced is the existence of lines passing through territory where ground resistance is very low, which are practically immune from outages due to lightning. The difference in protective effect of ground wires against induced strokes when well grounded and otherwise is not sufficient to account for this immunity as compared to other lines built over territory where ground resistances are high. On the other hand, if only direct strokes are of importance, the fact of low ground resistance completely accounts for this immunity. It is hoped that the future work in connection with lightning will give us more data as to the value of the current in the lightning strokes and also in regard to the potential of such a stroke when it strikes the ground wires of a transmission line. When such data are available it should be possible to design

a transmission line in such a manner that outages due to lightning will occur very rarely.

**K. B. McEachron:** In discussing this paper it would be helpful if Mr. Fortescue would supply certain information in regard to Fig. 1.

1. How many insulators were used in the test?
2. What was the rating of the arrester?
3. Was the arrester for grounded or non-grounded neutral service?
4. Does the applied surge shown represent a traveling wave, or was it a laboratory representation of a traveling wave?
5. If a laboratory impulse, does the rate of current rise and crest value of the current through the arrester correspond to those which would be found on an actual transmission line?

The answer to these questions are important, as they determine the form of the arrester characteristic volt-time curve during discharge.

Under the caption, "Lightning Arresters as Protection of Line against Flashover," Mr. Fortescue explains that if arresters are used in the station, the insulation of the line for one-half mile can be graded without increasing the outage factor of that portion of the line. Mr. Fortescue's statement is based entirely upon the assumption that the wave is traveling into the graded section with such a crest voltage and wave shape that the first insulator in the graded section will not have time to flashover in the time taken for the wave to travel to the arrester and the reflected wave to travel back. This fact is shown very clearly in Fig. 8 of the paper, in which the author has shown the number of suspension units which can be protected at various distances back from the lightning arrester.

It should be pointed out that this variation in number of insulators extending back from the station was not contemplated in the method No. 3 proposed by Montsinger and Dann. These authors propose a limitation of the line insulation to earth from points within 100 circuit ft. of the terminals of the apparatus to points approximately one-half mile therefrom, the values not in excess of the flashover voltage in Table I of their paper. It is obvious, I believe, that the method proposed by Montsinger and Dann is one in which the lightning arrester at the station will be unable to give protection at points even a few hundred feet from the lightning arrester.

For direct strokes with extremely steep wave fronts and high applied voltage much in excess of the flashover of the insulator, where flashover takes place on the front of the wave, it is probable that the curve in Fig. 8 does not apply. In other words if the flashover voltage of the insulator has been reached before the wave has had an opportunity to reach the arrester and return, the arrester could not give protection. It is probably true, under severe direct stroke conditions, that the insulator in the graded section would have flashed over, even if it had been equal to the insulation out on the major portion of the line. Thus it is probable that the grading could be so arranged that the number of outages from direct strokes in the graded section would not be materially increased by this reduction of insulation. It does not seem to me that the method proposed by Montsinger and Dann entitled, "method No. 3" or the improved method suggested by Fortescue of grading the insulation represents the best practise from the standpoint of ability of lightning arresters to prevent outages where such low levels of insulation may be placed.

In attempting to protect the line insulators against flashover by the use of line arresters, it seems that the arrester could only protect the insulator nearest itself. Unlike stations where most of the waves come traveling in over the line, the highest voltage is at the point of inception and this is the point where protection is required, and if a large percentage of the flashovers are caused by direct strokes, the line arrester could not protect insulator strings a half mile distance and it is doubtful if even insulators in the next span could be so protected unless direct strokes have a certain slowness of wave front, coupled with comparatively small energy. Transmission line arresters as designed at present will not safely handle severe direct strokes. These arresters are capable of handling currents corresponding to induced charges on transmission lines but it is doubtful if it is economically possible at this time to produce an arrester which will successfully handle large currents of the order of ten, twenty, or thirty thousand amperes, as may occur in even the moderate direct stroke.

Mr. Fortescue in his analysis shows that with arresters approximately one mile apart all steep waves having crest voltages of 23 per cent above the 60 cycle flashover will cause a string in the middle of span to flashover. Assuming a 500-ft. span and using Fig. 6 of Mr. Fortescue's paper, it appears that all waves having crest values of 65 per cent above the 60 cycle flashover value and a rate of rise of front, which is fast compared to one microsecond, could cause a flashover. The conclusion is that line arresters should be close together and they will not be safe against the effects of direct strokes unless the current is rather small. Another advantage in placing arresters close together is that in many cases two arresters will be able to help a third arrester in carrying the current, so that the total current carrying capacity will be somewhat increased over that of one arrester. It seems to me that the present type of transmission line arrester should be able to successfully protect in those cases where the current flow does not exceed the values which would be obtained under induced conditions. It is felt, however, that experience should be gained with this form of protection and it does represent a means of reducing the number of outages due to lightning. In general this form of protection will be probably most efficacious in reducing the per cent of outages on low voltage lines. This comes about because of the fact that the percentage of direct strokes to induced strokes which cause flashovers is probably greater on the high voltage line.

Discussing the paper by Messrs. Montsinger and Dann: The 60-cycle strength of apparatus insulation is determined by the magnitude of the 60-cycle voltage which is a definite value for a given system. At the present time the impulse voltage is not a fixed definite value, because the system insulation varies greatly and the protective measures employed vary also. I believe the best method at present which may be used to establish an insulation level is to install a gap close to the transformer terminals and depend on the lightning arrester to prevent the gap from sparking.

In general I do not believe the use of the gap alone or in combination with a fuse, as suggested by Messrs. Johnson and Bundy is desirable unless all other means fail, because the flashover of a gap gives rise to an extremely steep tail which will cause oscillations in inductive apparatus. Of course, if this gap can be set low enough and still not interfere with service, it may be that this form of protection will result satisfactorily in some cases. However, the usual operating practise does not indicate that gaps set as small as those suggested by Messrs. Johnson and Bundy can be employed successfully on transmission systems. The ideal protection for a transformer is a device which will hold the impulse voltage to a value slightly below the 60 cycle failure voltage of the insulation for all forms of applied waves. The chopping of a wave is not the best method of protection.

There has been in recent years a very considerable change in attitude with regard to arresters for high voltage systems. This has come about largely because of the increased knowledge of arrester performance and improved design. I am confident that the arrester represents the proper solution of the problem. The use of the gap in parallel with the arrester is advantageous, because it becomes a measure of arrester performance and gives the designer of the apparatus a definite mark to which to design. This scheme should be welcomed alike by the manufacturer of the transformer and the lightning arrester, and also the

operator who uses such equipment. It furnishes a demonstration of whether or not the arrester is performing properly and also supplies to the manufacturer of the transformer a definite limit of the impulse voltage which can be applied to the equipment. In my estimation this method of establishing a reference level of insulation is much to be preferred to method No. 3 suggested by the authors, which refers to the reducing or maintaining a certain level of insulation out on the transmission line for a distance of a half mile from the station.

Mr. Floyd in his paper, suggests that the arrester be made the basis for determination of coordination. This is interesting, but I do not believe that the point has been reached where this can be done. It seems the safest procedure is to base the insulation level on the gap using increased insulation on the bushing and transformer in succession, so that the transformer winding is the strongest link in the chain. The use of the gap not only simplifies the transformer designer's problem but it also simplifies the arrester designer's problem as an arrester which protected the gap under all conditions of wave front would be an adequate arrester, providing of course that the gap was properly chosen.

I do not favor changes in insulation to the coordinated level at a point one-half mile away from the station, because in such a case the arrester is not in a good position to protect service. If such insulation levels are to be established they should be graded with the weakest insulation nearest the arrester. However, the gap method is more definite and should be of value in proving the value of the modern arrester, as well as acting as a last line of defense for direct strokes or in case the arrester for some reason is temporarily out of service.

**J. F. Peters:** I am in entire agreement with the authors on the importance of coordinating the insulation of the various parts that make up a substation and also in agreement with their suggestion of caution being taken in the establishment of standards for insulating practises at the present state of the fundamental data.

However, I am not in complete agreement with their suggested ultimate basis for coordination. For instance, I do not believe that it is practical to introduce as many gradations into insulation between adjacent line insulation and the bushings of the apparatus. When we consider that the flashover value of line insulators, bus supports and bushings may vary 10 per cent due to constructional variations and then attempt to establish positive margins between these various steps, the final step, that of the apparatus bushing, will involve more expense than can be justified. If the flashover of one definite point be fixed in value, say the adjacent line insulation, a relief gap or lightning arrester, and all other insulating structures including bus supports, bushings and apparatus, are made higher with a comfortable margin, a more economical and entirely satisfactory coordination will be accomplished. Also, to determine the coordination between the various parts it is not necessary to consider the complete volt-time curve between 60 cycles and short impulses. This range of course must be taken into consideration in the laboratories where the design constants for the apparatus and insulators are determined but after they have been determined for the designer it should be sufficient to use a few points, perhaps one, in carrying out the coordination.

After obtaining the fundamental data in the field and laboratories it would be unsafe to apply these data without first considering how they agree with experience. The authors suggest relative values for three of the insulation levels, 100, 110, and 115 and state that those margins should exist for all ranges of waves having impulse ratios from unity to very short waves. That would mean that the margin should apply to 60 cycle flashover values. Now if we consider the line insulation suggested in the Montsinger-Dann paper as representing normal line insulation adjacent to stations then add 10 per cent for bus supports and 5 per cent more for bushing flashovers it would be found that bushings for high voltage apparatus should be increased 25 to 30 per cent, yet experience shows that these bushings are adequate as they are now being built. Experience, after all, is the proof of adequacy of any device, whether it be machine or insulation.

It is easy to conceive that after obtaining larger amounts of fundamental data both in the field and in the laboratories that our present ideas of insulation will be considerably modified but until such data is available it is my belief that the safest and soundest way to coordinate the insulation is the method given in the paper by Messrs. Montsinger and Dann.

**Edward Beck:** There has been some discussion of the relative importance of direct strokes and induced surges, and of the probable severity of direct strokes. The data secured by field investigations of natural lightning disturbances seems to indicate that on high voltage lines the voltages caused by induction from discharging clouds are not sufficiently high to cause concern and that the danger to insulation lies in the direct stroke. It has in the past generally been assumed that direct strokes into circuits produced voltages and currents of such magnitudes that it was impossible to cope with them. This opinion must be revised. Undoubtedly the direct strokes which occur are of varying intensity and it is the writer's opinion that the magnitude of the currents involved are only in unusual cases of the order of the higher values which have been mentioned. This opinion is based on field observations and experience with lightning arresters distributed along high voltage transmission lines for the purpose of reducing insulator flashovers.

In the spring of 1929 the company with which the writer is associated, with the cooperation of several operating companies made installation on 66-kv. and 110-kv. transmission lines totaling about 200 arresters spaced at intervals varying from one mile to several miles on different lines. These arresters are of the new autovalve type described before the Institute in October, 1929 and January, 1930, with cross section of discharge path equal to that used in the usual types of distribution arresters. They are installed on exposed transmission lines where flashovers have been frequent. They are thus exposed to severe service because one or two sets will always be near the origin of a disturbance, and the discharge currents passed by the arresters will be a function of the lightning voltage impressed on the line. It is highly probable that direct strokes have occurred to the lines on which these arresters are installed, in fact, the writer's opinion is that there have been numerous such cases because of the fact that outside of the protective zone of the arresters, flashovers have occurred. Yet so far, only one failure of a line arrester of this type has occurred, this being due to lightning. It is to be expected that the arresters used if subjected to discharge currents in excess of 10,000 amperes for the durations expected from the oscillographic records of lightning would be destroyed. If this is so, then the experience with these autovalve arresters indicates that the transient currents involved are not usually of the tremendous values which at various times have been ascribed to them. If direct hits into the line always involve the maximum voltages and currents that have been estimated, no reliable actual measurements exist, therefore the protection of high voltage lines against flashover by distributed lightning arresters would be impractical because the arresters would be destroyed. Fortunately, in the light of our experience with distributed high voltage arresters since the spring of 1929, this does not seem to be the case.

As stated in the paper by Mr. Cox and the writer presented before the Institute last winter, direct strokes are no doubt of varying intensity and in the writer's opinion it is probably only in unusual cases that they involve very high currents in the circuits which they strike. Thus the protection of transmission lines offers possibilities which are being thoroughly investigated. We hope to publish a report covering the progress of this work in the near future.

**L. V. Bewley:** The impulse sparkover of a given specimen

depends upon the applied wave shape and its polarity, the ultimate d-c. sparkover value $e_0$; and subsidiary factors such as temperature, barometric pressure, humidity, etc. Mr. Peek has found that most impulse sparkovers follow, to a surprising degree of accuracy, the equation

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right)$$

where

$e_0$ = ultimate d-c. sparkover
$t$ = time counted from the instant that the impulse is applied
$a$ = an empirical constant depending upon the type of gap, wave shape used, etc.

An equation of this type results from energy considerations in the case of a rectangular wave, and therefore suggests the possibility of specifying the impulse sparkover of a given gap and wave shape in terms of its rupturing energy $W$ and its ultimate d-c. sparkover voltage $e_0$.

The corona energy given to the gap is

$$W = \int_{t_0}^{t} (e - e_0)^2\, d\,t$$

or

$$\frac{W}{e_0^2} = \int_{t_0}^{t} \left(\frac{e}{e_0} - 1\right)^2 d\,t$$

where

$e = f(t)$ = applied impulse as function of time
$t_0$ = instant at which $e = f(t) = e_0$
$t$ = instant of sparkover

If

$e = f(t)$ is known, then $(e - e_0)^2$ integrates as

$$W = \int_{t_0}^{t} (e - e_0)^2\, d\,t = F(t) \Big/_{t_0}^{t} = F(t) - F(t_0)$$

Now if $e_0$ and $W$ are known for the given gap and wave shape, then the instant of sparkover is determined from the equation

$$F(t) - F(t_0) = W$$

and the corresponding sparkover voltage is

$$e = f(t)$$

If $(e - e_0)^2$ integrates into a transcendental equation, or if $f(t)$ is given as a curve whose equation is unknown, then the following graphical method is applicable:

(1) Draw the curve of the applied impulse $e = f(t)$, and the $e_0$ line intersecting $e = f(t)$ at $t = t_0$ and $t = t_1$

(2) Construct the curve of $(e - e_0)^2$ between $t_0$ and $t_1$

(3) By trial find the area $A$ under the $(e - e_0)^2$ curve out to a time $t$ (where $t_0 < t < t_1$) such that $A = W$. Then $t$ is the instant of sparkover and $e = f(t)$ is the sparkover voltage.

As examples of the application of the energy equation to different wave shapes, three cases are worked out below.

(A) Sparkover on a uniformly rising front

$e = f(t) = \alpha\, e_0\, t$ = applied impulse
$t_0 = 1/\alpha$ = value of $t$ for which $e = e_0$
$\beta = e/e_0 = \alpha\, t$ = impulse ratio

$$\frac{W}{e_0^2} = \int_{1/\alpha}^{t} (\alpha\, t - 1)^2\, d\,t = \frac{1}{3\,\alpha}\,(\beta^3 - 3\,\beta^2 + 3\,\beta - 1)$$

$$\beta^3 - 3\,\beta + 3 - \frac{1}{\beta} = \frac{3}{t}\,\frac{W}{e_0^2}$$

(B) Sparkover on top of a rectangular wave

$e = E$ = applied impulse
$t_0 = 0$
$\beta = E/e_0$ = impulse ratio

$$\frac{W}{e_0^2} = \int_0^t (\beta - 1)^2\, d\,t = (\beta^2 - 2\,\beta + 1)\, t = 1 + \frac{\sqrt{W/e_0^2}}{\sqrt{t}}$$

(C) Sparkover on tail of an exponential wave

$e = E\,\epsilon^{-\alpha t}$ = applied wave
$t_0 = 0$
$\beta = e/e_0$ = impulse ratio

$$\frac{W}{e_0^2} = \int_{t_0}^{t} \left(\frac{E}{e_0}\,\epsilon^{-\alpha t} - 1\right)^2 d\,t$$

$$\left[\left(\frac{1 - \epsilon^{-2\alpha t}}{2}\right)\beta^2 - 2\,(1 - \epsilon^{-\alpha t})\,\beta + \alpha\, t\right]\frac{1}{\alpha}$$

$$t_1 = \frac{1}{\alpha}\log\beta = \text{time at which sparkovers cease.}$$

Curves of these equations have been plotted in the accompanying figure. They show the same type of characteristics as obtained from experimental sparkover data, but the numerical agreement is not very accurate. The most surprising point

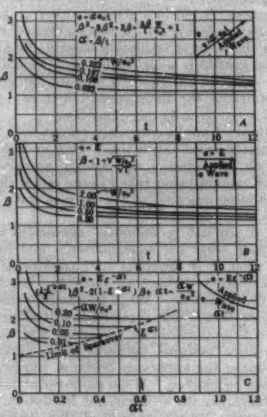


Fig. 6

brought out by a comparison of these curves with actual sparkover data is the considerable difference in the energy that it takes to break down a given gap with different types of waves.

Take, for example, the data on insulator sparkover given in Figs. 5, 7, and 17 of Mr. Peek's paper:

| Fig. | Type of wave | | $\beta$ | $t$ | $W/e_0^2$ |
|---|---|---|---|---|---|
| 5 | ½ | Rect. | 1.39 | 4 | 0.606 |
| 7 | Rising front | | 1.60 | 4 | 0.173 |
| 17 | 1½ | 40 | 1.45 | 4 | 0.703 |

From these and similar data it appears that much less corona energy is required to cause sparkover on a rising front than on the crest or tail of a wave; and therefore suggests that the time rate of change of voltage is of considerable importance in causing sparkover.

Mr. Peek has outlined in his paper the possibility of drawing the complete *impulse ratio-time lag* curve if the impulse ratio at the 50 per cent sparking point is known. It is of interest to carry out this suggestion in detail.

The equation of the "standard" test wave is

$$e = E_0 \left(\epsilon^{-mt} - \epsilon^{-nt}\right)$$

and if the front ($f$) is short compared with the length ($L$), then the tail of the wave may be approximated very exactly by

$$e = E\,\epsilon^{-m(t-f)}$$

where $E$ is the crest of the wave. The tail decays to half value at time $t = L$, so that

$$e = \frac{E}{2} = E\,\epsilon^{-m(L-f)}$$

or

$$m = \frac{\log 2}{(L-f)} = \frac{0.692}{(L-f)}$$

If sparkover ceases for an impulse ratio $\beta_1$ and after the time $t_1$ at which the tail of the wave crosses the $e_s$ line (ultimate sparkover value for unlimited time), there is

$$e = e_s = E\,\epsilon^{-m(t_1-f)}$$

or

$$\frac{E}{e_s} = \beta_1 = \epsilon^{m(t_1-f)}$$

hence

$$t_1 = \frac{1}{m}\log\beta_1 + f = (L-f)\frac{\log\beta_1}{\log 2} + f$$

But the impulse ratio follows the curve

$$\beta = 1 + \frac{a}{\sqrt{t}}$$

so that

$$a = (\beta_1 - 1)\sqrt{t_1} = (\beta_1 - 1)\sqrt{(L-f)\frac{\log\beta_1}{.692} + f}$$

where

$\beta_1$ = impulse ratio at 50 per cent sparking
$f$ = front of the wave
$L$ = length of the wave.

Thus on this basis, if the impulse ratio at 50 per cent sparking is known for a wave of given front and length, then the impulse ratio at any time lag may be found. For accurate numerical agreement, $\beta_1$ and $t_1$ should correspond to sparkover on the tail of the wave at a voltage equal to the sparkover voltage of a continuously applied potential.

**C. L. Fortescue:** Permit me to say in introduction that the rationalization of the insulation from transmission line to substation apparatus has nothing whatever to do with the question of the so-called standard wave. In rationalization what we seek to accomplish is to design the various members of a system in such a way that the strength under any condition of operation will progressively increase from a given point on the transmission line to the apparatus. What is required to determine how this shall be accomplished? The answer to this seems so simple and obvious that I cannot understand why there should be any room for differences of opinion. Obviously what must be determined is how long each member can withstand an applied voltage, beginning from the voltage at which it will just break down under continued application to values as high as are likely to be obtained under operating conditions. In mechanical engineering it is customary to base the strength of various members of a structure on the steady stress required to reach the elastic limit, the members being designed to withstand normal load with a factor of safety depending upon the type of stress to which it may be subjected. In electrical engineering we are somewhat better off in regard to the strength of our insulating members and we may actually test them so as to get information on their behavior for all values of stress and when such data are obtained we have the means for comparing the relative strength of the different members on an absolute basis.

The ability of the member to withstand various values of applied voltage and this ability measured by the so-called time lag or the length of time after the voltage is applied before the member flashes over, are the data required. Having obtained these data on the various members we can very easily compare them as to their relative strength for various values of applied voltage; thus considering the various types of gaps, we find on comparing the sphere gap with the needle gap, both of which have the same flashover value for a steadily applied voltage, that for high voltages the sphere gap is not so strong as the needle gap, that is to say, the sphere gap will not withstand the higher voltage as long as the needle gap. The curve showing the relation between applied voltage and the time required to flashover is the voltage-time lag curve, sometimes called the impulse time lag curve.

As in the case of mechanics it is necessary to devise testing machines by which the stress can be applied and accurately measured. The requirement of such a machine is that it shall be capable of maintaining the stress steadily until rupture takes place and this is true whether we use a mechanical machine for applying stress to a test piece or whether we use an electrical machine to apply stress to an insulating member or spark gap. The curves so obtained are fundamentally characteristic of the member and give all the necessary data as to its strength. The curve of the voltage of the type mentioned as the ideal for the test machine is sometimes called a flat topped wave. It is not possible to obtain an absolutely flat topped wave by any kind of electrical testing equipment but the closer we approach this ideal the more fundamental will be our test results.

I am gratified that there has been such a general discussion of this problem of rationalization. I shall try and reply to the points raised by the various speakers as briefly as possible.

Mr. Austin, in his discussion, suggests that there may be difficulty in balancing various members within 10 or 15 per cent. This, of course, is true to a certain extent but I do not anticipate any serious difficulty. As regards the deterioration of insulators due to smoke and dirt, this need not be considered for the reason that it scarcely affects the flashover value of insulators for time lags below 20 microseconds and longer time lags than this need not be considered. There may be one exception to this, in the case of insulators covered with salt spray where the distribution may be so upset that flashover will take place at lower voltages for a given time lag. Mr. Austin also mentions the fact that the limitation of the voltage in substations by means of arcs is hardly desirable from an operating standpoint. This has been realized for a long time and therefore lightning arresters have been developed. During the past few years, development of the lightning arrester has progressed to such a stage that at present a ceiling voltage as low as 2.5 times the rated voltage may be obtained. These new low ceiling voltage arresters are capable of protecting practically all the present types of substation equipment especially if an effort has been made to rationalize the system insulation.

In Mr. Jones' discussion there is an implication that outages due to direct strokes can be avoided by insulation alone. The results of our lightning investigations in the field show that it would be highly improbable that an insulating structure could be built which could withstand direct lightning potential without flashover. It is necessary to safeguard the insulating structure by various means such as for example the use of ground wires properly placed with low tower footing surge impedance or by means of suitably placed arresters.

Mr. Samuels implies that in connection with the discussions on rationalization there appears to be some confusion. My impression is that the confusion, if such exists, arises not from any intrinsic difficulty in the problem but from lack of straightforward thinking. It is true that there has been a considerable amount of data already published as to the characteristics of different structures that enter into the electrical system.

Some of these data will undoubtedly, in the course of time, have to be revised, especially such data as are being obtained by special wave forms which do not have the required characteristics of rising to a crest value in a very short time and remaining substantially flat through the whole range of breakdown values. The interjection of the question of wave standardization in this problem has been due to a complete lack of understanding of the nature of the problem which is not one of testing the system but is one of procuring the fundamental data which is required for the design of the system. I shall try to answer Mr. Samuels' questions in the order in which he has presented them.

Group A: Shall one part of a system have lower insulation than another part of the same system, and if so what part and how much lower? As I have stated in my reply to Mr. Jones' discussion, insulation is only one element in the problem of protecting the system against lightning. The lower limit of insulation of any system is the amount of insulation that will just withstand normal operating surges, such as those due to switching, without flashover. Any insulation above this value may be considered as part of the protective layout to prevent lightning outages. Since induced voltages are probably negligible for transmission lines above 66 kv., for such lines the design of the protective layout against lightning must be considered from the point of view of direct strokes. Three important factors in the design of the ground wire protection are:

1. Proper configuration of ground wires with respect to line wires so that they form an effective shield for the line wires against an oncoming stroke;

2. The proper tower clearances so that all possible discharge paths under these conditions will have the same strength. In this connection it should be noted that while it is desirable to have sphere gap characteristics between the line and tower structure, advantage cannot be taken of improved characteristics to reduce this clearance for the reason that, as I have mentioned in this discussion, a sphere gap having the same 60-cycle flashover as a needle gap will have a lower impulse strength for high applied voltages. For sphere gaps, where the spacing between the spheres is large as compared to the diameter of the spheres, for the same clearances, the impulse value for time lags of the order of one microsecond is not appreciably higher than for the needle gap;

3. The tower footing surge impedance should be rationalized with respect to the tower insulation so as to give the necessary protection. Thus in some cases where it is impossible or extremely costly to get low tower footing resistance it may be more economical to increase the number of insulators to the string and where tower footing surge impedances are extremely low it may be advantageous from an economic standpoint to use fewer insulators on the string.

Following the procedure outlined in the above paragraph, a line designed in this manner would through its entire length give the same degree of protection against lightning, which would not be the case if the same amount of insulation was used at every point on the line. In determining the position of ground wires it would be necessary to provide sufficient spacing from the line wires so that side flash, in case of the ground wire being struck, would be prevented. Unfortunately we do not have as yet sufficient data as to the potential of a lightning stroke when it hits a ground wire to decide definitely what this spacing should be, but assuming that the potential of ten million volts will be produced at the point where the stroke hits, the proper distance between ground wire and line wire should be of the order of 32 ft. which is the needle gap spacing which will just flash over with 10 million volts applied for one microsecond. However, it may not be economically feasible to use such a large spacing, especially for low transmission voltages.

Group B: What shall the insulation rating of each part be? This has already been answered under Group A for the case of line construction using ground wires. Where lightning arresters are used the length of string to give the same level of protection at different distances from the arrester has already been given in my paper.

Group C: What definite commercial test method shall be used to determine whether or not a piece of equipment has the specified insulation value? Voltage-time lag curves have been obtained and published for practically all of the elements that enter into the design of a system but in cases where such are not available and the 60-cycle flashover is known, the voltage time lag curve can be approximated from the known data.

The sub-questions appearing under Group A,

1. What shall be the flashover value of transformer bushings in relation to the insulation of transmission lines which are connected to the same bus? The best answer to this question is perhaps to insulate the transmission line to whatever the designer wishes, then limit the voltage in the substation where the bushing is located by (a) lightning arresters or (b) protective gaps which may take the form of reduced insulation or gaps of various natures.

2. What shall be the relation of the insulation of the transformer itself to that of its bushing? The transformer insulation strength should be coordinated with that of the bushing, past experience being given proper consideration in the coordination.

3. What shall be the insulation value of a breaker bushing in relation to that of the transformer bushing? There is little need for having a bushing of a different flashover value for the breaker and for simplicity it is advantageous to have the two bushings interchangeable.

4. What shall be the insulation value of an insulator on a bus to that of the bushing on transformers and breakers? As mentioned before, the substation should be protected by lightning arresters and gaps or a combination of the two and if the substation is to be protected the breakdown values of these gaps should be well below the bushing and bus insulation. If they are well below, it is then optional with the designer of the substation as to how much margin he wishes to have between protecting gaps and the various forms of insulation in the substation. This variation should perhaps be governed by the designs of the insulators and other equipment. It is essential only that there be a comfortable margin between the operating protective device and the flashover value of the insulation.

5. What relation shall there be between the insulation value of an insulator on a disconnect or a branch in relation to that of the bus or the bushings? This question is also answered by the answer to question (4).

6. What part shall be assigned to the lightning arrester in this discussion? From the author's point of view the lightning arrester plays the stellar role. The lightning arrester is the only device at present which can give satisfactory performance under repeated surges without causing outages, therefore, rationalization of the substation should be so carried out that the lightning arrester will function before any apparatus in the substation breaks down.

7. When shall the line insulation close to a station be made lower than the line insulation on the rest of the line? This should be done where protective gaps are not used. Where lightning arresters of proper characteristics are installed in the proper location it may not be considered necessary but it is advisable as a back-up protection in case the lightning arresters are removed for inspection.

Referring to Mr. Wallau's discussion, he calls attention to the difference in values obtained by General Electric and Westinghouse engineers for waves that are presumably similar and then he later on gives these inconsistencies as a reason for agreeing with Mr. Sporn's proposal to standardize wave forms on the basis of what is known about natural lightning waves—whatever the word natural may mean in this connection. One might just as well recommend to structural engineers to design bridge members on the basis of the natural stress they get under heavy

traffic conditions where a large number of automobiles start and stop suddenly on the bridge. What we are concerned with is relative strength, not the actual ability to withstand a particular wave form. A fundamental basis for obtaining relative strengths is to measure the time required to flashover when different values of voltage are suddenly applied to the insulator under consideration. The inconsistencies that Mr. Wallau calls attention to are not the result of the wave form but are due to differences in methods of measuring voltage and time lag. These discrepancies are not very serious and need not delay the application of the principles outlined in these papers. No doubt when men first began to measure the strength of materials, wider discrepancies than these arose but they did not prevent the development of the steam engine and a few other things that have forwarded civilization.

The development of methods and machines for measuring the strength of materials has been in progress for over a century and our friends expect us to reach the same state of perfection in measuring impulse strengths of insulating structures in three years of development. I would be surprised if in 10 or 15 years from now no discrepancies would be found in the measurements obtained by different bodies.

Let me once more reiterate that the so called standardization of wave form has nothing to do with the fundamental data on voltage time lag of insulating structures. About all that can be said in favor of a standard wave to represent lightning is that it might be of value in testing a system or equipment to find out whether it will withstand successfully, so called natural lightning. For obtaining design data, for rationalization, etc., it is of little value.

The specific information which Mr. McEachron wants concerning Fig. 1 is as follows: The number of insulators used in the test was four suspension insulators of the ball and socket type, 10 in. in diameter and 5¾ in. spacing. The arrester was of 73 kv. rating. The arrester was for non-grounded neutral service. It is of the autovalve type constructed of disks and mica separators and should not be confused with the new porous block arrester which limits the voltage to an even lower value. The applied surge is a laboratory representation of a traveling wave. By laboratory representation is meant that there were 500 ohms in series with the surge generator to represent current values as would appear on transmission lines. The laboratory current wave corresponds closely to that which would be found upon an actual transmission line if the voltage wave were similar to that shown in Fig. 1. In regard to Mr. McEachron's remarks in connection with the use of arresters for protecting transmission lines, I am sure that we are generally in accord on this question. I thought that I made it quite plain that it was necessary in considering such protection to determine a certain level and say for example that we will design this line so that any surge below this level will not flashover the insulators. Quite obviously a direct stroke to the line, as Mr. McEachron points out, at any point away from the arresters will cause a flashover at that point if the lightning stroke is sufficiently severe. In order that this last statement may not be misconstrued we may point out that it is quite probable that many of our smaller surges are due to side flashes from the main lightning stroke which do not cause severe surges.

Mr. Bewley's discussion on the energy of flashover deals with only two factors essentially, that is the voltage and the time. It is altogether erroneous to talk of energy of flashover in terms of purely voltages and time. Current oscillograms have been made of flashover with astonishing results. The most important of this work has been published in the paper by Messrs. Torok and Fielder and from the oscillograms in that paper it is evident that the current does not vary directly with the voltage and therefore it is almost out of the question to say anything of the energy of sparkover unless cathode ray oscillograms of the currents involved are made.

**F. W. Peek, Jr.:** It is futile to hope for an exact or perfect lightning wave from measurements on transmission lines. It is quite obvious theoretically that an infinite variety of waves may occur due to lightning. Of the very *many* waves measured, no two have been found that are exactly alike. This does not mean that standard waves for testing insulators and for coordination cannot be wisely selected at this time. Fortunately, it is not as complicated as it seems. Observations of lightning over many years show there are certain typical effects.

For high voltage lines the lightning sparkover of insulators is always much higher than the sixty cycle sparkover. In fact, on 220-kv. lines we have found that the ratio of the lightning sparkover to the sixty cycle sparkover, the impulse ratio, is usually over 1.8. These effects, which may be very severe because the voltages rise to such high values, may be produced as I have shown in my paper, by a number of different waves. I have found the ½/5 wave very convenient as a preferred or reference wave to produce these steep wave front effects.

Waves giving the effects of moderate steepness may occur at lower voltages and lower impulse ratios. Such waves become of increasing importance as the insulation of the line is decreased. The effects can be produced by full wave tests with a 1½/40 wave. It is my opinion that lightning characteristics of insulators and coordination are sufficiently determined by these two waves. I would, therefore, recommend that these waves be adopted as preferred waves.

I cannot conceive of the adoption of preferred waves in any way having a narrowing effect on research. Such waves should in no way influence types used in research and, as reference points and means of comparison, would be of great value. There has been an expression of pessimism by several in this discussion on the available knowledge of the lightning strength of solid insulation. I do not hold this view since we are able to predict, with great accuracy as shown by tests, the lightning strength of such complicated insulation structures as transformers. The non-resonating transformer has also simplified matters.

I have used, and strongly endorse the use of the cathode ray oscillograph whenever desirable. However, many of the smaller laboratories do not have cathode ray oscillographs. For this reason standard tests that are so simple that they can be performed accurately with sphere gaps as well as with the oscillograph are to be very highly commended.

The difference between the impulse curves from the different laboratories is due to attempt at comparison without consideration of all the variables. Obviously, two waves, each 20 microseconds in length but with different fronts, should not give the same voltage values.

Mr. Fortescue concludes by some formidable looking mathematics that induced voltages cannot be high and that all transmission line troubles must, therefore, be caused by direct strokes. A casual examination of his calculation indicates that the results are based upon a very high point charge and not, as stated, on a sphere cloud. If the calculation is corrected and actually based upon the sphere cloud it will be found that the results will indicate induced voltages of really dangerous values.

It is my opinion that our troubles result from both induced voltages and direct strokes. The direct strokes become of relatively increasing importance with increasing insulation.

I wish strongly to endorse the coordination method outlined in the paper by Messrs. Montsinger and Dann. In this connection, the remarks that Mr. McEachron has made are of interest.

**Philip Sporn:** Mr. Jones has commented on my criticism of the failure of the various insulator manufacturers to furnish data as to 60 cycle flashover of similar insulators that agree, and has pointed out that Mr. Austin has always attempted to take these factors into consideration in the data he gives. He believes that insulator strings have the same flashover characteristics under varying degrees of humidity as the needle gap and he

therefore takes care of the situation by expressing his 60 cycle flashover value of insulators in terms of spark gap values.

Disregarding for the purpose of this discussion the lack of accepted data in regard to spark over value of needle gaps under different conditions of humidity, it cannot be too strongly emphasized that Mr. Jones' facts themselves show the absolute unsoundness of Mr. Austin's practise. If a rod of a particular metal has an unusually large coefficient of expansion then a yard stick made of that metal is the very one *not* to use to measure the length of the rod in question under different conditions of temperature; in other words, the needle gap of all gaps is the one not to use as a calibrating means for determining 60 cycle spark over value of insulators.

I have I believe anticipated in my paper and answered Mr. Cox's main objections to the adoption of a standard impulse wave. However, I shall briefly summarize these again:

Admitting that complete volt time characteristics of all insulating media and structures is desirable it is a fact that such data will take many years to assemble. The proposed standard impulse test waves would enable the obtaining of these data (although these would give only four points—the 60 cycle value being of course the fourth point—on the volt time curve) in much less time. If the term "Standard Test Wave" is objectionable we might call them "Recommended Test Waves." This ought to eliminate a number of the objections. There has of course been no suggestion made as yet to alter the existing A. I. E. E. Apparatus Standards so as to call for an impulse test by applying one or all of the proposed test waves; nevertheless I am confident that we are definitely coming to it. It may be that this is the real reason back of Mr. Cox's objections.

I have always advocated the use of the lightning arrester where the economics of the situation permitted, hoping that some day it would demonstrate its complete economic justification while admitting that so far it had failed to do so. Mr. Treat's suggestion of *two* lightning arresters is a bit too much for me. If two arresters, why not three?

**V. M. Montsinger:** The idea seems still to prevail that the manufacturers of transformers want the operators to reduce the line insulation near the station. While this might generally result if standard transformers are to be used on account of the practise of over-insulating lines there is no occasion why higher insulated transformers cannot be used leaving the line as it is. In fact the proposed rules provide for this. It is well to point out again that it has never been the intention of the transformer subcommittee to dictate the level of line insulation even at the station, but rather take this as the stating level and build up to the transformer.

It is to be regretted that Mr. Sporn takes a pessimistic view on what is being accomplished in the line of coordination. We feel that a great deal has been done since he presented his memorable paper at Springfield in 1928. Perhaps the work has not been carried out along the exact lines he would prefer but since it has become standard practise with all progressive utility companies to use the best available data in making new station layouts and in fact in many cases in revamping existing layouts to obtain proper coordination we should feel encouraged.

As to the suggestion of incorporating our recommendations in A. I. E. E. Standards No. 13, Part II, in view of the policy adopted within the past year on Recommendations on Operation of Transformers does not belong in the main rules but rather should be combined with the new pamphlet, No. 100, which has just been published by the A. I. E. E. Part I, in some form, should be incorporated in Standards No. 13. The impression seems to prevail that once a rule is put into effect it cannot be changed. For the past few years there has existed a subcommittee which is so set up that desirable changes can be effected in very short time. It is the purpose of the Transformer subcommittee to make Standard No. 13 reflect up-to-date practises and we feel that it really does. Nevertheless as long as the recommendations are being followed in practise it does not matter so much whether or not they are in one of the Standards. If we wait until the recommendations are perfect they may never be standardized.

**G. D. Floyd:** I quite agree with Mr. Palueff that the relation which he has suggested between the number of flashovers and the height of conductor, etc., is only an expression of the tendency of effects of the various factors. He showed that for our Gatineau line the average number of flashovers worked out to 1.48, compared for the service record for 1929 of 1.75. For the 1930 season to date (Sept. 8th) there has not been a single flashover, which indicates that any formula set up to forecast a result such as the above must not be taken too literally, and in any case should be averaged over as great a circuit mileage of line as possible, and compared with the average flashover taken over a number of years operation.

Any explanation of why the co-ordinated insulation at our Leaside Station did not protect the transformer would be only conjecture, with the information available. A number of possibilities might be given, some of which are:

1. Direct hit on station bus very near transformer.
2. Insulation failure of lifting rod on 220-kv. circuit breaker, which was found shortly after, and appeared to be similar to the characteristic fracture of wood by lightning.
3. Incorrect co-ordination.
4. Possibility that it is not possible to protect apparatus against all incoming surges, of which the surge in question was one, by co-ordination only.

The tower footing resistances have been measured from the station out some distance, and these are quite low, of the order of 10-20 ohms. The station ground resistance is also extremely low, being a few hundredths of an ohm. The station ground wires are connected to the four line ground wires, which are of high conductivity, so that it seems reasonable to assume that the whole ground wire network and towers connected to it, are substantially at true ground potential.

Mr. McEachron does not state why he believes that the insulation level should be based on the gap rather than the arrester. Assuming that it is the fact that arrester operation at the higher values of surge current is still unknown, it seems that even with this handicap it would still be preferable, because of the straight line characteristic of the arrester for voltages of practically all durations. The spillway gap, by its very nature, has a characteristic which resists relatively high voltages if they are of short duration, and it cannot be expected that the solid and liquid insulation of a transformer will have even approximately the same volt-time characteristic as the gap. Therefore, the arrester is the logical unit around which co-ordination can be centered, and if some of its performance characteristics are still unknown, every effort should be made to ascertain them.

The subject matter of a great deal of the discussion of these papers indicate that we have not yet obtained sufficient information on the fundamentals of the problem to make more than an educated guess as to how best to solve it. Much of the discussion was confined to dissertations on the mechanics of the lightning bolt and the possibilities of direct hits and induced strokes, as well as to the relative merits of various laboratory methods, and to discrepancies between the same measurement made at different places. Until a majority of these things are established beyond doubt it will be necessary to proceed with caution, and not disturb the co-ordination that has become established by experience, without good and sufficient reason.

**A. E. Silver:** While the several papers and discussions on the subject of insulation might indicate rather wide differences in results obtained from research, ideas and reasoning are becoming better crystallized. As knowledge concerning the transient voltages affecting the performance of lines and apparatus is extended, greater agreement on the fundamentals can be expected

and satisfactory solutions to the insulation problem will be forthcoming.

The data which have been previously published on insulation characteristics as well as those contained in this symposium of papers, are all helpful to the intelligent use and coordination of insulation. Nevertheless, considerable work still remains to make them reasonably complete even for insulations now in common use. It is hoped that complete volt-time curves, or sufficient information for calculating them with reasonable accuracy, will soon be made available and that these data will be extended and modified in keeping with new knowledge as it is gained.

A word of caution might be spoken regarding attempts to write empirical formulas expressing the performance of lines with varying amounts of insulation, the influence of overhead ground wires, the relative frequency of occurrence of surge voltages of different magnitudes, attenuation of lightning voltages, and averaging of lightning surge wave shapes as they have been measured on lines of limited insulation strengths, etc., from data which are only partially reliable or representative.

The problem of insulation coordination is important and must be correctly solved and any compromising which may be resorted to, though expedient for the interim, must avoid the appearance of finality.

**H. L. Melvin:** Messrs. Lewis, Treat and McEachron have commented on the application of lightning arresters in the coordination problem while Mr. Peters is concerned regarding the possible influence of establishing successively higher insulation levels in a station on the insulation strength requirements of apparatus.

While lightning arresters or voltage limiting devices may play an important part in the coordination of system insulation, particularly when apparatus of inherently lower lighting insulation strengths are component parts, they are by no means a substitute for coordination. It should also be remembered that an economic justification must be established for the installation of arresters based on the protection afforded. Should such a device function perfectly to protect equipment when subjected to the most severe lightning discharges, then a coordinated system might have its component parts at practically the same insulation levels, which might be determined by consideration of generated overvoltages and switching surges. Pending the development of entirely dependable devices, or the knowledge which will permit of designing lines and stations so that the lightning current, which arresters may be called upon to discharge can be limited to the capacity of the devices, and for those situations where the installation of such arresters may not be justified, coordination of station insulation strengths by arranging the parts in successively higher steps would seem entirely logical and warranted. The application of arresters with a recognition of their limitations and for the purposes suggested by Mr. McEachron, would seem to be a very satisfactory procedure for the present at least.

The differentials suggested of 10 per cent between the line spillway and bus, 5 per cent between bus and apparatus bushings and the apparatus itself with a sufficient margin above its bushings, might lead to somewhat higher levels for stations and apparatus than present common practise, provided the spillway levels are established by insulation equivalent to the numbers of suspension insulator units as recommended by the Transformer Subcommittee. However, if the equivalent gap values as recommended by the Subcommittee are used as bases, the insulation levels would be somewhat lower. The data given in the paper by Messrs. Johnson and Bundy are quite illuminating in this respect, as the spillway gap settings used for 66-kv. and 110-kv. are even lower than proposed by the Subcommittee and evidently switching surges are not the cause of flashovers of these gaps. The point which it is desired to make is that, a proper or satisfactory value for the spillway has not been established due to insufficient knowledge regarding the values and character of surges arising within the system, but positive differentials between the various levels do seem essential if the flashovers which may occur at stations are to be localized at predetermined points. Furthermore if present trends and practises are incorrect or are not established upon sound bases, then the fundamental data should be obtained before final standardization is undertaken.

Attention should be called to the relatively slight consideration which is given to the distribution voltages in the studies of insulation and its coordination, whereas this part of the system is in many cases equally as important as the transmission. It will also be observed that rather glaring inconsistencies exist in practise, which may well be improved upon from the knowledge and data already available.

I would like to make the following general comments regarding the entire group of papers. They constitute another material contribution both of useful data as well as theoretical and practical discussion of this important problem. The unknown features have been well outlined and there seems to be little question but what they will be satisfactorily solved within a relatively short period. Complete knowledge of the lightning and surge voltage problem will not only make it possible to effect material improvements to service but economic benefits will be derived.

At the present time there seems to be possibly too much of a tendency among operating engineers to advise the manufacturers regarding the design of apparatus, likewise the manufacturers may be inclined to concern themselves unduly with transmission line design. It would seem therefore that if the operators would concentrate upon the task of discovering what are the magnitudes and characteristics of the surge voltages arising within the system and of natural lightning imposed upon the circuits while the manufacturers are devoting themselves to the design of insulators, apparatus and protective devices to give satisfactory service with these voltages applied (the two groups working in extremely close cooperation), a more satisfactory and practical solution to the entire problem will be found.

# Long Distance Cable Circuit for Program Transmission

BY A. B. CLARK[1] and C. W. GREEN[2]
Member, A. I. E. E. Member, A. I. E. E.

*Synopsis.—The rapid growth of the telephone cable network in this country has made it desirable to develop a system whereby this network may be utilized to transmit programs for broadcasting stations over distances upwards of 2000 miles. Such a system has recently been developed and given a trial on a looped-back circuit 2200 miles long with very satisfactory results. It transmits ranges of frequency and volume somewhat in excess of those now handled by the open-wire circuits which are used for program work, and also in excess of those handled by present-day radio broadcasting systems when no long distance lines are involved.*

*The paper deals first with the transmission requirements of broadcasting systems and then gives a description of this new cable system.*

* * * * *

As discussed in two recent papers,[3] one of which was presented before this Institute, telephone circuits are now extensively used for chain broadcasting. Radio broadcasting stations covering various local areas in the United States are connected together by wire circuits so that programs are delivered simultaneously to all of them. Thus, it is possible to deliver a program to the whole nation at once. About 35,000 miles of telephone circuits are now being regularly utilized for this service and about 150 radio broadcasting stations receive programs from one or more of the chains of wire circuits.

Today practically all of this service is being furnished by means of open wires using voice-frequency channels. Long distance cable routes are growing rapidly and are supplementing the open-wire routes, particularly those carrying very heavy traffic. Fig. 1 shows the long distance cable routes now in use in the United States, together with the additional routes proposed for installation within the next few years. The advantages in placing some circuits in these cables which will adequately handle program transmission service were evident and led to the development described in this paper.

Because of the special characteristics which program transmission circuits must possess it was necessary to develop an entirely new type of cable circuit, in which the method of placing the wires in the cables, the type of loading and all of the apparatus, including amplifiers and distortion correcting apparatus for both amplitude and delay, differ radically from other cable circuits. The development was recently completed and a trial installation made in which wires were looped back and forth in the cables between New York and Pittsburgh so as to produce a circuit 2200 miles in length. Tests were made on this circuit over a period of several months and very satisfactory results were obtained. It is, therefore, planned to make extensive application of this system and eventually program circuits may be provided in cable over practically all of the long toll cable routes.

So as to appreciate what is involved in the design of this system there will first be presented a discussion of the transmission requirements. Following this, the new system will be described and its more important transmission characteristics set forth.

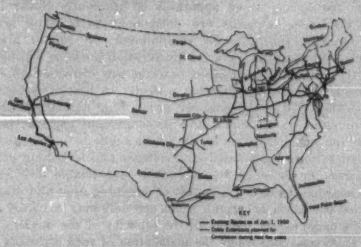


Fig. 1—Main Toll Cable Routes of United States and Canada

## Transmission Requirements

For program transmission the ideal, of course, is to provide a transmission line such that no distortion whatsoever will be caused to program material transmitted over the line whatever be its length. Ideally also, program pickup apparatus, radio transmitters, radio receivers and loudspeakers should be such that the program delivered from the loudspeaker should sound exactly like the original program delivered to a direct listener in the best location. To meet this ideal, however, would require that the whole audible range of frequencies, extending from about 20 to 20,000 cycles, and a tremendously wide range of volumes representing power differences of more than a million-fold be handled without any distortion whatsoever.

Actually the radio art is far from attaining this ideal.

1. Toll Transmission Development Engineer, Am. Tel. & Tel. Co., New York, N. Y.

2. Telephone Engineer, Bell Telephone Laboratories, Inc., New York, N. Y.

3. F. A. Cowan, *Telephone Circuits for Program Transmission*, presented at Regional Meeting of S. W. District of A. I. E. E., Dallas, Texas, May 7-9, 1929, A. I. E. E. Trans., Vol. 48, 1929, p. 1045; A. B. Clark, "Wire Line Systems for National Broadcasting," presented before the World Engineering Congress at Tokio, Japan, October, 1929, *Proceedings of I. R. E.*, November 1929, *Bell System Tech. Jl.*, January, 1930.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

It does not seem reasonable, therefore, to provide lines very much superior in transmission performance to the rest of the system since this would unnecessarily increase the cost for providing the service. However, telephone lines represent a fixed investment which must remain in service for many years in order to keep costs within reason and, furthermore, it is, in general, not practical to change the transmission characteristics of the lines once they have been installed. It is, therefore, necessary to take into account the fact that the broadcasting art has considerably improved in the past and is likely to improve in the future and provide telephone lines of sufficiently good characteristics to anticipate the improvements which are likely to come within a reasonable period of time.

These general considerations have led to the adoption of the following as practical standards of performance for the new cable system:

1. Frequency range to be transmitted without material distortion—about 50 to 8000 cycles.

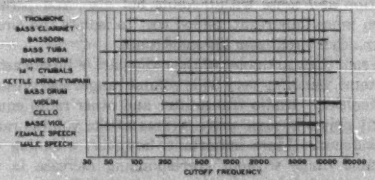



Fig. 2—Summary of Important Ranges Required for Different Instruments

——— Actual tone range
- - - - Accompanying noise range
× Cut-off frequency at which 80 per cent of the observers could detect the filter

2. Volume range to be transmitted without material interference from extraneous line noise—about 40 db. which corresponds to an energy range of 10,000 to 1.

Some of the more detailed considerations which have led to the setting of these standards will now be given.

*Frequency Band.* Fig. 2 gives some data in regard to the frequency range required for different musical instruments as well as speech. These data were obtained in the Bell Telephone Laboratories using an arrangement capable of picking up and reproducing practically the whole audible frequency range. Certain low-frequency instruments, such as organ pipes and bass drums, were not included in the tests owing to laboratory limitations. A number of observers listened to the reproduced material, first, when practically the whole frequency range was transmitted and, second, with either the high frequencies or low frequencies cut off by means of filters. The observers endeavored to note whether there was any perceptible effect when the filters were introduced but did not attempt to determine whether introducing the filters made the reproduced material sound more or less pleasing.

Referring to the figure, it will be noticed that at the lower frequencies little appears to be lost by cutting off frequencies below about 50 cycles. At the upper frequencies, however, with certain of the musical instruments something is lost by cutting off frequencies above 8000 cycles. Hissing sounds, sounds of a percussion nature, and sounds of jingling keys, rustling paper, etc., appear to be most affected by cutting off the high frequencies.

Tests have shown, however, that when the frequency range 50 to 8000 cycles is transmitted with very little distortion within the band the results obtained are very pleasing. The ordinary observer without making direct comparison tests is unlikely to detect the absence of the higher frequencies.

From the standpoint of radio transmission there will probably be some difficulties in handling the 8000-cycle range which has been tentatively set as a standard for the cable line. Each radio station, theoretically at least, is now being allowed only a 10,000-cycle band of frequencies and, since both sidebands are transmitted, each band is fully occupied when transmitting 5000 cycles. Since adjacent frequency ranges are not assigned to stations in the same locality, a certain amount of spreading out is, no doubt, tolerable, so that those listeners who are close to broadcasting stations should, in general, be able to pick up the 8000-cycle range without undue interference from other stations. The more distant listeners will have trouble if their sets take in the complete 16,000-cycle band required to handle, on a double-sideband basis, the 8000-cycle program range. Letting in this wide frequency range will bring in increased interference from other stations and will also increase the atmospheric interference.

In spite of this increased trouble which the distant listeners will have, it can no doubt be argued that it will do little harm for the radio stations to put out the full 8000-cycle band. The nearby listeners, if they have very good sets, will in general be able to appreciate this, while the distant listeners, if their sets are arranged to receive only a 5000-cycle band, should receive only slightly more interference from wide-band stations occupying adjacent frequency bands.

Evidently, if the frequency range were doubled so as to furnish the listener with practically the whole audible range of frequencies, these radio difficulties would be exaggerated. It seems certain that, if radio stations were to handle the whole audible band of frequencies, a reassignment of frequency bands to these broad-band broadcasting stations would be called for and also quite probably these radio stations would be forced to resort to single sideband transmission.

It is not sufficient merely to fix the limits of the frequency band. Limits to the allowable distortion within it must be established. Tests have indicated that it is desirable that different frequencies within the transmitted band should not suffer attenuations differ-

ing by more than about 5 db., corresponding to power differences of about three-fold.

The transmission delay[4] suffered by different portions of the frequency band must also be considered. This is necessary because, when transmission over long distance lines is involved, this delay tends to be different for different parts of the frequency band and the distortion produced is a function of the frequency-delay characteristics. Tests have indicated that the high frequencies, say those in the range 5000 to 8000 cycles, should not suffer delay in transmission over the line more than 5 to 10 milliseconds greater than the delay suffered by frequencies in the neighborhood of 1000 cycles. However, at the low end of the scale more delay may be tolerated: for example, 50 cycle waves may be delayed as much as 75 miliseconds more than those in the neighborhood of 1000 cycles without noticeable deterioration in quality.

Requirements must also be imposed as to "linearity" of the transmission, that is, constancy of efficiency with different current strengths. If the transmission departs too much from "linearity" several disagreeable effects may be produced: (1) Spurious frequencies which are by-products of the true frequencies will become large enough to be annoying, (2) strong sounds will not be reproduced as well as weak sounds, and (3) when weak sounds are transmitted along with strong sounds the strong sounds will tend to obliterate the weak sounds.

In the design of this program transmission circuit the criterion was adopted that transmission put over the circuit at the maximum prescribed volume level must not sound appreciably different than transmission put over the circuit at a considerably lower level, at which lower level the non-linear distortion is negligible.

*Volume Range.* A favorably-seated listener to a high-grade orchestra is treated to a wide range of volumes. Opinions differ as to just how wide a volume range can be appreciated by such a listener, but it seems certain that it is at least 60 db., corresponding to a power range of one million to one. The human ear can hear volume ranges in excess of 100 db. corresponding to a power range of ten billion to one. For loudspeaker reproduction it has been found that a room must be particularly quiet in order to be able to appreciate a volume range of 60 db. Rooms in three-quarters of the usual residences are probably too noisy for a volume range as great as this to be appreciated. A 40-db. volume range, corresponding to a power range of 10,000 to 1, can be appreciated in most rooms where radio listening is done and is quite satisfactory for most musical selections.

From the standpoint of design, the maximum volume of a wire program transmission system is limited by the requirement that the program must not be allowed to spill over unduly as crosstalk into neighboring circuits which may be carrying telephone messages or other programs. The volume may also be limited by the requirement that serious non-linear distortion be not introduced by effects produced in the vacuum tubes of the amplifiers or in any magnetic-core coils either in the apparatus or in the line. On the other hand, the minimum volume which a wire program circuit can handle is limited by the tendency of the noise present on the circuit to annoy the listener when the program volume is very weak. Crosstalk from other circuits into the program circuit also enters as an important consideration, since radio listeners must not be able to pick up intelligible conversations during those times when the program volume is very weak or when actual pauses occur in the programs.

From this, it is seen that the matter of widening the volume range of a wire program transmission system involves not only added cost to keep non-linear distortion and noise within limits but also, and perhaps even more important, added cost to isolate the circuit from other circuits on the same route.

From the standpoint of the radio part of broadcasting systems, handling very wide volume ranges also presents difficulties. Radio transmitter and other radio equipment noises become more serious as the volume range is widened. More important, however, widening the volume range without corresponding increase in the radio transmitter capacity reduces the effective range of a radio broadcasting station, since this increases the tendency for the faint parts of the programs to sink below the level of atmospheric and receiver-set noises.

At present it is understood that most radio broadcast programs where no long distance wire circuits are involved are being delivered with a volume range of about 30 db.[5] In order to anticipate improvements which may come in the broadcasting art, however, it has seemed desirable to provide wire circuits in cable which will handle a wider volume range than this and, accordingly, 40 db. has been taken as a working standard. This volume range appears to satisfy almost everybody with the possible exception of some who listen to broadcasts of symphony orchestras and the like. With the present limitations of volume ranges to about 30 db., there has been some complaint that much of the artistic quality and effectiveness of broadcasts of such high-grade music has been lost because of the fact that the operator manipulating the volume range control seemed to reduce the range an undue amount.

Studies are now under way looking toward systems which will compress the volume range transmitted over the line and expand it at the far terminal, but possible applications to radio systems may be difficult since receiver characteristics need to be considered.

If some volume range compression and expansion

4. "Delay" as used in this paper has the same significance as "envelope delay" used in literature on phase distortion. It is defined as $d\beta/d\omega$ where $\beta$ is the phase shift and $\omega$ is $2\pi$ times the frequency.

5. O. B. Hanson, "Volume Control in Broadcasting," *Radio Broadcast*, March, 1930.

system is not employed, ability to handle a materially wider volume range can only be obtained with considerable difficulty. In the radio part of systems it will require reductions in radio transmitter noises and involve loss in the effective range of radio stations, unless higher powered transmitters are employed. In the wire part of systems it may involve the use of amplifiers and loading coils capable of handling more power, means for materially reducing the crosstalk coupling between circuits and also means for making the program transmission circuits more quiet.

## Description of New Cable System

In this program transmission system the nominal telephone repeater spacing of 50 miles, common with message telephone circuits, is retained. The pilot-wire regulator system which compensates for changes in transmission caused by temperature changes in message circuits is also used for the program circuits.[6] The diagram in the top part of Fig. 3 shows several hundred miles of program transmission circuit, illustrating how it is divided up into repeater sections and pilot-wire regulator sections and also indicating the principal pieces of equipment located at the repeater stations.

As indicated on the diagram of Fig. 3, there are two classes of repeater stations, known as regulator stations and non-regulator stations. At the non-regulator stations the repeater gains are maintained at fixed values while at the regulator stations they are varied under control of the master pilot-wire regulating mechanism in such a way as to compensate for the transmission variations of the cable conductors caused by temperature changes.

At each non-regulating repeater station are placed:

1. An attenuation equalizer which corrects for the attenuation differences at different frequencies (at average temperature) introduced by the preceding repeater section.

2. A delay equalizer which corrects for the difference in delay at different frequencies introduced by the preceding cable section.

3. A one-way amplifier introducing sufficient gain to overcome the line loss, together with the added losses introduced by the attenuation and delay equalizers.

At the regulating repeater stations the arrangement is the same as at the non-regulating stations, except that another stage is added to the amplifiers. This stage includes a potentiometer associated with relays controlled by the master pilot-wire mechanism, the whole being arranged so as to compensate for the changes in transmission loss of the cable pairs caused by temperature changes.

In the lower part of Fig. 3 is shown a transmission level diagram, from which can be noted the losses and gains introduced by the different parts of the system, for a frequency of 1000 cycles.

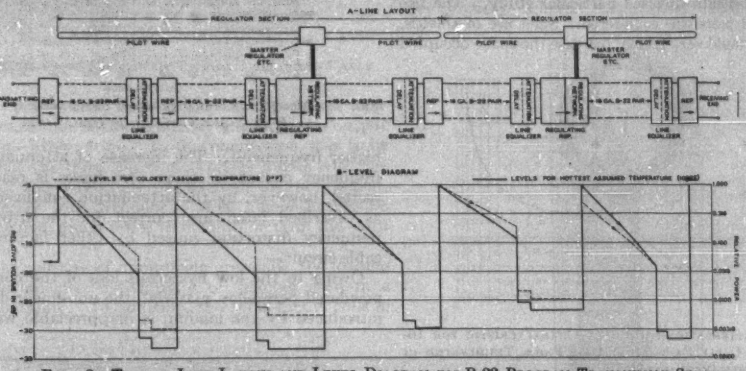



Fig. 3—Typical Line Layout and Level Diagram for B-22 Program Transmission System

*Cable.* The transmission paths are provided by means of 16 B. & S. gage non-phantomed pairs having a capacitance of 0.062 microfarad per mile. These pairs are loaded with 22-millihenry inductance coils spaced 3000 ft. apart. Present long distance message telephone circuits in cable have loading coils spaced 6000 ft. apart. The nominal cut-off frequency of the new circuit is about 11,000 cycles, permitting effective transmission of a frequency band extending up to about 8000 cycles.

The nominal impedance is about 800 ohms and the attenuation per mile, at 1000 cycles and average temperature, about 0.24 db. Fig. 4 shows the attenuation at average temperature plotted as a function of frequency, while Fig. 5 shows the line impedance.

Fig. 6 shows how the cable circuit attenuation varies with temperature at different frequencies. As will be seen from the curves, temperature change produces

6. A. B. Clark, *Telephone Transmission Over Long Cable Circuits*, A. I. E. E. Trans., Vol. XLII, 1923, p. 86.

effects not only in the series losses but also in the shunt losses. The series losses are changed largely because the resistance of the copper cable conductors changes with temperature and to a smaller degree because of changes in the effective resistance of the loading coils. The shunt losses change with temperature due largely to changes in the conductance losses and, to a lesser extent, changes in the cable capacity with temperature. The conductance loss is approximately directly proportional to frequency so that it has maximum effect at the highest frequency. The effect of temperature on the conductance loss is opposite to the effect of temperature on the series loss so that increase of temperature reduces the shunt loss.

The matter of securing the necessary electrical separation between the 16-gage program transmission circuits and the other circuits contained within the same lead sheath involved particular study. The use of shielded pairs was considered. Such use of shields, however, would very greatly increase the space occupied

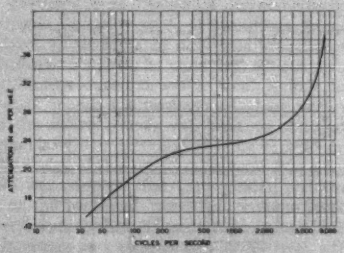



FIG. 4—ATTENUATION-FREQUENCY CHARACTERISTIC FOR 16-GAGE, B-22 CABLE PAIRS AT 55 DEG. FAHR. TERMINATED IN CHARACTERISTIC IMPEDANCE

by each program circuit and, therefore, considerably increase the cost. By careful design of the cable and control of methods of splicing, it was found possible to vaoid the use of shields. It was not found practicable, however, to make use of the phantom possibilities on the program pairs.

The method adopted was as follows: Restrict transmission over a particular 16-gage program transmission pair, as a general proposition, to one direction only. Place the program pairs assigned to transmission in one direction among the 19-gage quads used for four-wire transmission paths going in the same direction, and the program pairs transmitting in the other direction in the oppositely-bound four-wire group. Fig. 7 shows a cross-section of a typical cable containing six program transmission pairs, three for transmission in each direction.

*Loading Coils.* The 22-millihenry loading coils used on the program transmission circuit have cores of compressed powered permalloy, which is the magnetic material now generally used in the Bell System loading coils.[7] Their over-all dimensions are the same as those of the loading coils for the ordinary telephone circuits in toll cables.

Typical effective resistance-frequency curves for the loading coils are given in Fig. 8; these curves include current magnitudes greater than those involved in program transmission service. The core eddy current losses, varying with the square of the frequency, are principally responsible for the resistance increase at the

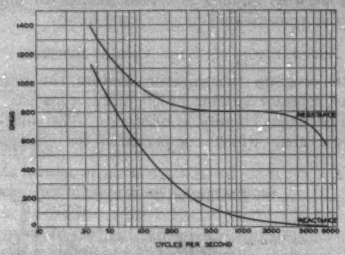



FIG. 5—MID-COIL CHARACTERISTIC IMPEDANCE FOR 16-GAGE, B-22 CABLE PAIRS AT 55 DEG. FAHR.

higher frequencies. The increase of attenuation with frequency caused by these core losses is readily corrected, however, by the attenuation equalizers which, as described later, also correct for the attenuation-frequency distortion caused by other factors in the cable circuit.

Owing to the low hysteresis loss of the compressed powdered permalloy material, the non-linear distortion introduced by the loading is inappreciable within the

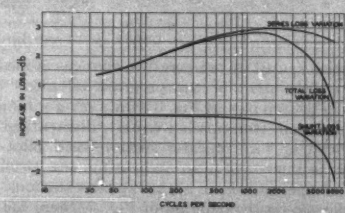



FIG. 6—ATTENUATION VARIATION OF 100 MILES OF 16-GAGE, B-22 LOADED CABLE CIRCUIT FOR A TEMPERATURE CHANGE FROM 55 DEG. FAHR. TO 100 DEG. FAHR.

range of volumes handled by this program system. For example, in a 1000-mile circuit for the condition where the power output from each repeater is one milliwatt (corresponding roughly to the average power when the program volume is maximum), the non-linear distortion that occurs in the loading causes an increase in the over-all transmission loss of the circuit of only

7. W. J. Shackelton and I. G. Barber, *Compressed Powdered Permalloy—Manufacture and Magnetic Properties*, A. I. E. E. TRANS., Vol. 47, April 1928, p. 429.

one db. at 8000 cycles, as compared to the loss for negligibly small power. At 1000 cycles, the loss increment for the same comparison is 0.13 db. The harmonic production in the coils is another measure of their excellence with respect to non-linear distortion. For a 400-cycle line current of 1 milliampere, the ratio of the third harmonic e. m. f. generated in an individual loading coil to the fundamental e. m. f. is equivalent to a loss of 80 db. The current magnitude above assumed corresponds approximately to the maximum repeater output (single-frequency basis) of 1 milliwatt; the

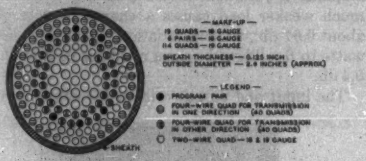



Fig. 7—Cross Section of Typical Full Sized Cable

average current that flows in the loading coils is very much smaller due to the smaller average repeater output and to line attenuation. In this connection, it is to be noted that the third harmonic voltage varies with the square of the magnitude of the fundamental current, and directly with frequency. The higher harmonics are, of course, much lower in magnitude than the third harmonic.

For the purpose of minimizing crosstalk, the loading coils are shielded individually by placing each in a metal container. In addition, the leads to the coils in

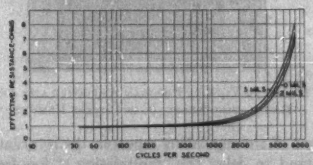



Fig. 8—Effective Resistance of 22 Millihenry Loading Coils Used on Program Transmission Circuits in Toll Cables

the stub cable and within the coil case are cabled in individually shielded quads, the "IN" and "OUT" leads of a loading coil being in the same shielded quad. As a result of these precautions, the crosstalk between the loading coils is practically negligible. Even at the highest frequencies involved in program transmission, the crosstalk is only of the order of two crosstalk units, corresponding to an attenuation of about 114 db.

The shielded program circuit coils required on a given cable are potted separately from the loading coils used on the telephone message circuits. These cases are of welded steel construction. A photograph of a 6-coil case for underground use is shown in Fig. 9. The underground type of case has a special protective coating supplemented by a wrapping of heavy paper.

*Amplifiers.* Fig. 10 is a schematic of the amplifier circuit as used at non-regulating repeater stations. (At regulating stations an automatic transmission adjustment stage is added, which will be described later.) Front and rear views of the amplifier, which is designed for relay-rack mounting in accordance with present-day telephone practise, are shown in Figs. 11 and 12. The lower panel is the amplifier, the upper the transmission adjustment stage, which will be treated later.

In the regular amplifier a standard Western Electric 102-F tube is used in the first stage and a 101-F tube in the second. The amplifier uses resistance coupling and the various coils which affect the transmission performance have very high inductance so as to give the device very uniform transmission performance at

Fig. 9—Six-Coil Underground Loading Case for Cable Program Circuits

different frequencies. The use of permalloy for the cores of these coils makes it possible to obtain the necessary high inductance without going to unreasonable coil dimensions. The gain is controlled by 5 db. and 10 db. artificial lines in the input circuit with a slide-wire potentiometer for the fine adjustments. Resistances in the grid circuit of the second tube allow an adjustment of the gain at high frequencies. Increasing the resistance causes a decrease in gain at these frequencies. The grid potential of the tubes is obtained from voltage drop in the filament circuit. The condenser in the grid circuit with its associated resistance serves to keep noise which may be present in the filament circuit from entering the grid circuit.

The ideal amplifier should give a constant gain for all frequencies over the band to be transmitted regardless of variations in magnitude of current. No extraneous frequencies should appear in the output and all the

frequencies in the band should be transmitted from input to output with equal velocity. With an average spacing of 50 mi. for the repeaters, 40 of these are required on a circuit 2000 mi. long so that obtaining proper performance allows only very small departures of the individual repeaters from the ideal characteristics.

With respect to equality of gain at different frequen-

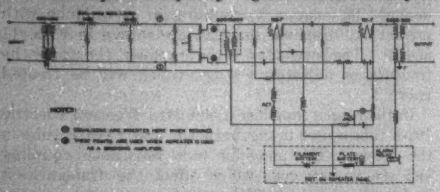


Fig. 10—Schematic of Non-Regulating Repeater for Cable Program System

cies, if the top and bottom frequencies of the band transmitted over a 2000-mi. circuit are not to drop more than, say, 2 db., below frequencies in the middle of the band, each amplifier is permitted to be only 0.05 db. down at the edges of the band. (This corresponds to a power difference of one per cent.) By the use of resistance coupling and high mutual inductance

Fig. 11—Front View of Program Amplifier and Associated Regulating Stage. (Can Covers Removed)

transformers throughout, the amplifiers developed for this system have been given the characteristics shown in Fig. 13. It will be observed that between 100 and 10,000 cycles the gain differences are less than 0.05 db. while at 35 cycles the gain is only 0.2 db. below the gain at 1000 cycles.

With respect to departure of the amplifier from linearity, the effects produced are largely caused by the vacuum tubes. Very little of such distortion is introduced by the amplifier coils. Measurements on one of these amplifiers have shown that with a single frequency output of one milliwatt, which is about the average power corresponding to the maximum program volume, the second harmonics are about 50 db. weaker than the fundamental, *i. e.*, differ in power from the fundamental in the ratio 1 to 100,000. Other harmonics are lower in magnitude.

Non-linearity in the amplifier also manifests itself by change in gain with current strength. In this amplifier a variation in load from one milliwatt to a much weaker load causes a change in gain of only about 0.01 db., while a variation in load from 60 milliwatts to 6 milliwatts causes a change in gain of about 0.4 db.

The input and output coils in the amplifier and, in

Fig. 12—Rear View of Program Amplifier and Associated Regulating Stage. (Can Covers Removed)

the case of the regulating repeater, the retardation coil also, tend to delay the transmission of low-frequency currents more than those of high frequency; an action which is due to the inductance of these coils shunting the circuit. As this reactance becomes less at the lower frequencies, the delay becomes greater. It can be reduced by increasing the values of shunting inductances. It is largely to reduce this effect that permalloy core coils of extremely high inductance are used, as noted above. The condensers appearing in series also cause delay at low frequencies and must be given capacity sufficiently great to keep the delay within proper limits. Inductance in series or capacity in shunt will also result in delay at the high-frequency end. However, in the frequency range covered by these amplifiers there is no difficulty in keeping this delay small enough to be negligible.

The delay characteristic of one of these amplifiers is

shown in Fig. 14. With 40 amplifiers in tandem, the over-all delay at 35 cycles is 75 milliseconds greater than at 1000 cycles, while there is no appreciable difference between the delay at 1000 cycles and the delay at higher frequencies.

*Attenuation Equalizers.* As will be observed from Fig. 4, the transmission loss of the cable circuit varies considerably with frequency. Since the amplifier has a flat gain characteristic, an attenuation equalizer is called for to correct the distortion introduced by the

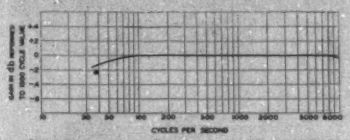



Fig. 13—Gain-Frequency Characteristic of Non-Regulating Repeater without Line Equalizer

cable. A diagram of one of these equalizers is shown in Fig. 15. In Fig. 16 is shown the loss introduced by a 50-mi. section of cable at average temperature, the loss introduced by one of these attenuation equalizers and the total loss of line and equalizer with the offsetting gain introduced by the amplifier.

*Automatic Device to Overcome Effects of Varying Temperature Transmission Adjusting.* As the temperature of the cable changes, its attenuation changes, the amount of the change being different at different frequencies. Referring back to Fig. 6, it is seen that on

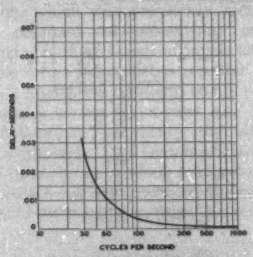



Fig. 14—Delay-Frequency Characteristic of Non-Regulating Repeater

a cable circuit 1000 miles long a temperature change from 55 deg. fahr. to 109 deg. fahr. causes changes in the transmission as follows:

At 100 cycles 18 db. change, power change of 63.

At 1000 cycles 28 db. change, power change of 625.

At 8000 cycles 3 db. change, power change of 2.

When it is appreciated that in an aerial cable a temperature change of 54 deg. fahr. may take place in only a day or two, the importance of compensating for this effect may be appreciated.

In order to compensate for this effect of varying temperature, a regulating stage is added to the amplifiers at the various regulator stations. Fig. 17 shows how the regulating network stage is added to one of the amplifiers and also shows the general nature of the regulating network circuit. Because of the peculiar and complicated way the transmission loss of the cable circuit varies with temperature, a somewhat complicated regulating network is called for. Front and rear views of one of these regulating networks are shown in Figs. 11 and 12, the upper panel being the regulating

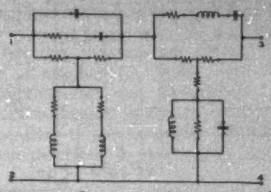


Fig. 15—Schematic Circuit of Attenuation Equalizer

network and the lower the normal amplifier. Fig. 18 shows how the gain characteristic of the amplifier is altered by different steps of the regulating network. This is very closely complementary to the change in cable loss caused by the temperature variations and thus it will be evident that the effects of the temperature changes are largely eliminated.

*Delay Equalizers.* The velocity of transmission through a loaded cable decreases as the frequency is increased toward the cutoff point of the loading. To

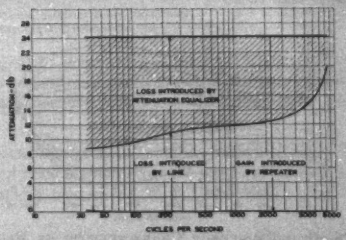



Fig. 16—Attenuation-Frequency Characteristic of Line Equalizer and 50 Miles of 16-Gage, B-22 Cable Circuits

neutralize this effect, delay-equalizing networks are inserted in the circuit which retard the lower frequencies, thus equalizing the velocity of transmission through the combination of cable and networks for all frequencies in the band to be transmitted. Fig. 19 shows the delay characteristic of a section of cable 50 mi. in length, with and without the delay-equalizing networks. The delay is seen to be maintained within $\pm$ 0.05 millisecond of a constant value. A schematic circuit of these networks is shown in Fig. 20. With the greatest length of cable circuits which will be used in this country

for program transmission, this amount of deviation per section is not sufficient to cause objectionable distortion. For a 50-mi. section uncorrected, the delay at 8000 cycles would be 0.9 millisecond greater than at 1000. A description of these delay-equalizing networks with the theory of their performance is being presented in another paper so that a more detailed description is omitted in this paper.

*Office Wiring.* Owing to the wide frequency range

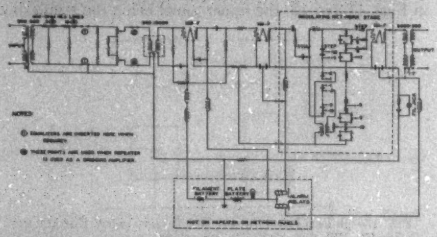


FIG. 17—SCHEMATIC OF REGULATING REPEATER FOR CABLE PROGRAM SYSTEM

transmitted over the circuit, special care must be taken with the office wiring. This is to avoid excessive variations in the losses introduced by this wiring due to changing humidity conditions. A new type of insulated cable is used in which the textile material of the insulating wires has been very thoroughly washed to remove all traces of foreign substances, so that the absorption of moisture with its accompanying increase in loss is greatly reduced.[8] The office cabling is also shortened

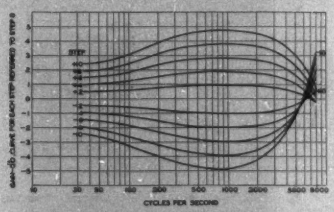



FIG. 18—GAIN-FREQUENCY CHARACTERISTIC OF REGULATING REPEATER WITHOUT LINE EQUALIZER

as much as possible, the outside cable connecting directly to the repeaters without passing through the usual test board. At points in the circuit sensitive to noise interference or crosstalk where the energy level of the transmitted signals is very low, the circuit units are connected by means of shielded pairs. This shield is connected to filament ground, as are also the cases of the various transformers which are insulated from the supporting metallic frame. The unavoidable noise potential existing between the frame and the filament circuit cannot then produce any appreciable disturbance in the circuit.

*Over-all Performance of System.* A measurement of the transmission loss of the 2200-mi. test length of B-22-N cable circuit gave results as indicated in Fig. 21. It will be observed that over the range from 35

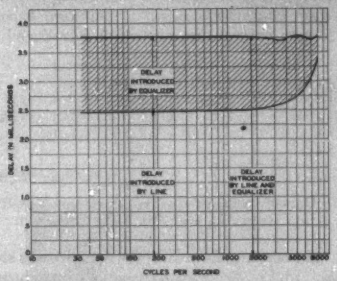



FIG. 19—DELAY-FREQUENCY CHARACTERISTIC OF 50 MILES 16-GAGE, B-22 CABLE WITH AND WITHOUT DELAY EQUALIZER

cycles to 8000 cycles the transmission loss was practically the same at all frequencies, departing only about ± 2 db. For comparison, another curve (*C*) is given on the same drawing showing the transmission characteristic which would have been obtained if distortionless amplification had simply been added to the line with no attenuation equalizers.

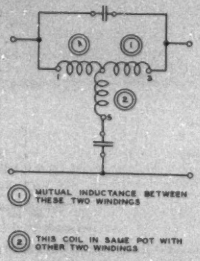



FIG. 20—SCHEMATIC CIRCUIT OF SECTION OF DELAY EQUALIZER

Note: For a 50-mile equalizer, three kinds of sections are used which vary in the resonant frequency and in the sharpness of resonance. The first three sections are of one kind, the fourth is of another, and the last seven are of the third kind

The delay-frequency characteristics of the 2200-mi. test length of B-22 circuit are shown in Fig. 22. Two curves are given, one for the circuit without delay equalizers, the other with delay equalizers.

With respect to non-linear distortion, it was found by test that when the maximum volume was held at about − 5 db. as read on a volume indicator, or about one

8. H. H. Glenn and E. B. Wood, *Purified Textile Insulation for Telephone Central Office Wiring*, A. I. E. E. TRANS., Vol. 48, April 1929, p. 576.

milliwatt of average power, the non-linear distortion became inappreciable. As a matter of fact, occasional bursts up to at least 0 db. were not badly distorted. It may be observed that the − 5 db. volume is about 10 db. less than repeaters of the same nominal capacity and loading coils of similar characteristics handle

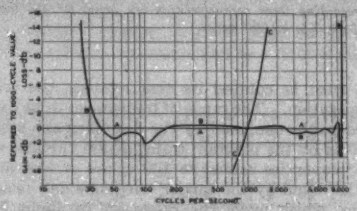



Fig. 21—Transmission-Frequency Characteristics of 2200 Mi. of 16-Gage, B-22 Cable Program Transmission Circuit

Curve A—Ideal characteristic
Curve B—Measured characteristic
Curve C—Line without equalizers

without appreciable distortion under regular message telephone circuit conditions.

The minimum volume which could be transmitted over the cable circuit, which was set by noise and crosstalk picked up by the program circuit, was found to be about − 50 db. at the repeater outputs. This means that the volume range carrying capacity of the circuit was about 45 db., just a little more than the figure 40 db. which was previously mentioned as a reasonable standard for present-day conditions of broadcasting. If short bursts of music are allowed to go up to the zero volume at the repeater outputs, the system can evidently handle about 50 db. volume range.

Using special pickup apparatus and loudspeakers capable of handling practically the whole audible frequency range, tests have been made over the 2200-mi. looped-back circuit in which comparison was made of the transmission with and without the cable included. When an 8000-cycle low-pass filter was included under both conditions it was found that listeners had considerable difficulty in consistently picking a difference. In fact, the ordinary observer could not be relied upon to pick differences consistently even when the 8000-cycle filter was not included.

## Conclusion

This development was undertaken to provide a system for obtaining satisfactory channels for the transmission of broadcast programs in the rapidly growing cable network of the Bell Telephone System. The time required to complete such a development and the need for advance planning in the cable plant made it essential that the channels be adequate to render service for a number of years. Improvements in broadcast reproduction may be expected to continue and may very well result in changes in the present frequency allocations to give space for wider bands. The cable system described in this paper was, therefore,

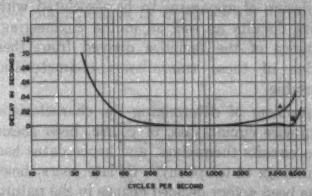



Fig. 22—Delay Characteristics of 2200 Mi. of 16-Gage, B-22 Cable Program Transmission Circuit

| | Curve | Delay at 1000 cycles |
|---|---|---|
| Circuit without delay equalizers | A | 0.106 sec. |
| Circuit with delay equalizers | B | 0.168 sec. |

developed to possess transmission characteristics superior to present-day radio systems, the margin anticipating improvements which may take place in the future.

## Acknowledgment

The authors gratefully acknowledge the assistance of many of their associates in the preparation of this paper, particularly that of Mr. H. S. Hamilton.

# The Transmission Characteristics of Open-Wire Telephone Lines

BY E. I. GREEN[1]
Associate, A. I. E. E.

*Synopsis.—Values of the primary transmission constants R, L, G, and C for open-wire telephone lines are presented, and the factors which affect these constants in practise are discussed. Consideration is then given to the constants which are of principal interest in telephone work, namely, the attenuation, the characteristic impedance, the phase constant, and the velocity of propagation. Data regarding these characteristics are given for the frequency range from 0 to 50,000 cycles.*

## Introduction

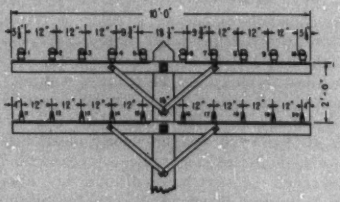
NEARLY 3,000,000 miles of open wire are now furnishing toll service in the Bell System, and this total is increasing at a rate of more than 100,000 miles a year. Hence, the subject of the transmission characteristics of open-wire circuits, in addition to being of considerable natural interest, is of no little importance in many branches of telephone work. In the design of apparatus to be associated with the open-wire circuits as well as in the engineering and maintenance of the facilities derived from them, a knowledge of these transmission characteristics is indispensable.

The problem of determining the characteristics of the open-wire circuits has, of course, been coexistent with the circuits themselves, and hence dates back to the beginnings of telephony. Of late years, however, there has been a very decided change in the nature and scope of the problem. This has resulted from many factors, particularly (a) the extensive application of carrier telephone and telegraph systems[2] and (b) the constantly increasing length of the long distance circuits. The first of these factors has extended the transmission range upward from about 3000 cycles to about 30,000 cycles, and may well extend it higher in the future. The second, in combination with the higher standards which are now applied in long distance transmission, has required greater accuracy in the data, emphasizing especially the importance of time and space variations in the characteristics. Also, recent changes in the construction of open-wire lines (to be described later) have necessitated substantial additions to the data.

There will be studied in this paper those inherent characteristics of open-wire lines which are used most frequently in telephone transmission work. These characteristics are: first, the attenuation, second, the impedance, and third, the phase characteristic, with which must be coupled its near relative, the velocity of propagation. The range of frequencies to be covered is fixed on the one hand by the d-c. telegraph systems, as well as by the program transmission circuits, whose lower frequencies extend to 100 cycles or less, and on the other hand by the carrier telephone and telegraph systems, which make the range up to about 50,000 cycles of interest.

## Line Construction Arrangements

In order to study the characteristics of open-wire lines it is necessary to know something of the constructional arrangements which are employed. The conductors most commonly used for the open-wire


10'-0"
12"
12"
12

There has recently come into vogue a different arrangement of wires which is designed to reduce the coupling between circuits and thus permit a maximum use of carrier facilities. This arrangement is portrayed in Fig. 2. In this newer configuration the separation between the wires of each non-pole pair is reduced to 8 in., and the horizontal separation between pairs is widened to 16 in.

The ordinary spacing between poles on open-wire toll lines is 132 ft., corresponding to a total of 40 poles

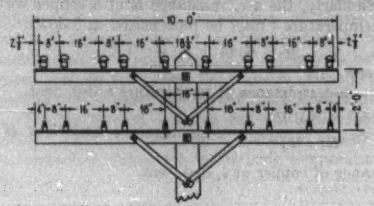


Fig. 2—Configuration of an Open-Wire Line with 8-In. Non-Pole Pairs

per mile. Where additional strength is required, the number of poles per mile may be as high as 50, while outside of the heavy sleet area it may be as low as 30.

The types of insulators employed on open-wire lines will be discussed under the heading of leakage conductance.

Two methods of transposing the wires are in current use. In the older of these, which is illustrated in Fig. 3, the wires are brought at the transposition pole to a "drop bracket." The transposition is accomplished

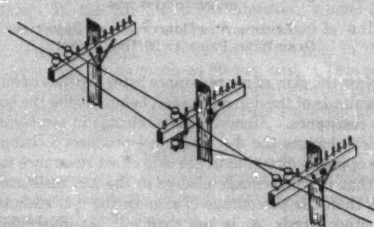


Fig. 3—Transposition of Wires with Drop Bracket

over a total distance of two spans by gradually rotating the plane of the wires through 180 deg. It will be seen that the wire configuration is abnormal throughout the two spans. In the newer method, the wires are crossed practically at a point. This may be done by means of two brackets known as "break irons," as illustrated in Fig. 4, or by means of a single bracket. The "point" transpositions preserve the nominal spacing between wires and thus avoid the irregularities in spacing which occur when drop bracket or "rolling" transpositions are used. With the point transpositions, however, two pairs of insulators are required at each transposition point as compared with a single pair of insulators at a non-transposition point. This results in an increase in the total number of insulators and in variations in the number of insulators on different pairs because of the different number of transpositions employed.

## Primary Constants

It should be noted here and now that the phenomena of line transmission are the same throughout all of the frequency range under consideration. Transmission over wires at high frequencies is accomplished in precisely the same manner as transmission at low frequencies, the wires acting as the guiding medium for the energy in both cases, and the same theory may be applied to both.

A review of the well-known theory for the propagation of alternating currents over wires will show that the line characteristics in which we are interested are dependent upon the four quantities known as the pri-

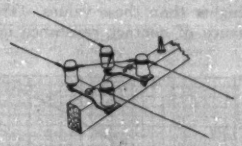


Fig. 4—"Point" Transposition on Break Irons

mary constants of the circuit. These are as follows:

$R$ = Series resistance in ohms per mile.
$L$ = Series inductance in henrys per mile.
$C$ = Shunt capacitance in farads per mile.
$G$ = Shunt leakage conductance in ohms per mile.

These quantities may be stated per mile of wire or per mile of circuit. In this paper all values will be per mile of circuit, or, as it is commonly expressed, per loop mile.

Unfortunately the constants $R$, $L$, $G$, and $C$ are by no means constant in practise. Indeed there could scarcely be a more fickle set of quantities. They are subject to change by a great variety of factors, of which the most important is, of course, the frequency. Hence it is evident that in order to determine the practical values of the attenuation, impedance, and velocity for open-wire circuits, we shall have to examine the behavior of the primary constants, $R$, $L$, $G$, and $C$.

## Resistance

First in the list of primary constants is generally named the conductor resistance. The method of computing the d-c. resistance is well known and requires no explanation here. In such computations it is assumed that the current density is uniform throughout the cross-section of the conductor. With alternating current, however, the familiar phenomenon of skin effect tends to produce a non-uniform current

distribution, and hence to increase the resistance. If the two wires of a circuit are close together, the effective a-c. resistance of each wire is likewise increased by the presence of the parallel conductor, due to what is known as proximity effect. In cable conductors, especially when used for carrier frequencies, proximity effect is very important, but it is negligible in open-wire circuits because of the large separation between wires.

The method of determining the skin effect resistance of round wires is presented in various publications, and the theoretical results have been experimentally confirmed on numerous occasions.[3] Values of the a-c. resistance of 165-, 128-, and 104-mil copper pairs at 20 deg. cent., (68 deg. fahr.) determined in accordance with skin effect theory, are plotted in Fig. 5. It will be noted that the increase in resistance due to skin effect is small in the voice range, but rather astoundingly large in the carrier range, amounting at the higher frequencies to from 200 to nearly 400 per cent.

Experimental evaluations of open-wire resistance are in extremely close agreement with the values given in Fig. 5.[4] For old wires, however, the resistance may be somewhat higher than these values. This is because of the presence of contact resistance in the twisted

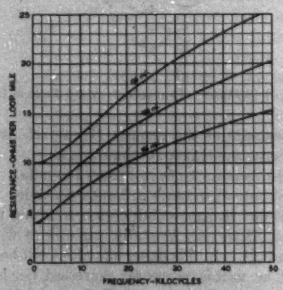



FIG. 5—A-C. RESISTANCE OF OPEN-WIRE PAIRS AT 20 DEG. CENT. (68 DEG. FAHR.)

sleeve joints in the wires and also perhaps because of an actual decrease in the conductor diameter occasioned by corrosion. The increase in the d-c. resistance of old wires due to these causes may be as much as 5 per cent. The corresponding percentage of increase in the a-c. resistance will, of course, be much smaller.

The d-c. resistance of a copper wire varies with temperature according to the familiar formula:

$$R_0 = R_{01}\,[1 + \alpha_1\,(t - t_1)] \qquad (1)$$

where $R_0$ and $R_{01}$ represent the d-c. resistance at temperatures $t$ deg. cent. and $t_1$ deg. cent. respectively, and $\alpha_1$ is the d-c. temperature coefficient of resistance of copper at $t_1$ deg. cent. At a temperature of 20 deg. cent. the value of $\alpha_1$ is generally taken as 0.00393.

Similarly, the a-c. resistance $R$ of a copper wire at a temperature $t$ may be represented as follows:

$$R = R_1\,[1 + A_1\,(t - t_1)] \qquad (2)$$

where

$R_1$ = a-c. resistance at temperature $t_1$ deg. cent.

$A_1 = \dfrac{1}{R_1}\dfrac{dR}{dt}$ = a-c. temperature coefficient of resistance of copper at $t_1$ deg. cent.

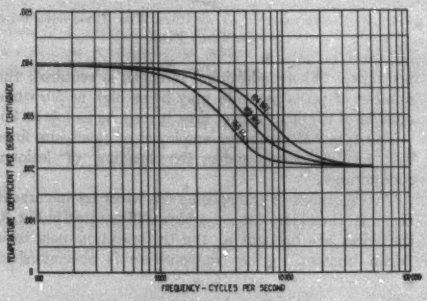



FIG. 6—A-C. TEMPERATURE COEFFICIENT OF RESISTANCE FOR OPEN-WIRE PAIRS AT 20 DEG. CENT.

Now the skin effect resistance ratio depends upon the magnitude of the d-c. resistance, being smaller the larger the resistance. Hence, a given change in temperature which changes the d-c. resistance produces a change in the opposite direction in the skin effect resistance ratio, so that the percentage change in the a-c. resistance is less than the percentage change in the d-c. resistance. In other words, $A_1$ is less than $\alpha_1$. As illustrated in Fig. 6, the a-c. temperature coefficient of resistance for open-wire pairs, starting at the d-c. value $\alpha_1$, straightway decreases as the frequency is increased, and at high frequencies approaches a value of $\dfrac{\alpha_1}{2}$. An explanation for this asymptotic value is presented in Appendix I.

The temperature assumed by the conductors of open-wire lines depends of course, upon the weather conditions which prevail in different sections of the country. In order to obtain information on this sub-

3. "Wave Propagation Over Parallel Wires—The Proximity Effect," J. R. Carson, *Phil. Mag.*, Vol. 41, April 1921, pp. 607-633; *Experimental Researches on Skin Effect in Conductors*, A. E. Kennelly, F. A. Laws, and P. H. Pierce, A. I. E. E. TRANS., Vol. 34, Part 2, 1915, pp. 1953-2021, and "Skin Effect Resistance Measurements of Conductors at Radio Frequencies," A. E. Kennelly and H. A. Affel, *I. R. E. Proc.*, Vol. 4, No. 6, Dec. 1916, pp. 523-574.

4. The value of $R$, and also that of the other primary constants, may be determined directly from open and short-circuit impedance measurements on a line short enough to avoid propagation effects. A longer line may be used instead, in which case it is necessary to correct for such effects.

ject, a study has been made of the Weather Bureau records for a number of representative cities in various parts of the country. The chief interest naturally centers in the extreme temperatures reached by the wires. It appears that on the average the air temperature will not drop below about − 20 deg. cent. (− 4 deg. fahr.) on more than about 10 days per year in the colder sections of the country, while a limiting temperature of about 35 deg. cent. (95 deg. fahr.) will not be exceeded on more than about 10 days per year in the warmer sections of the country. Because of imperfect radiation, the temperature of a wire in the sun will ordinarily exceed the temperature of the surrounding air by a small amount. A few tests have indicated that for open wires the increase over the air temperature on a warm day is not more than 5 deg. cent. Temperatures of − 20 deg. cent. (− 4 deg. fahr.) and 40 deg. cent. (104 deg. fahr.), therefore, appear to be representative values for the limiting temperatures assumed by open-wire lines. Reference to Equation (1) shows that this range of temperature gives possible variations in the d-c. resistance of 16 per cent below and 8 per cent above the value for 20 deg. cent.

The total annual change in resistance at any one place will, of course, be less than the sum of the above changes. In the Middle West, however, where the weather variations are much greater than in other parts of the country, the total annual change in d-c. resistance may be as much as 20 per cent. This section of the country has also the greatest diurnal range of temperature, giving a d-c. resistance variation of as much as 8 per cent.

## Inductance

The inductance of a circuit formed of two parallel wires whose distance between centers is negligible compared with their length is

$$L = 0.64374 \left[ 2.3026 \log_{10} \frac{2D}{d} + \mu \delta \right] \times 10^{-3} \text{ henrys per loop mile} \qquad (3)$$

where the diameter of each wire $d$, and the distance between their centers $D$, are expressed in the same units, where $\mu$ is the permeability, and $\delta$ is a factor depending on the frequency.

The tendency of alternating currents to concentrate on the surface of a wire evidently reduces the magnetic flux within the wire and decreases the internal inductance of the wire. In Equation (3) the internal inductance is represented by the factor $\mu \delta$. At low frequencies, for which the current is uniformly distributed across the cross-section of the wire, the value of $\delta$ is 0.25. For very high frequencies there is practically no magnetic flux within the wire, and the value of $\delta$ is zero. Between these frequency limits the value of $\delta$ is determined with the aid of skin effect formulas or tables.[5] For the wire diameters and spacings employed on open-wire lines the change in the total inductance due to skin effect is relatively small.

It is assumed in Equation (3) that the two wires are suspended in space or at a considerable distance from the ground and from other wires. In practise, the presence of other wires probably has some effect on the inductance, but for well transposed lines this effect is negligibly small.

The inductance at different frequencies of 165-, 128-, and 104-mil copper pairs having various spacings between wires is shown in the following table.

| Frequency-cycles per second | Inductance of open-wire pairs—henrys per loop mile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 165-mil | | | 128-mil | | | 104-mil | | |
| | 8-in. | 12-in. | 18.25-in. | 8-in. | 12-in. | 18.25-in. | 8-in. | 12-in. | 18.25-in. |
| 0 | 0.00311 | 0.00337 | 0.00364 | 0.00327 | 0.00353 | 0.00380 | 0.00340 | 0.00366 | 0.00393 |
| 1,000 | 0.00311 | 0.00337 | 0.00364 | 0.00327 | 0.00353 | 0.00380 | 0.00340 | 0.00366 | 0.00393 |
| 10,000 | 0.00305 | 0.00331 | 0.00358 | 0.00323 | 0.00349 | 0.00376 | 0.00338 | 0.00364 | 0.00391 |
| 25,000 | 0.00301 | 0.00327 | 0.00354 | 0.00319 | 0.00345 | 0.00372 | 0.00334 | 0.00360 | 0.00387 |
| 50,000 | 0.00299 | 0.00325 | 0.00352 | 0.00317 | 0.00343 | 0.00370 | 0.00331 | 0.00357 | 0.00384 |
| Infinite | 0.00295 | 0.00321 | 0.00348 | 0.00311 | 0.00337 | 0.00364 | 0.00324 | 0.00350 | 0.00377 |

As will be seen from Equation (3), the inductance varies with the logarithm of the separation between wires. In the table the values of inductance are shown for pole pairs, which have a separation between wire centers of about 18.25 inches, and for non-pole pairs having wire separations of 12 and 8 inches. The values of inductance given in the table have been closely checked by measurements on open-wire pairs.

## Capacitance

The capacitance of two parallel wires in space with a distance between centers which is negligible compared with their length is

$$C = \frac{0.019415}{\log_{10} \frac{2D}{d}} \times 10^{-6} \text{ farads per loop mile} \qquad (4)$$

It will be noted that the capacitance varies in inverse relation to the separation between wires.

As in Equation (3), it is assumed in this formula that the two wires are suspended in space or at a considerable distance from the ground and from other wires. On an actual line the capacitance of a pair is changed to an appreciable extent by the presence of other wires, and to a slight extent by the capacitance to ground. The true capacitance between the two wires under actual conditions may be derived from the direct capacitances between all wires and the direct capacitances of all wires

5. See, for example, Circular No. 74 of the Bureau of Standards, "Radio Instruments and Measurements."

to ground.[6] The capacitance is not changed to any great extent by skin effect.

The means of insulation and support provided at each pole have an appreciable effect on the capacitance of a pair of wires, especially in wet weather. This is due to the fact that the insulators and, under certain conditions, the pins and parts of the crossarms, act as the dielectric of small condensers which are, in effect, shunted between the line wires. These effects are being discussed in a companion paper.[7] The percentage increase in capacitance due to the insulators varies with different weather conditions and different types of insulators, ranging from about 0.5 to 4 per cent of the capacitance between line wires.

Values of the capacitance of 165-, 128-, and 104-mil pairs in space and on a 40-wire line are given in the following table:

| | Capacitance—$\mu f$ per mile | | | | | |
|---|---|---|---|---|---|---|
| | 165-mil | | 128-mil | | 104-mil | |
| Wire spacing | In space | On 40-wire line | In space | On 40-wire line | In space | On 40-wire line |
| 8 in. | 0.00977 | 0.00996 | 0.00926 | 0.00944 | 0.00888 | 0.00905 |
| 12 in. | 0.00898 | 0.00915 | 0.00855 | 0.00871 | 0.00822 | 0.00837 |
| 18.25 in. | 0.00828 | 0.00863 | 0.00791 | 0.00825 | 0.00763 | 0.00797 |

As before, values are given for pairs having wire separations of 8, 12, and 18.25 in. These values include an allowance for the dry weather capacitance of the insulators. The difference between the values in space and on a 40-wire line indicates the importance of the effect of the other wires, the insulators, etc., upon the capacitance. The capacitance values given in the table are fairly representative of the values that will obtain on well transposed lines.

The values of inductance and capacitance which have been given are based on the assumption that the nominal separation between wires is preserved throughout the entire line. This is not the case when drop bracket transpositions are employed. As has been pointed out, the wires are brought closer together at the drop brackets, thereby increasing the capacitance and decreasing the inductance. The amount of the change in inductance and capacitance due to this cause ranges from 1 to 5 per cent for the transposition arrangements designed for carrier system operation.

## Leakage Conductance

The leakage conductance per unit length of circuit, which is represented in the transmission formulas by the symbol $G$, is by far the most erratic of the primary constants. Since it is a momentous factor in the attenuation its investigation has been very actively prosecuted over a considerable period of time.

The determination of the value of $G$ for direct current is quite simple, involving merely a measurement of the actual conductance between wires for a length of circuit short enough to avoid propagation effects. For alternating currents, however, it is customary to employ an equivalent value of $G$ which includes all of the losses suffered by the power transmitted over the pair except the normal $I^2R$ loss in the wires themselves. This inclusion of numerous little-understood losses in the general term leakage has at times served to insulate the individual losses from analysis. Methods of determining the value of the "equivalent leakage conductance" and of analyzing its component losses are available, however.[8]

The nature and magnitude of the different losses which occur at the insulators are being discussed in detail in a parallel paper.[7] Accordingly, only a brief mention will be made in this paper of the types of insulators which are now in use on the open-wire lines of the Bell System, and of the values of leakage conductance experienced with these different types.

The $DP$ or double-petticoat glass insulator illustrated in Fig. 7 is now standard for use on all important toll circuits, except those equipped with the special carrier insulators discussed below. On a number of older circuits single-petticoat glass insulators, known as toll insulators, (see Fig. 7) and double-petticoat porcelain insulators are still in place.

In view of the numerous and complex sources of leakage loss, it is not surprizing that the leakage conductance for a given pair at a particular frequency varies with changing weather conditions and with the age of the insulators over a very wide range of values. Because of this wide range of variation it is possible to give here only selected leakage values which serve for engineering purposes. Values of the total leakage conductance for open-wire pairs equipped with $DP$ insulators are plotted in Fig. 8. These values are intended to represent the highest values ordinarily obtained on an old circuit which is in a good condition of maintenance. The wet weather values have been so chosen that they should be exceeded on only a few days of the year, while the dry weather values represent the performance that should be expected from any circuit on a clear, dry day.

Particular difficulty is experienced in selecting standard values of d-c. leakage owing to the fact that the range of values encountered in practise is exceedingly great. The measured values depend to a great extent on the degree to which the line is kept free from tree branches, foliage, moss, broken insulators, and other possible sources of leakage. These special

6. See Technical Report No. 54 of the Railroad Commission of the State of California, Joint Committee on Inductive Interference, entitled "Inductive Interference Between Electric Power and Communication Circuits," 1919.

7. "A Study of Telephone Line Insulators," by L. T. Wilson. Presented at the Summer Convention of the A. I. E. E. Toronto, Ont., Canada, June 23-27, 1930.

8. *Methods of Measuring the Insulation of Telephone Lines at High Frequencies*, by E. I. Green, A. I. E. E. Trans., Vol. 46, 1927, pp. 514-519.

sources of loss, of course, represent a much smaller part of the total leakage losses at carrier frequencies.

The standard values of leakage conductance are derived for a line having 40 pairs of insulators per mile. Where the number of insulators differs greatly from this figure, it is necessary to correct the leakage values accordingly. Differences in the number of insulators per mile result from the use of different types and numbers of transpositions, different pole spans, double crossarm construction, etc.

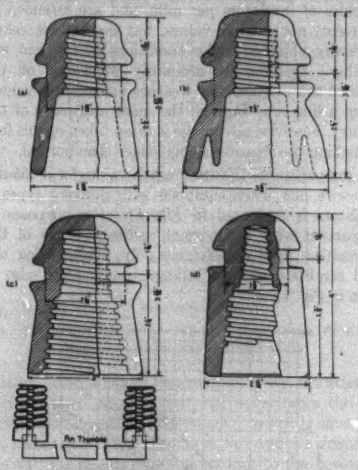



FIG. 7—TYPES OF INSULATORS EMPLOYED IN THE BELL SYSTEM

a. Toll insulator
b. *D P* insulator
c. *C W* insulator and pin thimble
d. *C S* insulator

Considerable study has been given to methods of reducing the leakage conductance, particularly at carrier frequencies, and two new types of insulators have been developed for this purpose. In these there is used an improved dielectric (borosilicate glass) which has a low power factor and a reasonably low dielectric constant, as well as good chemical stability. Two expedients for eliminating losses in the pins and crossarm are employed. In the *C W* insulators, illustrated in Fig. 7, two metal shells or thimbles are bonded together and placed over the wooden pins. In the *C S* insulator, also shown in Fig. 7, steel pins are employed and the two steel pins of the pair are bonded together. In the past few years *C S* insulators have been applied to the open-wire lines of the Bell System in increasingly large numbers.

With these two types of insulators a substantial reduction in the total leakage conductance is brought about. The best available figures for the limiting values of leakage conductance for these types are shown in Fig. 8. A further advantage obtained through the application of the new insulators is that of stabilizing the attenuation at carrier frequencies. Experience has indicated that the *C S* and *C W* insulators reduce the daily leakage (and attenuation) variations due to change in weather conditions to about one-third and one-half, respectively, of their value for *D P* insulators. This degree of stabilization is not indicated by the differences between the dry and wet weather leakage values shown in the figure, but it must be recalled that these values represent extreme conditions, while the stabilization referred to above is for average conditions.

## ATTENUATION

The attenuation constant is the real part $\alpha$ of the propagation constant $\gamma$ as given in the familiar formula

$$\gamma = \alpha + j\beta = \sqrt{(R + j L \omega)(G + j C \omega)} \qquad (5)$$

The attenuation constant is also given by the following expression

$$\alpha^2 = 1/2\left[\sqrt{(R^2 + L^2 \omega^2)(G^2 + C^2 \omega^2)} - (L C \omega^2 - R G)\right] \qquad (6)$$

Where $L^2 \omega^2$ is large compared to $R^2$ and $C^2 \omega^2$ is large compared to $G^2$, it can be shown[9] that Equation (6) reduces to

$$\alpha \doteq \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} \qquad (7)$$

This formula is very useful for computing the attenuation of open-wire circuits at carrier frequencies, in which case its accuracy is adequate for all practical purposes. It is frequently of value also for quick computations of the approximate attenuation of open-wire circuits in the voice range.

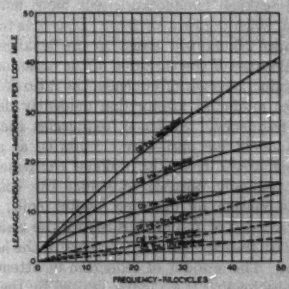



FIG. 8—LEAKAGE CONDUCTANCE OF OPEN-WIRE PAIRS EQUIPPED WITH DIFFERENT TYPES OF INSULATORS

The first term of Equation (7) represents the series losses, and is commonly referred to as the "resistance component of attenuation," while the second term represents the shunt losses, and is called the "leakage

9. See "Transmission Circuits for Telephonic Communication," by K. S. Johnson, N. Y., Van Nostrand, 1927.

component of attenuation." It will be observed that the resistance component of attenuation varies inversely with the quantity $\sqrt{\frac{L}{C}}$, while the leakage component varies directly with the same quantity. This quantity $\sqrt{\frac{L}{C}}$, as will be seen later, represents the nominal characteristic impedance of the circuit.

It is shown in Appendix II that a circuit of fixed resistance and leakage conductance will have minimum attenuation when the ratio of $L$ to $C$ is such as to make the resistance component equal to the leakage component. Because of the variation of the resistance and leakage conductance with frequency, the ratio of $L$ to $C$ which gives minimum attenuation evidently depends upon the frequency. At voice frequencies the resistance component for open-wire circuits is, as a rule, considerably larger than the leakage component, so that it is generally possible to reduce the voice-frequency attenuation by inserting loading coils, which increase the value of $L$ and thus reduce the resistance component at the expense of an increase in the leakage component. The amount of reduction in attenuation obtainable by loading is evidently limited by the value of the leakage component and by the additional resistance which is contributed by the loading coils. For open-wire circuits at carrier frequencies the value of the leakage component of attenuation is quite large in comparison with the resistance component, and coil loading would, in general, be detrimental. At the present time the use of loading on the open-wire circuits of the Bell System has been practically abandoned. Owing to the importance of other factors, especially the line crosstalk, it is ordinarily impracticable to design the open-wire circuits to secure precisely the minimum attenuation at the highest working frequency. In the carrier frequency range, however, the wet weather attenuation of the pairs most commonly used is not materially higher than the theoretical minimum.

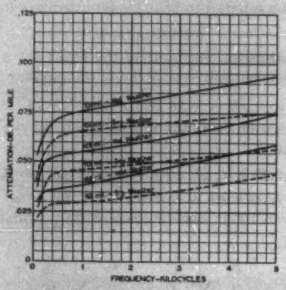



Fig. 9—Voice-Frequency Attenuation of Open-Wire Pairs Equipped with $D$ $P$ Insulators

Values of the attenuation constant of open-wire pairs of different gages when equipped with $D$ $P$ insulators are presented in Figs. 9 and 10. The values are plotted in db. per mile.[10]

The attenuation values of Figs. 9 and 10 have been determined for a temperature of 20 deg. cent. (68 deg. fahr.) and for the dry and wet weather values of leakage conductance previously presented. It will be recalled that these values of leakage are derived on the basis of 40 pairs of insulators per mile, and are intended to represent, not average values, but the highest values ordinarily obtained under conditions of dry and wet weather. Systems are ordinarily engineered on the basis of the extreme wet weather attenuation values. When a line runs through the more arid parts of the country, however, advantage is often taken of this fact by making the repeater spans longer than normal.

A comparison of the attenuation values for a 165-mil open-wire pair when equipped with different types of insulators is presented in Fig. 11. For purposes of comparison with the normal values a curve of the attenuation due to resistance only, representing the ideal condition of zero leakage conductance, also is given in Fig. 11.

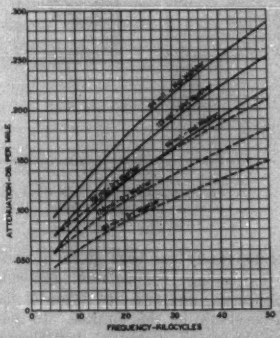



Fig. 10—Carrier Frequency Attenuation of Open-Wire Pairs Equipped with $D$. $P$. Insulators

The values of line capacitance employed in determining the attenuation values of Figs. 9, 10, and 11 include an allowance for the average capacitance increase due to the insulators. The attenuation curves shown are strictly applicable to pairs having a wire separation of 12 in., but they are approximately correct for spacings of 8 and 18.25 in.

When the number of pairs of insulators per mile

10. "Decibel—The Name for the Transmission Unit," by W. H. Martin, *Bell System Tech. Jl.*, Vol. VIII, No. 1, January 1929, pp. 1-2.

differs greatly from the standard value of 40, a correction is applied to the attenuation values. Special curves make it possible to obtain this correction conveniently. Curves are also available for correcting the standard attenuation values to take care of changes in temperature.

It should be understood that the attenuation of an open-wire pair varies from time to time over a wide range of values, and therefore it is not to be expected that the values of attenuation measured at any particular time will necessarily coincide with the theoretical

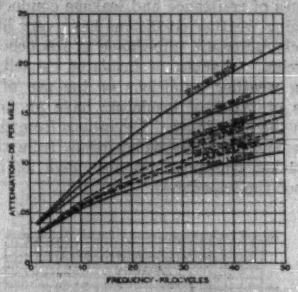



Fig. 11—Attenuation of 165-Mil Open-Wire Pair for Various Conditions of Insulation

values. It should also be understood that the attenuation measured on an actual pair never bears the perfectly smooth relation to frequency which is shown on the standard attenuation curves, but exhibits irregularities varying in magnitude according to the irregularities existing on the line. Thus the curve of attenuation as measured on a very well transposed open-wire pair,[11] which is delineated in Fig. 12, represents about as smooth an attenuation curve as it is possible to obtain on an open-wire circuit. The attenuation values shown on this curve are somewhat lower than the standard values for similar pairs. This is doubtless explained by the fact that the insulators on this particular pair were new, and the further fact that the measurements were made in winter when the temperature was low.

An illustration of the significance of the attenuation data given above may be of interest. One of the longest carrier telephone systems now in service extends from Davenport, Iowa to Sacramento, California, a total distance of about 2100 miles. The highest frequency employed in this system is approximately 28,000 cycles. Using the attenuation values for a 165-mil pair at 28,000 cycles, it appears that the dry weather attenuation for the entire length of this system might be approximately 220 db. or less, and the wet weather attenuation about 330 db. This means that without amplification along the line the ratio of the transmitted power to the received power might vary from $10^{22}$ to $10^{33}$. Since the attenuation of a repeater section is ordinarily limited to from 25 to 40 db. ten repeaters are employed to span the total distance, and in order to compensate for the attenuation variations a gain regulating mechanism known as a pilot channel must be used.

In the preceding illustration it was assumed that the range of variation in attenuation increases in direct proportion to the length of the circuit. Although this may theoretically be possible, it has been found in practise that the attenuation variations during any given period of time increase less rapidly than the circuit length. The reason for this is that augmenting the length of the circuit obviously reduces the likelihood of experiencing extreme wet weather conditions simultaneously over the entire line. A practical example of how the open-wire attenuation varies from time to time is afforded by Fig. 13, which shows the measured attenuation changes on a line 110 miles long during the period of two light rainstorms.

One further point is of interest in connection with the subject of open-wire attenuation. Inductive or conductive coupling between a pair and the other circuits on the line may result in the absorption of energy in these circuits. Fortunately, the losses due to this cause are small on well transposed lines. On inadequately transposed lines, however, this interaction with other circuits, in addition to producing small losses

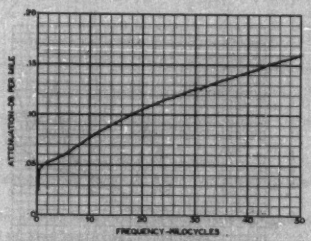



Fig. 12—Attenuation Measured on a Well-Transposed 128-Mil Open-Wire Pair with 8-In. Spacing

over a wide range of frequencies, may cause incredibly large losses over a narrow band of frequencies, producing what is known as an "absorption peak" in the attenuation curve. This interesting phenomenon is illustrated in the attenuation curves of Fig. 14, which show how two very pronounced absorption peaks on a line about 300 miles in length were smoothed out by the application of improved transpositions. The magnitude of one of these absorption peaks will be appreciated when it is realized that the received power at the peak

11. Methods of measuring the attenuation, impedance, and crosstalk are discussed in *High-Frequency Measurements of Communication Lines*, by H. A. Affel and J. T. O'Leary, A. I. E. E Trans., Vol. 46, 1927, pp. 504-513.

frequency is about one two-hundredth of that at the adjacent frequencies.

### Impedance

The characteristic impedance is defined by the well-known formula:

$$Z_0 = \sqrt{\frac{R + j L \omega}{G + j C \omega}} \text{ ohms} \tag{8}$$

It is doubtless unnecessary to explain why this impedance must be matched in the apparatus.

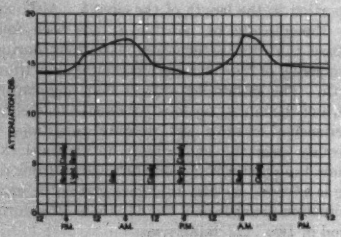



Fig. 13—Measured Variations in the Attenuation of an Open-Wire Pair

When $R$ is small compared to $L\,\omega$ and $G$ is small compared to $C\,\omega$, the value of $Z_0$ evidently becomes

$$Z_0 \doteq \sqrt{\frac{L}{C}} \tag{9}$$

This is known as the nominal characteristic impedance.

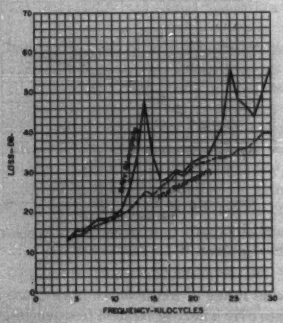



Fig. 14—Absorption Peaks on an Open-Wire Pair

It will be noted that this impedance is a pure resistance. In the carrier range the actual impedance of an open-wire pair is substantially equal to the nominal characteristic impedance.

Values of the characteristic impedance in dry weather of open-wire pairs with 12-inch wire spacing are presented in Fig. 15. These values have been derived from the standard values of inductance, capacity, and leakage conductance and from resistance values at 20 deg. cent. The basis for the impedance value of 600 ohms resistance, which has become almost a tradition in so many phases of telephone work, will be obvious from Fig. 15. The impedance curves for pairs with 8-in. and 18.25-in. spacing are similar to those of Fig. 15, the resistance values for these spacings being about 45 ohms lower, and 40 ohms higher, respectively, than the values shown for 12-in. spacing.

Changes of resistance and leakage conductance due to changing weather conditions have very little effect on the characteristic impedance at frequencies above 1000 cycles. Changes of insulator capacity due to changing weather conditions or the use of different numbers or types of insulators have an appreciable effect on the impedance. Deviations from the normal spacings between wires which result from the use of drop bracket transpositions also have an important effect upon the impedance.

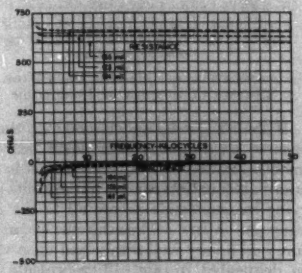



Fig. 15—Carrier-Frequency Impedance of 12-In. Open-Wire Pairs

Like the measured attenuation, the impedance which is measured for an open-wire pair is affected by the presence of line irregularities. Hence, the measured impedance is never a smooth function of frequency, but displays slight irregularities throughout the entire range. This is apparent from Fig. 16, which gives a curve of the impedance measured on a well transposed pair. This curve is in remarkably close accord with the generalized values of impedance, the maximum deviation from the theoretical curve being about 2 per cent.

Like the attenuation, the impedance of an open-wire circuit in a narrow band of frequencies may be radically changed by interaction with adjacent circuits. These large irregularities in the impedance commonly accompany absorption peaks in the attenuation, and are, of course, due to the inadequacy of the line transpositions.

### Phase Change and Velocity of Propagation

The imaginary component $\beta$ of the propagation constant is known as the phase constant because it indicates the change in the phase of the voltage and current in circular radians per unit length of line.

The value of the phase constant is given by

$$\beta^2 = 1/2\left[\sqrt{(R^2+L^2\omega^2)(G^2+C^2\omega^2)}+(L\,C\,\omega^2-R\,G)\right] \quad (10)$$

If $R^2$ and $G^2$ are small compared to $L^2\omega^2$ and $C^2\omega^2$ it is clear that

$$\beta \doteq \omega\sqrt{L\,C} \text{ radians per mile} \quad (11)$$

For an open-wire pair the value of $\beta$ is approximately 0.035 radian per mile, or 2 deg. per kilocycle per mile. The latter figure is a convenient one to remember.

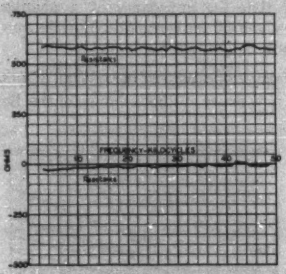



Fig. 16—Impedance Measured on a Well-Transposed 128-Mil Open-Wire Pair with 8-In. Spacing

The constant $\beta$ also enters into the familiar expression for the velocity of propagation

$$V = \frac{\omega}{\beta} \text{ miles per second} \quad (12)$$

The velocity of propagation on open-wire lines approaches the velocity of light, which is 186,000 miles per second. The velocity is reduced below this value by the increase of capacity due to the presence of the other wires and the insulators, by the internal inductance, and by the presence of resistance and leakage conductance. Values of the velocity of transmission for open-wire pairs are presented in Fig. 17. At frequencies above a few hundred cycles the velocity of transmission is, apart from the effect of line irregularities, practically constant throughout the frequency range.

In the last few years increasing attention has been focused upon the phase characteristic of the open-wire circuit. One of the reasons for this is that different velocities of transmission for different frequency components in a signaling band (which are obtained when the phase shift of the circuit is not a linear function of the frequency) may give rise to what is known as phase distortion, and it may be necessary to correct this distortion by suitable networks.[12,13]

### Characteristics of Phantom Circuits

Phantom circuits, which are derived from two pairs or side circuits by transmitting over the wires of one pair in parallel and using the wires of the other pair in parallel as a return, have been employed in the telephone plant for voice-frequency transmission for a number of years. Their use for carrier transmission is limited chiefly by the difficulty of reducing the cross induction with other circuits at high frequencies.

Phantom circuits are generally derived either from horizontally adjacent non-pole pairs or from vertically adjacent pole pairs. Thus wires 1 and 2 are "phantomed" with wires 3 and 4, wires 5 and 6 with wires 15 and 16, etc. In some of the newer transposition arrangements the non-pole pairs are not phantomed, since it has been found that the omission of the phantom permits the operation of a larger number of carrier systems on one line without excessive mutual interference.

The resistance of a phantom circuit is evidently half of the corresponding value for the side circuit.

If the two wires forming one of the sides of the phantom circuit are designated 1 and 2, and the wires

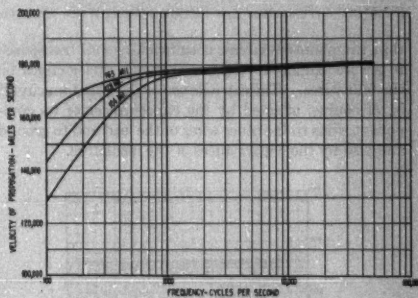



Fig. 17—Velocity of Propagation for Open-Wire Pairs

forming the other side are designated 3 and 4, the inductance of the phantom circuit is

$$L = 0.32187\left[1.1513\log_{10}\frac{4\,D_{13}\,D_{14}\,D_{23}\,D_{24}}{D_{12}\,D_{34}\,d^2}+\mu\,\delta\right]$$

$$\times\,10^{-9} \text{ henrys per loop mile} \quad (13)$$

where $D_{13}$, $D_{23}$, etc. represent the spacing between the

12. "Distortion Correction in Electrical Circuits with Constant Resistance Recurrent Networks," by O. J. Zobel, *Bell System Tech. Jl.*, Vol. VII, No. 3, July 1928, pp. 438-534.

13. *Wire Transmission System for Television* by D. K. Gannett and E. I. Green, A. I. E. E. Trans., Vol. 46, 1927 pp. 946-953; (*Bell System Tech. Jl.*,) Vol. VI, No. 4, October, 1927, pp. 616-632.)

wires 1 and 3, 2 and 3, etc., and where $d$, $\mu$, and $\delta$ have the same significance as in Equation (3).

The capacitance of a phantom circuit in space is

$$C = \frac{0.07766 \times 10^{-6}}{\log_{10} \dfrac{4\, D_{13}\, D_{14}\, D_{23}\, D_{24}}{D_{12}\, D_{34}\, d^2}} \text{ farads per loop mile} \quad (14)$$

Equations (13) and (14) are based on the assumption

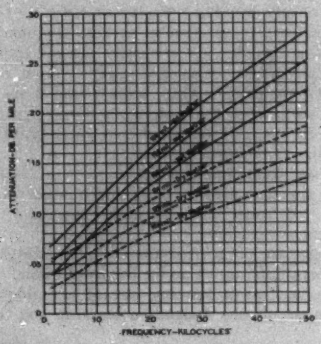



Fig. 18—Attenuation of Phantom Open-Wire Circuits

that the phantom circuit is sufficiently well transposed to secure balanced voltages, currents, and charges on the four wires. The capacitance of the phantom circuit is, of course, affected by the capacitances of its component wires to the other wires of the lead and to ground and also by the capacitances of the insulators.

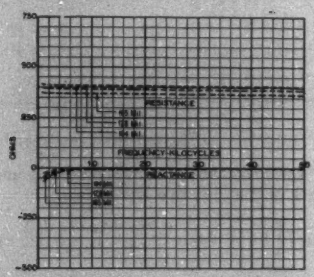



Fig. 19—Impedance of Phantom Open-Wire Circuits

The losses which contribute to the leakage conductance of phantom circuits are similar to those which have been discussed for side circuits. The ratio of the phantom circuit leakage conductance to that of the side circuit will depend upon the relative magnitudes of these different losses. Varying relations between the different types of losses give a ratio of phantom circuit leakage conductance to side circuit leakage conductance which might conceivably range between the extremes of 1 and 6. For practical engineering purposes, however, the leakage conductance of the phantom circuit is generally assumed to be twice that of the side circuit.

Curves of the attenuation of non-pole pair 12-in. phantom circuits of different gages are depicted in Fig. 18. In most cases the attenuation of the phantom circuit is somewhat less than that of the corresponding side circuit. Frequently, however, the advantage of lower attenuation is under practical conditions more than offset by the large noise and crosstalk effects experienced on the phantom circuits.

Values of the dry weather impedance of 12-in. phantom circuits are presented in Fig. 19. It will be observed that the impedance of a phantom circuit averages about 60 per cent of the impedance of a 12-in. side circuit.

## Characteristics of Iron-Wire Circuits

There now exists on the toll lines of the Bell System

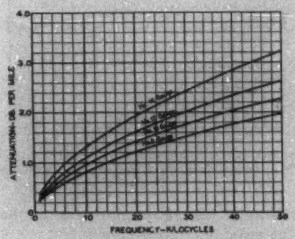



Fig. 20—Attenuation of Iron Wire Circuits

a small amount of galvanized iron or steel wire. Nos. 12 and 14 B. W. G., with diameters of 109 and 83 mils, respectively, are the gages most commonly found. Steel wire and BB iron wire are both used, the latter being of more frequent occurrence. These iron-wire pairs display such large values of modulation and high-frequency attenuation that they are generally quite unsuitable for carrier transmission.

The skin effect resistance of iron wire may be computed by standard theory, provided that the values of the resistivity $\rho$ and permeability $\mu$ are known. The values of $\rho$ for BB iron and steel wire are about 12.8 and 14.8 microhm-centimeters respectively. It will be noted that these values are about seven and eight times the resistivity of copper. For currents of telephonic magnitude at frequencies from about 500 to 50,000 cycles, it has been found that the value of the permeability $\mu$ of iron wire of the above sizes ranges from about 110 to 50. Study of the available data indicates that the best average value of $\mu$ at 1000 cycles is about 85 and that the effective value decreases with

increasing frequency. Because of the high d-c. resistance and the large skin effect ratio which results from the high permeability, the resistance of iron wire for alternating currents is extremely great.

Except at low frequencies, where the internal inductance of the iron wire is large, the total inductance of an iron-wire circuit is not far different from that of the corresponding copper circuit. The capacitance and leakage conductance of iron-wire circuits are substantially the same as for similar pairs of copper wire.

Typical attenuation curves for several gages of BB iron wire in dry weather are shown in Fig. 20. These curves are based upon experimental results. It will be noted that the attenuation of an iron-wire circuit averages about ten times that of the corresponding copper-wire circuit. It should be understood that the attenuation values for an iron-wire circuit are subject to rather wide variations in practise, particularly because of the effects of corrosion. There is some change in the attenuation of an iron-wire circuit with change in weather conditions, but this is a relatively small percentage. The impedance of an iron-wire circuit has same order of magnitude as the impedance of a similar copper-wire circuit.

## Appendix I

### Temperature Coefficient of Resistance at High Frequencies

In the skin effect literature cited in the text, it is shown that at high frequencies the a-c. resistance $R$ is

$$R = 0.00979 \sqrt{f R_0} \tag{15}$$

where $R_0$ is given by Equation (6) and $f$ is the frequency. Differentiating with respect to $t$, and substituting, we find that

$$A_1 = \frac{1}{R_1} \frac{dR}{dt} = \frac{1}{2} \alpha_1 \sqrt{\frac{R_{01}}{R_0}} \tag{16}$$

and for ordinary ranges of temperature

$$A_1 = \frac{\alpha_1}{2} \tag{17}$$

## Appendix II

### Condition for Minimum Attenuation

The attenuation at high frequencies is given by Equation (7). Differentiating this with respect to $\sqrt{\frac{C}{L}}$, and setting the result equal to zero, it is found that the condition for minimum attenuation is

$$\frac{L}{C} = \frac{R}{G} \tag{18}$$

which is another way of saying that

$$\frac{R}{2} \sqrt{\frac{C}{L}} = \frac{G}{2} \sqrt{\frac{L}{C}} \tag{19}$$

so that the resistance and leakage components must be equal in order to have minimum total attenuation.

# A Study of Telephone Line Insulators

BY L. T. WILSON*
Non-member

*Synopsis.—This paper discusses the major factors contributing to the (total) leakage conductance of telephone line insulators, especially at carrier frequencies up to 50,000 cycles. The influence of both the design and material of the insulators and pins on each factor is discussed and illustrated by test data.*

*The electrical performance of three different designs is analyzed to illustrate, in a general way, the relative importance of the several factors.*

## Introduction

To the layman, the long strings of large power insulators suspended from tall steel towers naturally present a more imposing picture than do the small telephone insulators mounted on the crossarms of relatively short wooden poles.

To the engineer, however, these little insulators present problems quite as stimulating and interesting in the telephone field as do the large insulators in the power field.

It is the purpose of this paper first to discuss briefly how some of these interesting problems arose and then to cover in more detail a study of the major phenomena involved in insulator leakage and finally to show how the knowledge gained from that study has helped bring about improved telephone insulators, some of which will be described.

## Origin of Problem

For many years the requirements of telephone insulators were relatively easy to meet because the frequency of the currents transmitted did not exceed about 3 kc. and because the leakage of insulators is generally low at such frequencies.

Therefore, the familiar glass insulators such as are shown in Figs. 1 and 2 sufficed, the former design (D. P. type) being employed on the longer circuits and the latter (toll type) or the shorter ones. Indeed they still suffice very generally, especially where only currents of voice frequencies or less are transmitted.

The advent of carrier systems employing higher frequencies ranging from about 3 to 30 kc. changed the insulator requirements substantially. At first these systems were few in number and relatively short in length and the insulator problem accordingly less important.

The rapid growth of carrier systems during the past decade,[1] the longer circuits to which they have been applied, and improved standards of long-distance transmission have all been factors in increasing the requirements imposed upon the insulator and in correspondingly augmenting the importance of the problem.

It may now be remarked that the problem has been mainly one of securing economical insulators giving improved performance at these higher frequencies. In addition the low frequency performance of new designs had to be maintained substantially as good as that of the old designs.

## Leakage Phenomena

This study has been confined almost entirely to the pin type of insulator.

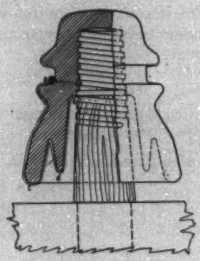


Fig. 1—Standard D. P. Insulator and Standard Wood Pin

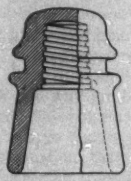


Fig. 2—Standard Toll Insulator

When an alternating potential exists between a pair of wires at the point where those wires are supported by insulators, a current flows from the one wire to the other. This current may be resolved into two components, one in phase with the potential and one in phase quadrature leading the potential.

This in-phase component which, of course, represents an energy loss is the one of chief interest here and in using the word leakage we refer to this component, or more accurately to its equivalent conductance.

*Department of Development and Research, Am. Tel. & Tel. Co., New York, N. Y.

1. See *Carrier Systems on Long Distance Telephone Lines*, H. A. Affel, C. S. Demarest, and C. W. Green, A. I. E. E. Trans., Vol. 47, 1928, p. 1360-1386.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

Of course, both components in flowing through the resistance of the line conductors produce energy losses but these are so small as to be omitted here. Except these, all other energy losses which occur due to the presence of insulators whether they actually occur in the insulators proper or elsewhere will be charged to insulator leakage.

It is convenient to divide insulator leakage into several sources. This division is an arbitrary one, because some of the sources are not independent of each other and are, as will be seen later, difficult to separate experimentally.

The division follows:

| | | |
|---|---|---|
| A-c. and d-c. | A. | Leakage directly through insulator material to pin. |
| | B. | Leakage directly over insulator surfaces from line conductor to pin. |
| A-c. only. | C. | Dielectric absorption in insulator material. |
| | D. | Dielectric absorption in pins. |
| | E. | Displacement current losses in crossarms and pins. |
| | F. | Losses due to unbalanced displacement currents in external resistances such as those of crossarms, poles, etc. |
| | G. | Displacement currents flowing over insulator surfaces through high resistance. |

It should be noted that while all the items play a part in a-c. leakage only the first two enter in the d-c. case.

These items[2] will now be discussed individually and will be treated generally as they exist under wet rather than dry weather conditions. In this connection most of the experimental evidence that will appear was obtained from tests on insulator test lines located near Phoenixville, Pa. The measuring equipment employed there has already been described in another paper[3] and for lack of space will not be further discussed here although certain improvements have been made since that paper was prepared.

## Item A—Direct Leakage To Pin

This item refers to that leakage through the insulator material which is directly due to the conductivity of the material, for example via path *a b*, Fig. 1. Item *A* has been listed chiefly for completeness because it is fairly well known that for most materials commonly employed, this source of leakage is very small. In the present study it has been found to be negligible in magnitude.

Item *B*, therefore, becomes the controlling source of leakage for direct current and accordingly deserves consideration. However, it will be given even more consideration because its magnitude, being so closely dependent on the shape, size, location, and condition of the insulator surfaces throws light on those factors which will later be shown to play a very large part in leakage for alternating currents.

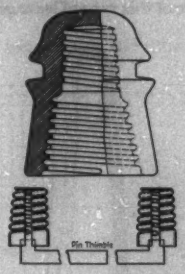



Fig. 3—Standard C. W. Insulator and Pin Thimble

## Item B—Direct Surface Leakage

*1. General Characteristics.* Item B refers to that leakage over the insulator surfaces which is directly due to the conductivity of those surfaces, for example, via path *a c d e*, Fig. 1.

The outstanding characteristic of this type of leakage is the enormous changes in magnitude it exhibits under changing weather conditions.

For example, Fig. 4 shows the results of measurements made on a telephone line in Texas equipped with insulators of the type shown in Fig. 3. This test, made in clear weather, shows the large change in leakage produced simply by the condensation of moisture on the insulator surfaces. The peak value may be seen to be about 2500 times the smallest value measured.[4] Had

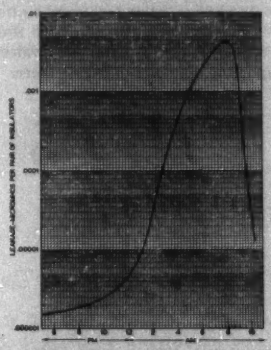


Fig. 4—Illustrates Large Variation of D-C. Surface Leakage in Dry Weather

2. The existence of several of these factors appears to have been well appreciated by Mr. R. D. Mershon as early as 1908, although Mr. Mershon's measurements were made at frequencies below 100 cycles where many of the items are extremely small in magnitude. See *High Voltage Measurements at Niagara*, by R. D. Mershon and Discussion, A. I. E. E. Trans., Vol. 27, 1908, pp. 845-929.

3. See *Methods of Measuring the Insulation of Telephone Lines at High Frequencies*, E. I. Green, A. I. E. E. Trans., Vol. 46, 1927, p. 514-519.

4. Such tests indicate the negligible effect of Item A.

it rained along the entire length of line the peak might readily have been 10 times greater and the corresponding ratio would have been 25,000. These ratios are higher than would be commonly found because the line was quite new but they serve to indicate the wide range in the magnitude of this type of leakage.

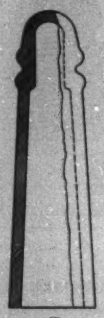


Fig. 5—Experimental Design with Long Skirt

Fortunately, direct surface leakage even at its higher values in a sufficiently small part of the total leakage, especially at carrier frequencies, to make its wide variations substantially less serious than the foregoing ratios have indicated.

2. *Influence of Insulator Design.* To make this leakage conductance small it will be apparent from elementary considerations alone that the length of the path should be as great and its cross-section as small as possible. The latter depends on both the thickness and width of the moisture film, the width, in turn, depending upon the diameter of the surfaces.

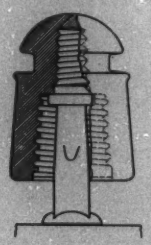


Fig. 6—Experimental Design with Short Corrugated Skirt (C. P.) Mounted on Standard Steel Pin

The length of path may be increased by simply lengthening the insulator. The cross-section of the film may be made small by decreasing the diameter of the surfaces. Both methods are employed in the experimental design shown in Fig. 5 which will be recognized as extreme, at least with respect to mechanical strength. This design under test gives excellent performance for direct surface leakage, having under various weather conditions from one to 25 per cent as much leakage as the more reasonable design shown in Fig. 6.

Another, but somewhat less effective way of increasing the length of path is the use of one or more petticoats. This method has a mechanical advantage in keeping the over-all insulator length small but the effectiveness of the longer path is partly lost due to the necessary increase in diameter. An example of this method is the design shown in Fig. 1 which gives about half as much leakage as that of Fig. 2.

Still another way of increasing the length of path is the use of corrugations (Fig. 6, for example). The data at hand while not conclusive, indicate that corrugations are of questionable value.

The third dimension of the conducting path, namely its thickness, can be controlled to some extent by insulator design. The thickness of the water film is determined by the rate of rainfall and by a balance between the forces tending to make the film adhere to the surfaces and the force of gravity tending to pull the water away.

To reduce the amount of water intercepted by the insulator for a given rate of rainfall, it is again advantageous to make the insulator diameter as small as possible.

To facilitate the running off of the water intercepted, the surfaces in the conducting path should be nearly vertical and smooth. These remarks apply mainly to the outside surfaces.

As to the inside surfaces the situation is somewhat different. These are protected from direct rainfall and become wet by splashing, condensation, creepage, and by moisture carried by air currents.

To prevent splashing from the crossarm it might appear desirable to provide the insulator with a wide flaring kind of shed but experience has shown that such sheds may be quite ineffective or even detrimental. It will be convenient to discuss the action of one type of shed later.

It has been found preferable to employ an insulator of small diameter. The effects of the splashing can be reduced by placing the insulator higher from the crossarm and by restricting the area of the opening between the pin and the insulator where the rising drops of water must enter.

These drops may readily rise a foot or more as casual observations show. To raise an insulator completely out of range obviously would lead to a cumbersome and mechanically unsatisfactory construction. However, some advantage may be had in elevating the insulator.

For example, consider Fig. 7 which shows the insulator of Fig. 6 mounted on a long pin. This pin, which was designed for another purpose, has an enlarged section which restricts the area between the pin and the insulator. The improved performance is, therefore,

the result of two effects: one, that of elevating the insulator; the other, that of restricting the area between the pin and the insulator.

An attempt was made to separate these effects by providing a third set-up in which the insulator is mounted on the pin of Fig. 6, this short pin being supplied with a rubber washer of the proper size and location to simulate the enlarged section of the long pin.

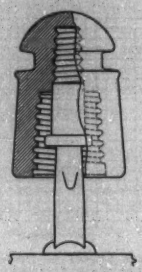


Fig. 7—C. P. Design on Long Steel Pin with Baffle

The relative performance of these three arrangements is given in Fig. 8 where $S$ stands for short pin; $S\,B$, short pin with baffle; and $L\,B$ long pin with baffle. These results were obtained during a hard shower within a month after the installation of the rubber washers and give some idea of the effectiveness of the two expedients.

In discussing the influence of insulator design on this type of leakage the question naturally arises as to the part played by the pin on which the insulator is mounted.

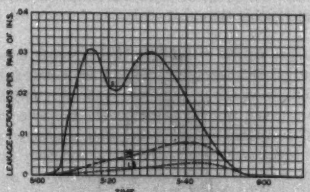



Fig. 8—Illustrates Effect of Pin Length and Baffle on D-C. Surface Leakage

Wood pins of the type commonly employed on telephone lines are found to contribute somewhat to the total insulation, depending on the dryness of the wood and on the efficiency of the insulator itself.

The effect of the pin may be measured by comparing insulators mounted on wood pins in the standard manner with similar ones mounted on wood pins which have been covered with a thin metal foil, the coatings of a pair of pins being electrically joined. Thus, both the pins and the crossarm between them are short circuited.

Fig. 9 shows the results of such a test on the type of insulator shown in Fig. 1. At the start of the rain and during the first few hours the wood appears to reduce the leakage considerably but as the rain continues and the pin takes up moisture its effect seems to decrease to nil.

While similar tests on this and other types of insula-

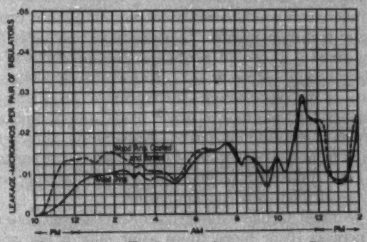



Fig. 9—Illustrates Effect of Coating and Bonding of Wood Pins on D-C. Surface Leakage

tors give corresponding results, still other tests indicate that at times, the wood continues to help out for many hours. One such test covering a period of about 23 hours showed, for this same type of insulator (Fig. 1), that the wood pin reduced the leakage by 30 per cent on the average.

On the other hand, similar tests for the design of insulator shown in Fig. 10, very frequently show the pin to have negligible effect.

While the foregoing tests have shown an advantage in favor of the wood pin, that conclusion holds only for the conditions of the test; namely, both wood and metal

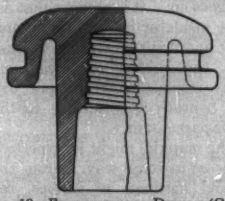


Fig. 10—Experimental Design (C. D.)

pins having the same diameter. When an insulator is specifically designed for a metal pin both the pin and insulator diameters can usually be made small because of the greater mechanical strength of the metal pin. The advantages of the design of small diameter, as previously discussed, may readily offset the slight disadvantage of the metal pin and the net result may be an actual gain.

*3. Influence of Insulator Material.* While the insulators are new, the molecular attraction between the

insulator material and water plays a very important part; so important, in fact, that tests on such new insulators frequently give an unreliable basis on which to make decisions. On new glass insulators and particularly on those of borosilicate compositions, the rain water does not seem to wet the surfaces but rather stands in individual separate drops. The phenomenon is so marked that the surfaces have the appearance of having been oiled or waxed.

Under such conditions the conducting path is broken up and is discontinuous. Naturally its conductivity is very small. It would be fine if this property of the material could be preserved. Unfortunately along with exposure to weathering there comes an increasing tendency for the drops of water to spread out and unite to form a continuous path. Apparently, this action results from the collection of impurities on the surfaces, for such molecular phenomena are well known to be very sensitive to any contamination.

The direct surface leakage has been observed generally to increase 10 or more times after only a few weeks exposure. In one particular case where it rained the same day that the new insulators were installed, their surface leakage was observed to be less than one per cent of that measured on insulators of the same shape and material which had been aged for about two years.

This study of insulators has shown that while changes in design may affect changes in direct surface leakage by a factor of, say, 10, changes in kind of material affect this leakage by a factor of two or less after long exposure. In general, then, the material may be said to be less important than the design. Purely general considerations indicate this conclusion in view of the surface nature of the phenomenon. Consider an insulator of a given design exposed to the elements for several years. More and more foreign matter will collect on the surfaces as time goes on. It is obvious that as this process continues, the insulator material is becoming less and less important and it is conceivable, at least, that given time enough, this surface of foreign matter would determine the insulator performance irrespective of the material beneath this surface coating. At this point, design is paramount.

However, the material might be expected to influence the aging process in some way. From this viewpoint smoothness and hardness of surface, together with chemical stability, appear to be desirable qualities.

This study has been confined chiefly to various kinds of glass. In general, these have all had smooth surfaces, but they have varied in hardness and chemical stability. For example, borosilicate glasses are said to be generally harder and chemically more stable than the common alkali group.

The relative performance of one sample from each of these respective groups is given in Fig. 11. Both were molded to the design of Fig. 12. This particular test which was made after more than a year of exposure shows only a small difference between the two glasses. A previous test (exposure of nine months) showed quite the same results while still earlier tests had indicated the borosilicate as quite superior to the alkali glass.

While the foregoing tests illustrate the point made above as to the relative importance of design *vs.* material they cannot be considered as conclusive evidence on the relative merits of these two glasses for direct surface leakage.

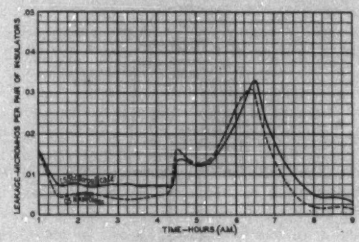



Fig. 11—Illustrates Effect of Insulator Material on D-C. Surface Leakage

Probably more important than either hardness or chemical stability, which directly affect surface leakage, is the transparency of the material which affects leakage only indirectly, through the medium of insects apparently small spiders. These spiders build nests on the inner surfaces and seem to prefer dark or dimly lighted spaces for their homes. Therefore, the more transparent the insulator, the less attractive home it makes; and of opaque materials, probably white ones are accordingly less attractive than dark colored ones.

Other factors which enter into the spiders' choice appear to be those of space and of protection from the elements. These latter factors are functions of insulator design rather than material.

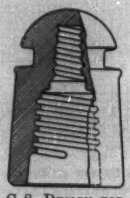


Fig. 12—Standard C. S. Design for Use With Standard Steel Pin

There has been little opportunity to study these factors on the insulator test lines, due to the lack of spiders. Only one specific case has been found where their effect was marked. This was a case where small borosilicate insulators were given an opaque metal coating. After this coating had been on several months the direct surface leakage increased to several times the value for the similar uncoated ones. An investigation

showed spider nests under many of the coated insulators.

On the other hand, several types of larger insulators have showed no such effect when coated, although some of these have been exposed for several years. These results are not conclusive. They merely indicate that design, as well as transparency of material, is a factor.

An experience of the telephone plant in the use of opaque insulator material (porcelain) showed a serious reduction of efficiency after a few years of exposure, apparently explained by the action of inserts.

*4. Specific Conductivity of Film.* The specific conductivity of the rain itself before it reaches the insulators is determined by the nature and amount of impurities collected in its fall. Both the kind and amount of impurities must vary greatly in different localities, for example, industrial centers as compared with open country. Then again, the amount in any given locality must vary throughout any storm on account of the cleansing action of the rain on the atmosphere.

On reaching the insulators the rain will suffer a further increase in conductivity depending on the

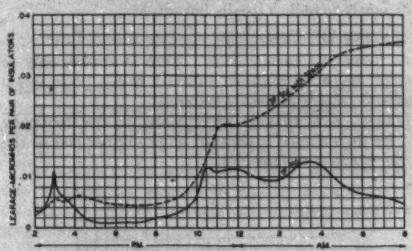



FIG. 13—ILLUSTRATES EFFECT OF SHEDS ON D-C. SURFACE LEAKAGE

impurities it finds there. Smooth vertical surfaces should be advantageous in reducing the collection of dust.

After a prolonged dry period in which the surfaces have become dust coated, the conductivity may be quite high at the start of rain. As the rain continues a certain amount of cleansing action occurs on the exposed surfaces and also to some extent on the unexposed surfaces, depending on the splashing. A decrease in leakage corresponding to this cleansing action has occasionally been observed.

Thus, in a locality where rain is infrequent but where dew, for example, might wet the insulators, the leakage might conceivably be quite high.

This phenomenon can be produced artificially and emphasized by placing roofs over the insulators, thus preventing any direct cleansing action of the rain.

Roofs of sheet metal six inches in height, five inches in width and twelve inches in length were placed over insulators of the design in Fig. 1. The ends were left open to permit passage of line wire.

While still new and clean these protected insulators showed less leakage than the unprotected ones of the same design. However, after a few months the protected insulators became covered with a thick layer of dust blown under the roofs by wind. Then when it rained, enough moisture reached the surfaces to wet the dust, but not enough to have much cleansing action. The surface leakage then becomes very high, as will be apparent from Fig. 13.

## ITEM C—DIELECTRIC ABSORPTION IN INSULATOR MATERIAL

*1. General Characteristics.* When a dielectric is subjected to a varying potential field a certain amount of the electrical energy is dissipated in the material in the form of heat, depending on the nature of both the material and the field. This phenomenon is commonly called dielectric absorption.

Such a field exists between the line and tie wires on one side and the pin on the other. The insulator material lies more or less in this field and, therefore, dielectric absorption is naturally to be expected. While it is convenient to refer to a single insulator it should be remembered that two insulators are in series between wires at any one point.

The chief characteristic of the leakage resulting from this phenomenon is its variation with frequency. Approximately, it increases directly with the frequency. In the voice range its magnitude is generally negligible, but may become appreciable in the carrier range, particularly at the upper end.

Item *C*, like item *B*, increases in wet weather, but to a far less degree. This increase, which is brought about by the enlargement of the field caused by the wetting of the insulator surfaces, cannot be directly separated from the increases in the several other sources. Indirectly, however, a general idea of the magnitude of item *C* in wet weather can be obtained in the following two ways.

Both methods are based on the observation that the increase in capacitance between the wire and pin produced by metal-coating the outside of the insulator is invariably greater than the corresponding increase caused by wetting the uncoated insulator. For example, the increase due to coating the insulator of Fig. 3 exceeded the maximum increase observed for any rain by at least 40 per cent. More commonly this figure would be 100 per cent both for this and other shapes.

Therefore, if such metal-coated insulators (mounted on bonded metal pins for reasons appearing in the discussion of items *D* and *E*) be measured in dry weather the leakage conductance so found is likely to exceed by a substantial amount the wet-weather value of item *C*.

Another procedure consists in calculating the leakage of the metal-coated insulator. This method requires a knowledge of the wire-to-pin capacitance and the phase angle of the insulator material.

Fig. 14 shows the measured value for the insulator of Fig. 1 when molded from a clear flint glass. The phase angle of this particular glass is not known. However, the wire-to-pin capacitance is known. Using this known value, the leakage has been calculated for two measured values of phase angle for flint glasses, between which the value of this particular glass probably lies.

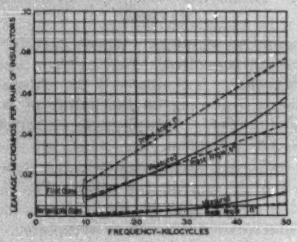



Fig. 14—Variation of (C) With Frequency for Standard D. P. Design

Similarly, the measured and calculated leakage are shown for this same design of insulator when molded from a borosilicate glass of known phase angle.

Neither method is capable of high accuracy, but they need not be for our present purpose of determining the order of magnitude of item *C*.

Consider item *C* at 50 kc. where its relative importance is greatest. At this frequency the metal-coated flint-glass insulator gave a measured leakage which is only about 10 per cent of the total wet-weather leakage of such an insulator as commonly used uncoated. So it appears that even at this high frequency, item *C* is less than 10 per cent of the total leakage of this particular design and material. This particular sample of flint-glass is not the best of the common alkali glasses nor is it the worst; so this round number of 10 per cent is a fair average value to use for alkali glasses.

The corresponding value for the borosilicate glass of which the sample was representative is about 4 per cent.

*2. Influence of Design.* The absolute magnitude of item *C* is influenced somewhat by design because of the effect of shape on capacitance. An idea of the magnitude of this effect can be obtained by comparing Fig. 14 with Fig. 15. Both designs were cast from the same batch of glass so that material plays a small part in comparing the two designs.

In general, for a given size of pin, the capacitance is decreased by enlarging the insulator diameter, particularly at the wire groove. Similarly, for a given outside diameter, the capacitance is decreased by making the pin diameter less. In general, too, the shorter the insulator, the less the capacitance.

Through the ordinary range of shapes the absolute magnitude of item *C* will not vary more than about three to one, and expressed as a percentage of the total wet-weather leakage, it is doubtful if item *C*, in the worst combination of poor design and poor material studied, could reach as high as 20 per cent.

The foregoing remarks apply to insulators on metal pins. When wood pins are used, the capacitance is less and *C* is correspondingly less. If the pin is dry, *C* is extremely small, if the pin is wet, *C* is still considerably less than it is for the same insulator on a metal pin.

*3. Influence of Material.* The range of the absolute value of *C* for various kinds of glass is much greater than it is for various designs. Phase angle of the material is frequently used as a criterion but Hoch[5] has shown that for insulator purposes, the product of phase angle and dielectric constant is a better criterion. Using the latter, a range of more than 20 to 1 is found for the glasses studied.

From the standpoint of item *C* alone, on account of its small relative magnitude there is little justification in going to high grade glasses, especially as these are more costly, unless other sources are first reduced sufficiently to make *C* really important.

## Item D—Dielectric Absorption in Pins

*1. General Characteristics.* Item D applies only to pins of dielectric material (usually wood) or to metal pins with cobs of dielectric material.

Like *C*, *D* is roughly proportional to the frequency and its importance is greatest at the upper end of the carrier range of frequencies.

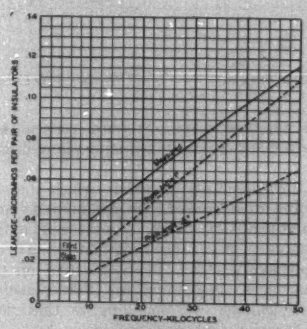



Fig. 15—Variation of (C) with Frequency for Standard Toll Design

Again, like *C*, *D* increases in wet weather due to the accompanying increase in wire-to-pin capacitance. It also increases because of absorption of moisture by the pin.

Fortunately, due to the small value of *C*, particularly when dielectric pins are used, a rough measure of *D* can

5. See "Power Losses in Insulating Materials," E. T. Hoch, *Bell System Technical Journal*, Vol. 1, No. 2, November 1922, pp. 110-116.

be obtained by again making use of metal-coated insulators.

Fig. 16 shows two measurements of the leakage in dry weather of metal-coated insulators on wood pins. These insulators are similar in shape to that of Fig. 1, and were molded of a borosilicate glass.

Due to the low capacitance when wood pins are used and to the high quality of glass, item $C$ can be neglected here.

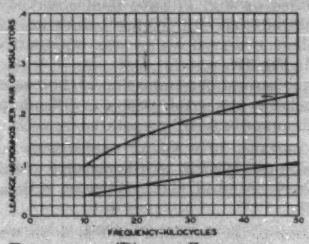



Fig. 16—Variation of (D) with Frequency for Standard D. P. Design

Item $E$, which is to be discussed in the next section, enters here to some extent, but the cross-section of the crossarm is so much greater than that of the pins that this item, while it cannot be neglected, is probably small.

The measured leakage then closely represents that due to dielectric absorption in the pins under the conditions of the test, namely, metal-coated borosilicate insulators.

To the extent that metal coating gives greater capacitance than does wetting the insulator the value of $D$ is magnified by these measurements. On the other hand, to the extent that the capacitance is reduced by the high quality of glass, the measurements give too low a value of $D$ for alkali glasses.

As these effects approximately balance each other, the measured values are fairly representative of $D$ for the alkali group.

The difference in the two values measured at different times is mainly due to the moisture content of the pins, the higher value corresponding to the higher moisture content.

Consider the insulator of Fig. 1 made of alkali glass and mounted on wood pins. Item $C$ will be small, very small when the pin is dry; and while appreciably larger when the pin is wet, it is still considerably smaller than its value for a metal pin of the same dimensions. $D$, on the other hand, is large, even when the pin is dry; so in this example, $D$ may be said to be considerably more important a factor than $C$.

In the case of this same design molded from a borosilicate glass, $D$ becomes relatively even more important a factor.

*2. Influence of Design.* The general remarks which applied to $C$ as to insulator diameter and length and as to pin diameter apply to $D$.

*3. Influence of Insulator Material.* For a given design, the lower the dielectric constant of the insulator material, the lower $D$ will be.

*4. Influence of Pin Material.* Some study of this subject has been made, but the results are not sufficiently conclusive to report.

## Item E—Displacement Current Losses in Crossarms

*1. General Characteristics.* This item will first be considered as it applies to insulators on metal pins. The path of the displacement current is as follows: the current passes from one line wire through the capacitance of the one insulator to its pin, thence through the crossarm to the other pin and finally through the capacitance of the other insulator to the other wire. The capacitances of the two insulators are thus in series. The adjective "displacement" has been applied to the current because its magnitude is mainly determined by the insulator capacitance.

The losses produced in the crossarm by this current obviously depend on the electrical equivalent of the crossarm and on the insulator capacitance. If the former were a pure resistance with a magnitude small compared with the reactance of the series capacitances, then $E$ would increase approximately as the square of the frequency. Experimentally, $E$ is generally found to increase at a rate lying between the first and second power of the frequency over the range studied.

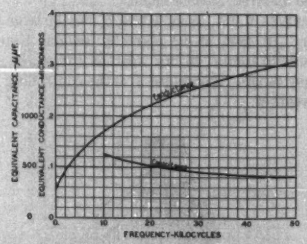



Fig. 17—Variation of Equivalent Parallel Capacitance and Conductance with Frequency for 25 Crossarms in Parallel Dry Weather Measurement

A knowledge of the electrical equivalent of the crossarm, together with the insulator capacitance, permits $E$ to be calculated.

The constants of the crossarm between steel pins six inches apart, as measured on a dry day, are given in Fig. 17. From this measurement, the magnitude of $E$ has been calculated for individual insulator capacitances of 4 and 20 m. m. f., and the results are shown in Fig. 18. The capacitances of most of the insulators studied lie within these two limits.

Fig. 18 also shows the value of $E$ as measured for the insulators of Fig. 19. This measured value of $E$ was obtained as follows: The leakage of the insulators was measured first with the crossarms short-circuited by tying a wire from each pin to the other. Then the wires were removed and the measurement repeated.

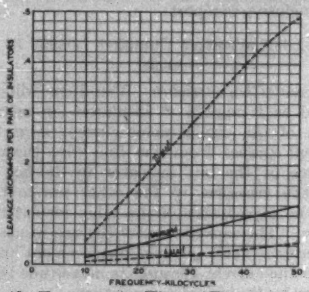



Fig. 18—Variation of (E) with Frequency in Dry Weather

The difference between these measurements is $E$, if other sources are assumed to have remained unchanged. This assumption appears justified from the following test of its validity. The measurement of $E$, together with the measured constants of the crossarm, enables the insulator capacitance to be calculated. Such a calculation has been carried out and the value of capacitance so obtained checks very closely the value obtained by direct measurement.

The curves of Fig. 18 show that $E$ may be large in dry weather. In fact, it is generally several times the magnitude of item $C$ in dry weather and at the upper frequency range. Therefore, $E$ is the controlling factor in dry weather.

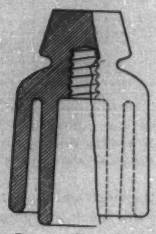


Fig. 19—British Post Office Design

As to the effect of weather conditions on $E$, the increase in insulator capacitance brought by wet weather tends to greatly increase the losses. On the other hand, the large decrease in the crossarm impedance resulting from rain tends to decrease the losses. As a net result of these opposing effects, $E$ is generally less in wet than in dry weather. In fact, after several hours of rain, $E$ has been found to be almost negligible.

The upper curve in Fig. 20 shows $E$ for the insulator of Fig. 1 foil-coated and mounted on steel pins with composition cobs. This curve was obtained in dry weather. The lower curve of Fig. 20 shows the magnitude of $E$ for the same insulators after 1½ hours of rain.

The equivalent conductance of the crossarms varies over a wide range depending on the weather. For instance, values of d-c. conductance 40 times as great as that recorded on Fig. 17 have been observed and the data indicated that still higher values are probable. The smallest observed value was one-tenth of that recorded in Fig. 17.

The experimental determination of the magnitude of $E$ for insulators on wood pins is a difficult problem, because $E$ cannot be readily separated from $D$.

The importance of insulator capacitance on $E$ has already been established, so a knowledge of this factor for insulators on wood pins enables an estimate of $E$ to be made.

For example, the insulator of Fig. 1 on wood pins gives a measured capacitance in dry weather of about

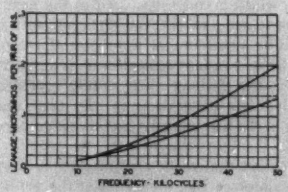



Fig. 20—Measured Leakage Due to (E)

4 m. m. f. $E$ for this value is given by the bottom curve of Fig. 18. In this particular example, $E$ is quite small in dry weather. The general decrease in $E$ accompanying wet weather indicates that this item does not contribute much of the leakage of insulators on wood pins, at least after the crossarm is very wet.

*2. Influence of Insulator Design.* The wire-to-pin capacitance varies perhaps three to one for the designs covered in this study. The corresponding range in $E$ is obviously great. Therefore, insulator design has an important influence on the magnitude of $E$.

*3. Influence of Insulator Material.* The materials studied have not shown a range in dielectric constant of more than about two to one. The corresponding range of wire-to-pin capacitance is even less; so insulator material may be said to have a relatively small influence on $E$.

*4. Influence of Pin Spacing.* Item $E$ is naturally expected to be influenced by the pin spacing. However, the data bearing on this effect are too meager to report.

### Item F—Losses Due to Unbalanced Displacement Currents Flowing in External Impedances such as Crossarms, Poles, Etc.

*1. General Characteristics.* In general characteristics, $F$ is very similar to $E$. As $E$ is caused by a displacement current which flows directly from one line wire to the other via the crossarm in the manner already discussed, so $F$ is similarly caused by unbalanced displacement currents flowing through crossarms, poles, etc. There is not sufficient space in this paper either to present details of the theory of these losses or to describe the many interesting tests made to illustrate the effect.

In brief, $F$ is due, first, to any difference that may exist between the capacitance of the insulator on one wire and that on the other wire, and second, to other unbalances in capacitance such, for example, as those caused by the presence of other wires.

The first of these causes will be recognized to be very similar in nature to a second order effect of $E$ and is accordingly small in magnitude, at least if the same kind of insulator is employed on each wire; so $F$, due to this particular cause, is normally small.

The second source is the more important one. $F$, resulting from it, is greatest in dry weather, like $E$. Here, $F$'s importance is so great that transpositions in the insulator test line were found necessary, despite the line being only 200 ft. in length. The dry-weather leakage of many of the insulators under test is so small that, without transpositions, errors caused by the presence of other wires have amounted to several hundred per cent.

The variation of $F$ with frequency is much the same as $E$.

Also, like $E$, $F$ is less in wet than in dry weather.

The general remarks made in the discussion of Item $E$ regarding the influence of insulator design and material apply also to $F$.

For the well transposed lines used for carrier circuits and for the reasonably well balanced insulator capacitances that the standard construction gives, $F$ contributes little to the total wet-weather leakage.

### Item G—Displacement Currents Flowing Over Insulator Surfaces through High Resistance

*1. General Characteristics.* Over the carrier range of frequencies this item is the most important source of leakage in wet weather. It probably contributes more than all other sources combined. On this account, it may not be amiss to repeat here an already known theory which fits the results of the present study fairly well.

Consider an insulator, the outside of which is wet. Divide this surface into elements of area and take, for example, one of them near the bottom of the insulator. Assume a small displacement current to flow from the pin to this element through the small capacitance which exists between them. Now for this current to reach the wire, it must flow through the thin film of moisture lying between the element chosen and the wire. This film offers a high resistance to the current, not high enough, however, to seriously limit the current, but, nevertheless, sufficient to produce heat losses. These losses when integrated over the entire insulator surface become important and qualitatively, at least, account for the characteristics of item $G$.

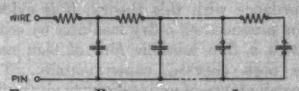



Fig. 21—Electrical Equivalent of an Insulator for the Production of (G)

Fig. 21 shows in much simplified form an electrical equivalent of this action. An inspection of this figure will throw some light on the subject.

For one thing, it is clear that the apparent wire-to-pin capacitance will decrease with increasing frequency. Wet-weather tests invariably show this effect. (Incidentally, this effect tends to reduce the magnitude of $C$ and $D$, at the higher frequencies.)

It is also apparent that the conductance of this simplified circuit is zero at zero frequency and a maximum at very high frequencies. In the intervening range the conductance at first rises nearly as the square of the frequency, then the relations becomes more nearly linear and finally tapers off to a final constant maximum value.

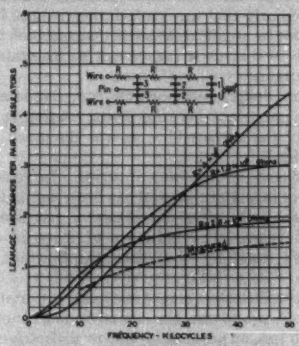



Fig. 22—Calculated and Measured Value of (G) for C. P. Insulator

If the distributed capacitance of an insulator were accurately known, as well as the resistivity of the surface film, the magnitude of $G$ could be calculated. Unfortunately, both factors are difficult to determine with precision.

However, it is useful to carry out such a calculation, even though the factors be not accurately known.

Fig. 22 shows the variation of $G$ with frequency,

as calculated for the assumptions indicated on the drawing. The assumed distributed capacitance and surface resistivity are intended to represent those of the insulator of Fig. 6. A measured value of $G$ for this insulator is shown by the dotted curve. The agreement is not very good, being no more than qualitative. However, the accuracy of the assumptions is not sufficiently high to expect a much better agreement.

In accordance with this theory, it is evident that $G$ could be produced on a dry insulator by coating the surface with a thin metallic film of high resistance. This has been checked experimentally. The dry-weather conductance of an insulator of given shape and material can readily be increased ten or more times by such a coating. In its general magnitude this increase corresponds to that of the uncoated insulator between dry and wet weather.

Referring again to Fig. 21, $G$ will be seen to be zero when the resistivity of the circuit is zero. Thus, if a metal coating of low resistance be placed on the outside surface, the value of $G$ would be made negligible for that surface. However, such a coating causes the losses on the inner surfaces to increase. The net result is usually a substantial reduction in leakage, as shown by many tests comparing coated with uncoated insulators.

*2. Influence of Insulator Design.* From the foregoing discussion, the importance of insulator capacitance is quite apparent. For $G$ to be small, it is not only desirable that the total capacitance shall be small, but particularly that any capacitance remote from the wire groove be small, unless the resistance of the path from wire to that capacitance can be maintained at a very high value.

Insulator design is important from this standpoint. It is also important because of its relation to the resistivity of the surface film, as was discussed in some detail under $B$.

*3. Influence of Insulator Material.* In general, the influence of insulator material has been less than that of design, especially after the insulator has aged for a couple of years. The influence of material on $G$ is determined both by the dielectric constant of the material and its surface resistivity.

While the dielectric constant of the materials tested varies about two to one, the corresponding range of $G$ is very much less, on account of the low dielectric constant of the air which occupies a part of the dielectric path.

The factor of surface resistivity is probably the more important one. For example, its effect on $G$ probably accounts for most of the increase in leakage at high frequencies that accompanies aging, which is a very substantial one.

As to the relative importance of these two factors, tests have been made on only one design. At this writing the tests register a slight balance in the favor of a good surface over a good (low) dielectric constant.

The influence of material on $G$, while not great, gives the chief justification from the electrical standpoint for employing the better but more costly glasses.

## Conclusion

*Description of New Insulators.* Two new insulators are available for use on carrier circuits of the Bell System. These replace the standard D. P. insulator of Fig. 1 in those cases where the additional expense of the new insulators is justified.

One of the new types is designed for use on the wood pins of existing lines. It is known as the C. W. insulator and its design is shown in Fig. 3. The pair of pin thimbles illustrated at the bottom of that figure is first placed over the two wood pins, then the insulators are screwed into place over the thimbles, forcing the latter well into the threads of the wood. The thimbles are constructed of thin copper and are bonded together by a tinned copper strip.

The other new type is designed to screw directly over a steel pin. This is known as the C. S. insulator and its

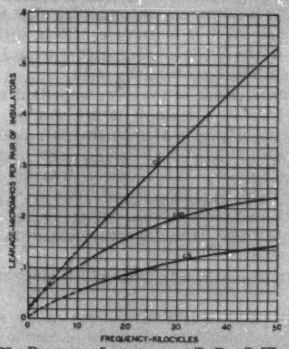



Fig. 23—Relative Leakage of D. P., C. W. and C. S. Insulators as Measured at Phoenixville, Pa., in Moderate Rain

design is shown in Fig. 12. At each crossarm the two steel pins are bonded by means of a wire underneath the arm.

Both new designs are molded from borosilicate glass. This glass is more expensive than the alkali glass used in the old D. P. design. On this account, and on account of the pin thimbles in one case and the steel pins in the other, the new insulators cost more to install than did the old ones.

Both of the new designs were brought out several years ago before this study had conclusively demonstrated the importance of surface losses (item $G$). It will, therefore, be of some interest to discuss their performance in the light of the more complete knowledge.

*Performance of D. P., C. W., and C. S. Insulators.* The leakage of these three types, as measured on the insulator test line at Phoenixville, Pa., in a moderate rain, is given in Fig. 23. This measurement does not

give a true picture of the relative efficiency of the three types because no two of them are aged alike. Besides, the relative efficiency varies considerably with different weather conditions. However, the measurement will serve our present purpose, which is to analyze the total leakage of each design and thus give a perspective which could not well be brought out in the detailed discussion of the several sources of leakage. It should be pointed out and emphasized that the allocation of the total leakage to its component parts can be only very approximate.

Fig. 24 shows an estimate of the leakage contributed by the several sources for the D. P. design. The leakage directly through the insulator material is negligible and item *A*, therefore, does not appear. Similarly, the leakage due to unbalanced displacement currents flowing in crossarms, poles, etc., is considered negligible and, therefore, item *F* does not appear.

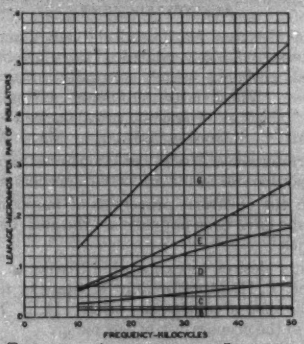



Fig. 24—Estimated Allocation of Leakage for D. P. Insulator

At a frequency of 30 kc., for example, *B*, the direct surface leakage or d-c. leakage, is about 5 per cent of the total. The dielectric absorption in the glass *C* is about 10 per cent. The dielectric absorption in the wood pins *D* is about 20 per cent. The crossarm losses *E* contribute about 10 per cent and, finally, the losses on the insulator surfaces *G* contribute about 55 per cent.

Fig. 25 shows a similar estimate for the C. W. design. Here the bonded pin thimbles shield the wood pins from any electric field and thus eliminate dielectric absorption *D* from the pins. Similarly, by short-circuiting the crossarms, the losses occurring there are eliminated. Accordingly, both items *D* and *E* are made negligible and do not appear.

Of the remaining factors, the direct surface leakage *B* contributes about 12 per cent of the total (at 30 kc., for example). The losses in the glass *C* are liberally estimated at about 5 per cent. Finally, the surface losses *G* contribute over 80 per cent of the total.

Comparing the C. W. performance in this test with that of the D. P. we find that most of the improvement shown by the C. W. has resulted from the elimination of items *D* and *E*. Due to the single skirt design of the C. W. and the pin thimbles, item *B* has been increased in magnitude. The loss in the glass *C* has been decreased by the use of borosilicate glass. However, the most important item *G* has been only slightly reduced, and if C. W. insulators in this test were aged as far as the

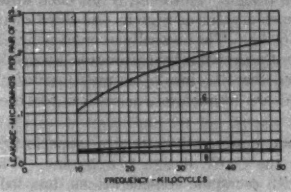



Fig. 25—Estimated Allocation of Leakage for C. W. Insulator

D. P., the C. W. might show no improvement with respect to *G*. The pin thimble construction tends to increase the insulator capacitance and thus tends to make *G* larger for the C. W. than for the D. P. design. The use of a borosilicate glass with its lower dielectric constant counteracts this action somewhat.

The estimated division of losses for the C. S. design is given in Fig. 26. The use of metal has eliminated any dielectric absorption *D* from occurring in the pins. The bonding of the pins by wire has eliminated crossarm losses *E*.

Of the remaining factors, the direct surface leakage B contributes about 4 per cent or less of the total at 30 kc. The losses in the glass *C* are liberally estimated at 10 per cent or less, while the surface losses *G* contribute about 85 per cent or more.

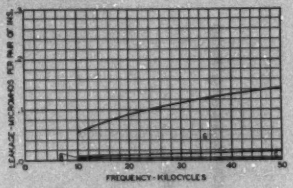



Fig. 26—Estimated Allocation of Leakage for C. S. Insulator

In this design the absolute magnitude of *B* has been decreased somewhat, chiefly because the small diameter of the steel pin permits a small diameter of insulator, the advantages of which were pointed out in the detailed discussion of this item.

The low capacitance made possible by the small steel pin has helped to make both *C* and *G* relatively small, although most of the improvement in *C* is due to the borosilicate glass.

The improvement in the surface losses $G$ over the D. P. design is quite marked.

For the new designs the two factors $B$ and $G$ are the controlling ones. In this particular test $B$ happens to be quite small in magnitude, and would naturally lead one to conclude that $B$ had been made unnecessarily small at the expense of $G$, especially since these two items in many respects place conflicting requirements on insulator design. However, $B$ has been observed at times to reach a value as high as one-third of the total leakage at 50 kc. The necessity of engineering for such cases makes the design more reasonable, especially when it is recalled that the insulators must serve for direct current and low frequencies, as well as for the carrier range.

Of the new designs, the electrical superiority of the C. S. over the C. W. design is apparent. This fact, together with economic considerations, has led to the almost universal choice of the C. S. rather than the C. W. type for the field of application of the new insulators in the telephone plant.

The utility of the C. S. insulators in the telephone plant will be more clearly apparent from a consideration of the reduction in attenuation which their use brings about.

The losses in transmission over a pair of wires at carrier frequencies come chiefly from two sources: one, substantially fixed in magnitude, depending mainly on the resistance of the wires; the other, quite variable in magnitude, depending on the leakage conductance between the wires and, therefore, on the weather.[6]

In the case of 165-mil copper wires on 12-in. spacing these two components of loss are approximately equal in wet weather when the older type of insulators are used. The C. S. type cuts this variable component about in half at 30 kilocycles thus reducing the total wet-weather attenuation of these wires to about 75 per cent of its former value. For smaller sizes of wires the percentage reduction is correspondingly less.

The benefits of the lesser attenuation can be utilized in the plant in various ways, depending on local conditions; for example, in increasing repeater spacing, in employing smaller gages of wires, or in increasing the number of insulators per mile to provide for better transposition designs.

In addition, the new insulators, in having reduced the variable component of loss, improve the stability of carrier circuits to a marked degree.

## Acknowledgment

Only the electrical features of the new designs have been discussed. Closely related to these are the many mechanical problems which naturally arise in new construction. These latter problems, during the development of the new designs, came under the supervision of Mr. C. S. Gordon, assisted by Mr. J. T. Lowe.

The Corning Glass Works has cooperated in molding special experimental insulators of various compositions.

Data on the electrical properties of numerous glass compositions have been supplied by the Bell Telephone Laboratories.

The writer desires to express his thanks to Messrs. F. A. Leibe, L. R. Montfort and L. Staehler for assistance in the measurements and to Mr. H. R. Nein for assistance in the preparation of this paper.

6. For a more detailed discussion of attenuation see a parallel paper, *The Transmission Characteristics of Open-Wire Telephone Lines*, by E. I. Green.

# A General Switching Plan for Telephone Toll Service

BY H. S. OSBORNE*

Fellow, A. I. E. E.

*Synopsis.—This paper outlines a comprehensive plan for improved switching of long haul toll telephone traffic in the United States and eastern Canada. A brief discussion is given of the methods of designing the toll plant to give adequate transmission efficiency for all connections established in accordance with this plan, including a new method of providing amplification at intermediate switching points replacing the cord circuit repeater method.*

* * * * *

## Introductory

On January 25, 1915, telephone service was, with due ceremony, inaugurated between the Atlantic and Pacific Coasts of this country. This occasion marked a great step forward both technically and commercially. Before that time, the limit of practicable telephone transmission had been about 1500 miles. The transcontinental service was made possible by the completion of numerous important developments and particularly by the perfection of telephone repeaters and of means for applying them to long wire circuits.

Until then the Pacific States and their neighboring states had been isolated telephonically from the eastern and midwestern parts of the country. The demonstration of commercially practicable telephone circuits across the continent gave a great impetus to the idea of universal service, that is the provision of a telephone plant such that telephone service could be given at commercially attractive rates between any two telephones in the country.

In the fifteen years since the opening of the first transcontinental circuits, the ideal of universal service has to a large extent been realized. Practically all the telephones of the United States and a large part of Canada now have provision for connection with the countrywide toll telephone network, more than 99 per cent being included. To achieve universal service, however, involves a great deal more. Circuits must be provided in such numbers and so arranged that connections between any two telephones can be established quickly and without too many intermediate switching points. Also the telephone plant must be designed for such standards of transmission that these connections, when established, will permit satisfactory conversation. In general, the technical advances which have been made during the last fifteen years to achieve the present standards of toll service have been described from time to time before the American Institute of Electrical Engineers, and it is not within the scope of this paper to review them.

Associated with this development of the telephone plant has been a very rapid increase in traffic. Fig. 1 indicates this increase in the United States and Canada since 1915. A striking characteristic of this growth is that the increase has been much more rapid for the longest lengths of haul than for the shorter lengths of haul. For example, during the last five years in which

Fig. 1

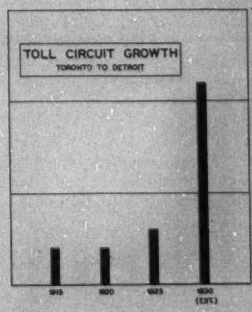



Fig. 2

the messages on lengths of haul up to 250 mi. approximately doubled, the messages on hauls from 250 to 1000 mi. increased five times and those over 1000 mi. increased more than ten times. This characteristic is also illustrated in Figs. 2, 3, and 4 which show respec-

*Transmission Engineer, Am. Tel. & Tel. Co., New York, N. Y.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

tively the growth in the number of circuits between Toronto and Detroit, 240 mi. in length; Buffalo and Chicago, 550 mi. in length; and direct circuits from New York and Chicago to the Pacific Coast, averaging about 2500 mi. in length. This particularly rapid growth in very long haul traffic has made it practicable to establish a considerable number of long-haul circuit groups and has greatly assisted in the problem of handling satisfactorily calls between widely separated points. It has led to the condition today in which 74 per cent of the long distance (Long Lines) messages are handled over direct circuits and 20 per cent with one intermediate switch.

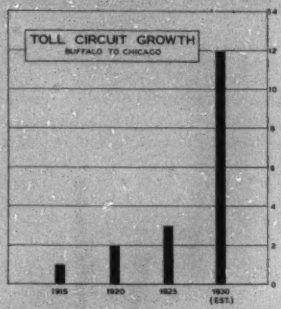



Fig. 3

The part of the business on which it is most difficult to give a high grade of service is naturally the scattering business between widely separated points. In these cases each item of traffic, that is the business between two specific points, is relatively small but the number of items of traffic is great. The number of messages involved in each item of traffic does not justify direct circuits and in very large numbers of cases it is necessary, in order to provide a connection, to make more than one intermediate switch. This applies at present to six per cent of the long distance telephone business of the country. All measures of the quality of service—speed, accuracy, and transmission—show that the difficulty of handling the service satisfactorily increases rapidly with the number of intermediate switches involved.

The development of the toll business has led to a great increase in the amount of business between large numbers of widely separated points. There has also been an extensive trend toward concentration of the plant used in handling the business in important toll offices and along important routes. The long haul toll business is now handled at about 2500 "toll centers" out of approximately 6400 central offices in the United States and eastern Canada. Furthermore, the technical developments in toll circuits have led to great increases in the numbers of circuits along a given route. The extension of the use of carrier telephone has increased the capacity of a 40-wire pole line from 30 circuits to 70 circuits. On the heaviest toll routes, moreover, circuits are now provided by means of toll-cable construction, a single cable carrying 200 or 300 circuits. During the past year or two, the growth has been so rapid as to stimulate a very large amount of construction of underground toll conduit routes, providing in many cases for several thousands of telephone circuits on a single route.

## General Toll Switching Plan

The conditions outlined above form the background which has made it both possible and important to adopt a new fundamental arrangement for the layout of toll plant and the routing of toll messages. This is called the "General Toll Switching Plan." The purpose of this plan is to provide systematically a basic plant layout designed for the highest practicable standards of service consistent with economy, including speed, accuracy and directness of routing between any two points in the country, and suitable transmission standards. This involves the layout of the plant in such a manner as to limit, so far as it is practicable to do so, the number of switches required for providing a connection between any two telephones and the establishment of standards of design and construction providing satisfactory transmission over any route thus established. The plan is, therefore, of particular value in improving the service conditions of switched toll traffic, that is, traffic requiring the connection of two or more toll circuits.

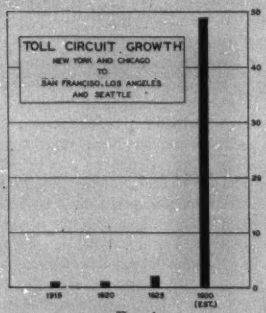
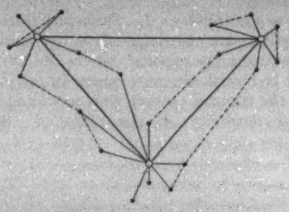



Fig. 4

The general features of the plan will be understood by reference to Figs. 5 and 6. Fig. 5 shows the application of the plan to a limited operating area such, for example, as a state. Within the area are selected a small number of important switching points designated as "primary outlets." Each toll center is connected directly to at least one of these outlets and all primary outlets within the area are directly interconnected. This makes

possible the interconnection of any two toll centers within the area with a maximum of two switches and within the part of the area served by one primary outlet, with a maximum of one intermediate switch.

The primary outlets were selected after a careful study of the present switching and operating conditions



Solid Lines—Fundamental routes of general plan
Dashed lines—Supplementary direct-circuit groups
○ Primary outlet
● Toll center

Fig. 5—General Toll Switching Plan Application in Local Company Area

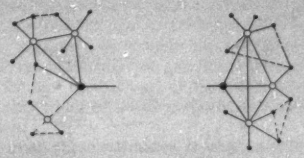
and the probable development of toll traffic within the various areas with a view to obtaining the minimum number of primary outlets capable of handling the traffic economically. The routings provided by the plan are supplemented by direct circuits, or by other routings where the amount of business justifies such additional circuits as indicated by the dashed lines in Fig. 5. In general, the requirement is made that these supplementary routes shall be at least as satisfactory, in regard to both number of switches and transmission, as the routes provided by the fundamental switching plan. However, when the supplementary routes are used only as alternates to a primary routing they may be somewhat less satisfactory in these respects.

The tentative selection of primary outlets is shown in Fig. 7. It is interesting to note that it is found practicable to take care of switching for the 2500 toll centers of the United States and eastern Canada by the establishment of approximately 150 of these as primary outlets.

For handling the business throughout the country eight of the primary outlets are designated as regional centers, which are indicated in Fig. 7. The method of routing calls is indicated by Fig. 6. Each primary outlet is connected with at least one regional center and with as many more as practicable. Each regional center is directly connected to every other regional center in the country. By this means, any one of the primary outlets, which are the 150 most important switching centers in the country, can be connected to any other primary outlet in the country with a maximum of two switches and within the area served by a regional center with a maximum of one intermediate switch. As an illustration of the concentration of switching which results, New York serves as regional center for the entire northeastern section of the United States and eastern Canada.

The extent to which intermediate switching is limited by the application of this plan is indicated by Table I, which shows the maximum number of switches required under the plan between different types of toll centers. It is estimated that the percentage of long-haul messages requiring more than one intermediate switch will, by means of this plan, be reduced by more than 50 per cent.

As an example of the benefit resulting from the adoption of this plan between two remote points, consider a connection which was requested between Pembroke, Ontario, and St. Anthony, Idaho. Under the old routing instructions, such a call required intermediate



Solid lines—Fundamental routes of general plan
Dashed lines—Supplementary direct-circuit groups
● Regional center
○ Primary outlet
● Toll center

Fig. 6—Illustration of Interconnection of Important Switching Offices Throughout Bell System

switches at Ottawa, Toronto, Chicago, Denver, Salt Lake City, Pocatello and Idaho Falls, a total of seven. The chance of establishing such a connection within satisfactory limits of time was, of course, relatively small and the resulting circuit, when established, did not permit the conversation to be held. Under the

TABLE I
GENERAL TOLL SWITCHING PLAN
Maximum Number of Switches

| To— / From | Same Regional Area | | | | Another Regional Area | | | |
|---|---|---|---|---|---|---|---|---|
| | Regional center | Primary outlet | Toll center directly connected to regional center | Toll center directly connected to primary outlet | Regional center | Primary outlet | Toll center directly connected to regional center | Toll center directly connected to primary outlet |
| Regional center | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 2 |
| Primary outlet | 0 | 1 | 1 | 2 | 1 | 2 | 2 | 3 |
| Toll center (directly connected to regional center) | 0 | 1 | 1 | 2 | 1 | 2 | 2 | 3 |
| Toll center (directly connected to primary outlet) | 1 | 2 | 2 | 3 | 2 | 3 | 3 | 4 |

general toll switching plan, this call will be routed with switches at Ottawa, New York, Denver, and Pocatello, a reduction of three switches. Furthermore, the circuits involved in this connection will be designed with such transmission standards as to give satisfactory conversation.

The routes provided by the plan for country-wide service are also supplemented by more direct routes of equivalent or better service characteristics in cases where the volume of business is sufficient to make this economical. Furthermore, the routes to regional centers are, in some cases, supplemented by alternate routes through what are called "secondary outlets." These are distinguished from the primary outlets in that they do not necessarily have direct circuit connections to all toll centers in their areas but serve a useful purpose as an alternate route for the toll centers connected to them.

The essential features of the general toll switching plan from the standpoint of the interconnection of the switching offices may be summarized as follows:

*Regional Centers.* Regional centers are switching offices strategically located to cover the various parts of the country. They are completely interconnected with direct circuits, thus forming the basis of a country-wide toll network.

*Primary Outlets.* Primary outlets are switching offices having direct circuits to one or more regional centers, each outlet having direct circuits to all toll centers in the area for which it is the primary outlet. Also, each primary outlet is connected to every other outlet within as large an area as is practicable, usually within a State.

*Supplementary Offices.* 1. Secondary Outlets. Secondary outlets are switching offices having direct circuits to one or more regional centers and are intended primarily to furnish alternate routes for toll centers for reaching the regional centers, thus providing a greater degree of flexibility in the plant. 2. Secondary Switching Points. Secondary switching points are additional switching offices intended to provide routes which are more direct, thus reducing back haul for intra-area business.

Fig. 7—Map Showing Location of Points Tentatively Selected as Regional Centers and Primary Outlets in United States and Canada

## Transmission Considerations of General Toll Switching Plan

An important part of the development of the plan was the determination of proper transmission requirements such that any toll connection established in accordance with the plan would have satisfactory transmission efficiency.

Before the perfection of telephone repeaters the

provision of satisfactory transmission efficiency depended largely upon limiting the total attenuation loss of the complete circuit. At the present time the perfection of repeaters has practically removed that limitation. For example, the attenuation in a New York-Chicago circuit in cable is such that without the use of repeaters the ratio of input power to output power for speech currents transmitted over the circuit would be $10^{46}$, while by the use of repeaters at the terminals and at 17 intermediate points the ratio actually is 10.

The removal of the limitation formerly set by circuit attenuation makes possible the increase of the efficiency of circuits to the limit determined by some other characteristic of the circuit. There are various things which under different conditions may determine this limit. One is the effect on transmission of echoes, namely, portions of the speech currents reflected back from the distant end of the circuit or from intermediate points. Another is the distortion due to the building up of greater transmission gain at certain frequencies than at others, which effect may result if repeaters introduce too great an amplification into the circuit. As an extreme case, this might result in a sustained oscillation or singing on the circuit. Other effects which may be important are those of crosstalk between telephone circuits, or of noise induced in the telephone circuits from outside sources, both of which are increased by increasing repeater gains. On the longer connections, echoes are almost always the controlling factor, whereas on the shorter connections, such effects as crosstalk, singing, and noise generally are limiting. A reduction in any of these effects generally involves more expensive types of construction.

The difference between the attenuation loss of the circuit and the total transmission gain introduced into the circuit by repeaters is spoken of as the net equivalent. For long telephone circuits, it is generally economical to provide sufficient repeater gain so that the circuit can be operated at the minimum net equivalent permissible, this minimum equivalent being determined by the transmission factors just mentioned. Therefore, in establishing satisfactory transmission efficiencies for the over-all toll connections in accordance with the toll switching plan, each link must be designed on the basis of the minimum working net equivalent which it will contribute to an over-all connection made up of several circuits switched together.

The establishment of satisfactory and economical transmission requirements for the toll circuits laid out in accordance with the plan involves the following steps:

1. The establishment of satisfactory over-all net transmission equivalents.
2. The coordinated design of all classes of toll circuits, and of the subscribers' circuits, toll switching trunks, and tributary trunks connected to them, in such a way that the desired over-all transmission standards will be given at a minimum total cost when suitable transmission gains are provided by repeaters in the toll circuits and at toll switching points.
3. The economical and satisfactory distribution of transmission gain, permitting all toll circuits to be operated at their minimum working net equivalents when this is desirable.

The over-all transmission equivalents to be given under the plan are based on standards which have heretofore been used for a large part of the toll business but which it has been impracticable to meet in many cases between widely separated points. With the means now available for operating circuits at their minimum working net equivalents, it was found that satisfactory over-all transmission equivalents could be provided under the plan even for the maximum number of switches using standards for the construction of toll circuits very comparable with those already applied to new circuits. Expressed in terms of the transmission reference standard, the plan set up gives a maximum of 25-db. over-all equivalent within one interconnected area (two intermediate switches) and a maximum of 31-db. between any two telephones of the United States and eastern Canada.

In order to determine the most economical distribution of these over-all equivalents, a study was made based upon the estimated total number of toll circuits of each class in 1932 and their distribution by length. It is also necessary to include the corresponding estimates for the plant between the toll office and the subscriber, the loss in this part of the plant being on the average about half of the over-all net equivalent of the connection.

Based upon these estimates, it was possible to determine, by an economic study, the distribution of the over-all minimum net equivalent between these various parts of the circuit which would give minimum total expenses. The toll terminal losses and the minimum net equivalents for toll circuits established in this way are shown in Table II.

TABLE II
GENERAL TOLL SWITCHING PLAN
Transmission Design Data

| Classification of toll circuit involved | Minimum working net loss of toll circuit—db. | Maximum via operating equivalent—db. | Transmission margin—db. |
|---|---|---|---|
| Toll center to primary outlet | 3.0 | 4.0 | +1.0 |
| Toll center to regional center | 3.5 | 4.0 | +0.5 |
| Primary outlet to regional center | 3.5 | 3.0 | −0.5 |
| Regional center to regional center | 4.0 | 3.0 | −1.0* |
| Primary outlet to primary outlet | 4.0 | 3.0 | −1.0 |
| Toll center to toll center | 6.0 | 6.0 | .. |
| Direct toll circuit (for terminal use only) | 9.0 | .. | .. |
| Toll terminal loss | 7.0 | .. | .. |

*Circuits equipped with echo suppressors may be designed with greater negative margins.

In addition to the circuits involved in multi-switch business, the studies connected with this plan necessarily include circuits used for terminal business only, and others for which switching is limited to a single intermediate switch at points where transmission gain is not required. These circuits are associated with the plan because the portions of the circuit between the toll center and the subscriber are common for these circuits and for circuits directly involved in the general plan. Design standards for these classes of circuits are also shown in Table II.

## Provision of Transmission Gain at Intermediate Switching Points

The third step mentioned previously is the determination of the best distribution of repeater gains to permit the individual circuit to be operated by itself or in conjunction with other toll circuits at approximately the minimum net equivalent as determined by the several effects mentioned previously. In so far as the gain of repeaters permanently inserted at intermediate points in a toll circuit is concerned, this is a matter of economical design of the circuit and has been adequately covered in other papers. We are interested here, however, in considering the provision of gain at the intermediate switching points when two toll circuits are connected together.

As indicated previously, echo effects usually control on the longer connections, whereas crosstalk, singing, and noise will usually control on the shorter connections. This is due to the fact that for the great majority of toll circuits the echo effects on individual circuits increase more rapidly with length than do crosstalk and noise. Singing tendencies also increase at a rapid rate with increase in length on two-wire circuits but tend to be independent of length on four-wire cable and carrier telephone circuits which are used to a large extent to provide the circuits between the primary outlets and regional centers and between the regional centers. Furthermore, when two or more toll circuits are connected together, the echo effects of the individual circuits add together almost directly, whereas the effects of crosstalk, singing, and noise increase at a much less rapid rate. The result of these general considerations is that when a toll circuit is switched to another toll circuit, the over-all combination can, in general, be operated at a lower net equivalent as determined by echo effects than the sum of the two circuits when operated individually, in which case the minimum equivalent is determined by the crosstalk, singing, and noise effects. Therefore, it is necessary in the case of connections built up by connecting together a number of toll circuits to introduce repeater gain at the intermediate switching points. If gain were not introduced at intermediate points, it would be necessary in order to obtain the same over-all results on connections involving more than one toll circuit to design and build a considerably more expensive type of toll circuit plant in which the crosstalk, singing, and noise effects would be greatly reduced.

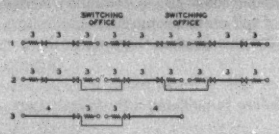
In the past, gain was inserted at intermediate switching points by the use of cord circuit repeaters. These familiar devices consisted of telephone repeaters inserted in the cord circuits and associated by means of double plugs with the toll circuits and with individual balancing networks designed for each toll circuit. By this means intermediate gains of from 4 to 10 db. were inserted at the switching points when connection was made between two toll circuits.

The use of cord circuit repeaters has been an outstanding element in the provision of improved transmission on switched connections. It has, however, some disadvantages which have increased in importance with the increase in transmission efficiency of circuits and with the rapid development of toll business. The routine for inserting the cord circuit repeaters when needed is necessarily somewhat cumbersome, involving considerable expense for operators' labor and for increased use of the toll circuits by operators. Furthermore, under practical conditions it was found not to be possible to insure that the cord circuit repeaters would always be used when required by the routing instructions.

Recent developments in the types of toll circuit have greatly increased the numbers of toll circuits provided with repeaters at their terminals as a part of the most economical circuit design. When such repeaters are available, the desired switching gain can be obtained by making use of the gain available in these repeaters. The great increase in the number of terminal repeaters required for other reasons, important reductions in the cost of repeaters and the savings of operators' labor and circuit time have made it practicable to provide, at certain points, terminal repeaters for every circuit, thus doing away entirely with cord circuit repeaters at these points. With the terminal repeater arrangement, the insertion of transmission gain on switched connections is done automatically by taking out of each circuit on such connections a section of artificial line. This is, of course, the equivalent of increasing the gain of the terminal repeater.

Satisfactory transmission results for all connections under the general toll switching plan involve the insertion of repeater gain on all connections switched at important switching points. This will be carried out by the terminal repeater plan just described. The artificial lines or pads which are cut out of the circuit on switched connections have losses of from 1 to 4 db., depending upon the circumstances of each case. This means that when two toll circuits are switched together, from 2 to 8 db. is automatically subtracted from the connection at each switched point. The arrangement is indicated schematically in Fig. 8. The design of each circuit must, of course, be such that when either end of the circuit is connected to a subscribers' station, the repeater gain at that end will not be greater than

that permissible under the terminating condition, but that when two or more of such circuits are connected together for a long built-up toll connection, the complete circuit will operate at as nearly as is practicable its minimum working net equivalent. While under these conditions the permissible values of the pads associated with the terminal repeaters naturally vary in individual cases, it has been found possible to work out for general use a series of values which should give satisfactory results. These are indicated in Fig. 9. It will be noted that these values are such that a circuit switched at both ends to other toll circuits is operated at either 0.5 db. or 1 db. less than its minimum working net equivalent, this deficit being made up by a corresponding margin at the ends of the circuit. For example, by reference to Fig. 9, it will be noted that whereas the design values of the three intermediate links of a five-link connection equate to 11 db., these links will contribute a total loss of only 9 db. On the other hand, the end links will contribute a total of 8 db., whereas their design values equate to only 6 db. The 2-db. marginal deficiency in the intermediate links is compensated for by the 2-db. marginal surplus in the end links. When intermediate links are used as end links in built-up connections, the switching pads at the terminating ends restore the necessary positive margins.




Typical transmission data
1. Circuits between switching pad offices in terminal condition
2. Circuits of No. 1 interconnected at switching pad offices
3. Connection between non-pad offices switched at pad office

Fig. 8—Diagram Illustrating Terminal Repeater-Switching Pad Method of Operation—Typical Transmission Data

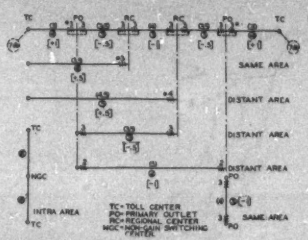
The design of the very long intermediate circuits, such as some of those connecting two regional centers, requires special consideration and treatment to meet the transmission requirements specified. By making use of a fundamental feature of four-wire circuits equipped with echo suppressors and by employing circuits with the highest velocities of propagation for this purpose, these circuits may be designed in practically all cases to contribute not more than the desired operating equivalent for an intermediate link. Four-wire circuits equipped with echo suppressors are unique in that at the longer circuit lengths the increase in minimum net equivalent with further increase in length becomes very slight.

Two general arrangements for removing the switching pads from and restoring them to the toll line circuits are available, depending upon the type of switchboard facilities involved. Either arrangement requires the modification of both the toll line circuit and the switchboard circuits. One method controls the switching pad by a marginal relay in the sleeve of the toll line circuit. In the other arrangement, the pad is under the control of relays operated by battery supplied from a simplex bridge in the connecting circuits.

With the general toll switching plan the number of places in which switching gain is required is greatly limited, being, as pointed out above, a total of about 150 out of 2500 toll centers. This number will be somewhat increased by secondary switching points in which it is found economical to insert switching gain in order to save the back-haul involved in following the routing provided by the plan. However, the net result is that under the toll switching plan the number of points at which switching gain is provided will be materially limited, with corresponding economies.

## Establishing the Program of the General Toll Switching Plan

The full application of the general toll switching plan involves a large number of individual rearrangements of plant layout, the establishment of certain new circuit groups and the rerouting of a considerable amount of switched business, the conversion of the switching offices to the terminal repeater arrangement, and the modification of the transmission requirements of certain of the circuits. The date at which these rearrangements will be completed is naturally different for different sections of the country and is determined by the regular program of plant additions and rearrangements to take care of increasing business and of needed service improvement. The existence of a comprehensive plan of this sort insures that the program of rearrangements as carried out will be along the lines of greatest economy and maximum improvement in service. The present plans of the telephone companies in the United




Transmission data
( ) Minimum working net loss
○ Operating via equivalent
[ ] Transmission margin
Maximum toll circuit equivalent.....17 db.
Maximum over-all connections.....81 db.
Assumed limiting toll terminal loss..... 7 db.
*Value of pad in terminal links dependent on noise and cross-talk conditions

Fig. 9—General Toll Switching Plan for Handling Switched Toll Traffic—Transmission Data

States and Canada indicate that the plan as now established will be very closely approximated by the actual plant in the course of about five years.

## Future View

Such a plan as has just been discussed is naturally not a static thing but is subject to continual modification to bring it into correspondence with changed conditions. In connection with such changes it is of interest to consider briefly the probable long time trend of the development of the plan.

One possible ultimate development would be the increasing connection of primary outlets to a single regional center so that ultimately only one regional center would be necessary. If this were to take place, the regional center would undoubtedly be Chicago. Fig. 10 is interesting as showing the extent to which the primary outlets already are connected directly with Chicago, over one-half of them having such direct connection.

If Chicago ultimately became the only regional center, it would reduce the maximum number of switches to three. It seems evident, however, that such a plan would have many disadvantages. It seems clear that with such an arrangement, numerous secondary regional centers would be necessary to avoid uneconomical back-haul of large amounts of traffic, and the economies of such an arrangement do not look promising. Furthermore, it would lead to a tremendous congestion of through switching at one point, this congestion going far beyond the limits of economical concentration and leading to serious operating difficulties.

A second, and it is believed more promising, general trend would result from the gradual increase in the number of regional centers as the continued development of business makes this economical. With this growth would come also a continued increase in the number of toll centers connected directly to a regional center. By this process there would be a continued growth in the number of toll centers which can be interconnected with a maximum of two intermediate switches, and it is possible that ultimately the primary outlets can drop out of the picture completely, giving a maximum of two intermediate switches for the entire country. While any such outcome is evidently many years away, it seems probable that it is along these lines that the growth in development of the plan should be directed.

Although this direction of development avoids the congestion which would be brought about by the single regional center plan, even under this plan the rapidly growing amount of toll switching to be done in large metropolitan centers offers a very important problem

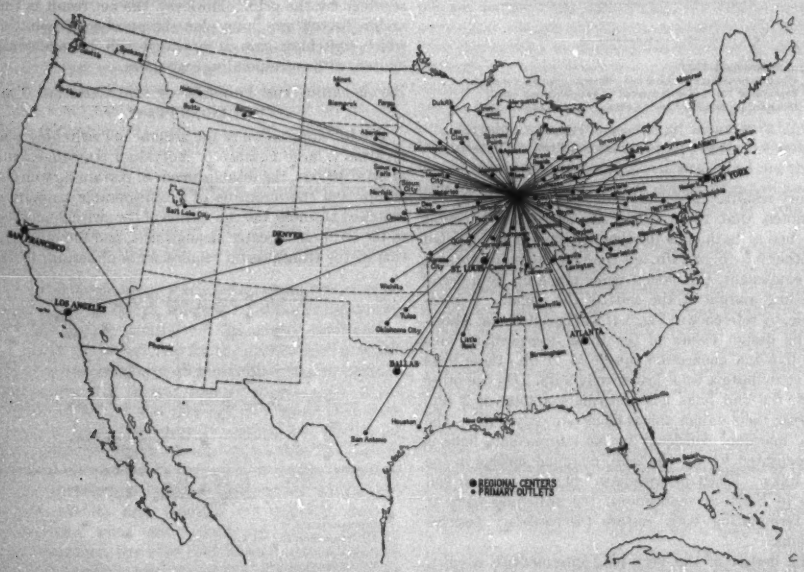



Fig. 10—Map Showing Number of Primary Outlets and Regional Centers Having a Direct Circuit Group to Chicago

for the future. Toll switching at these points is rapidly outgrowing the capacity of a single manual switchboard, as the switching of local calls did long ago. Equipment changes are being made which increase this capacity, but they can be only a temporary relief. Looking to the future, an increasing amount of the outgoing traffic will be handled by operators in the local central offices, reaching the toll line over toll tandem trunks. It is evident, however, that the ultimate solution of the problem will involve the use of machine methods for the selection of the toll line by the operators, as is now done in certain segregated toll tandem systems.

The entire trend of recent years is thus to decrease the differences between the handling of exchange messages and of toll messages. At the present time more than 95 per cent of the toll messages are completed while the subscriber remains at the telephone, with speeds of completion only slightly slower than those of exchange messages. Transmission standards, while naturally somewhat better for the shorter distances involved in exchange messages, are, nevertheless, rapidly bebecoming comparable. The present view of trends for the future is for continuation of this process, perhaps even to the use of similar types of machine equipment at central offices for switching the various classes of messages.

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# Long Telephone Lines in Canada

BY J. L. CLARKE[1]
Associate, A. I. E. E.

*Synopsis.—This paper describes the development of long distance telephone facilities in Canada and also outlines certain plans for provision of additional long-haul circuits in the future.*

* * * * *

## Historical

THIRTY-FIVE years ago a telephone line was constructed from Montreal to Toronto, a distance of 360 mi. At that time technical limitations were such that about 400 mi. was the maximum distance over which good telephone service could be given; hence the above mentioned circuit was then considered to be a very long telephone line.

Since that time the telephone horizon has expanded in a very marked degree, and with this expansion has come a change in ideas as to what constitutes a long telephone circuit.

For many years telephone development in the Dominion of Canada was local in character; service was started in small areas isolated from each other and gradually these areas spread out and became linked with adjacent areas. On account of the great extent of the country and the sparseness of the population, economic difficulties exercised a severe restraint on the construction of the longer links which were required to bridge the gaps between the various settled areas of the country.

Telephone connections between certain of these areas and the Bell System in the United States were early established and this provided a means of communication between different sections of Canada at a time when direct circuits through the Dominion were not economically feasible.

This arrangement possessed marked advantages; first, it provided telephone service between different communities in Canada which would otherwise have been without it; second, it permitted this traffic to grow until it finally reached a point at which it became possible to prove in the building of direct links through Canada.

By the year 1927 the progressive linking together of the various areas throughout which telephone service was being given had reduced the number of these separated territories to four: first, the Maritime Region including the Provinces of Nova Scotia, New Brunswick, and Prince Edward Island; second, the Central Region, including the settled portions of the Provinces of Ontario and Quebec; third, the Western Region, including a large part of the Provinces of Manitoba, Saskatchewan and Alberta; fourth, the Pacific Region, including the southwestern part of the Province of British Columbia. Taking geographical distances into consideration, it may be stated roughly that these regions are located about 1300 mi. apart, reckoning from the middle of one region to the middle of the adjacent region.

Fig. 1 is a map of the Dominion of Canada showing the regions where there is appreciable telephone development.

In the gaps between these regions the nature of the country was unfavorable for telephone line construction; the road connections were incomplete and the settlements were few and far between. Between the western region and the pacific region, the massive ranges of the Rocky Mountains extend for hundreds of miles.

Fig. 1—Map of Dominion of Canada showing Telephone Development

The central and western regions are separated by nearly a thousand miles of very rough and almost uninhabited country. The terrain in this section is very difficult to traverse; there is a continuous succession of rocky hills and ridges which exhibit no regularity of form or direction. Interspersed among these hills are patches of muskeg and small lakes.[2]

Between the maritime region and the central region, there is a long stretch of rough and sparsely populated country.

This last mentioned gap was not entirely without roads and certainly presented less difficulties than either of the other two and in 1928 a pole line was constructed in this section and telephone conductors

1. Transmission Engineer, Bell Telephone Co. of Canada, Notre Dame, Montreal, Que., Can.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

2. It may be noted that in 1929 certain sections of road in British Columbia which were necessary to bridge various gaps between existing roads were completed, and it is now possible to travel by automobile from Vancouver to Calgary although the route is somewhat circuitous.

There is as yet no highway extending through the section of country lying to the North of Lake Superior.



30-130

were erected to provide circuits from Quebec and Montreal to Saint John, N. B.

This left two unbridged gaps, but completing these missing links by means of the erection of pole lines crossing these sections involved formidable problems both in construction and in maintenance of lines after construction.

There existed an alternative method of carrying telephone circuits across these gaps. The main lines of both the Canadian Pacific Railway Company and the Canadian National Railways crossed both of these sections and the telegraph systems of these railways possessed pole lines along the railroad right-of-way. The possibility of making use of one or other of these pole lines to carry telephone circuits was carefully investigated and this plan was found to be practicable.

Negotiations were originated with these railway companies and an arrangement was made with the Canadian Pacific Railway Company for the use of facilities by means of which telephone communication could be established. The necessary telephone repeaters were obtained and placed at suitable locations, and a telephone line was put into operation between Sudbury and Winnipeg in August, 1928; a few months later connections were established by similar means between Vancouver and Calgary.

There is another important factor which had to be taken into consideration; that of ownership of facilities. In the United States, the telephone system of the American Telephone and Telegraph Company and its associated companies extends from coast to coast, whereas in Canada, the telephone service is provided by a number of independent organizations. Prolonged negotiations were necessary in order to arrive at an understanding in this matter, and to evolve a mutually satisfactory plan in accordance with which steps could be taken to inaugurate a system of long-haul telephone circuits of a type suitable to provide universal service between all sections of the Dominion, and to coordinate the construction, maintenance, and operating practises of the various telephone systems to the extent necessary to permit the satisfactory functioning of these interregional circuits.

Cooperation between the various telephone systems in Canada was greatly facilitated by the existence of an organization known as the Telephone Association of Canada in which all of the larger telephone systems in the Dominion were represented.

## Existing Circuits

At the present time, the long circuits shown in Table I are in operation.

These telephone lines are all two-wire voice frequency circuits. Some of the circuits are located on the same pole line as commercial telegraph circuits for long distances—in one case for approximately 1000 mi. This caused the telephone circuits to be exposed to severe inductive effects from the telegraph currents and special means had to be adopted to avoid undue interference which would have resulted in excessive noise in the telephone circuits.

TABLE I

| Circuit | Approximate length of circuit | No. of through line repeaters |
|---|---|---|
| Montreal-St. John | 620 mi. | 4 |
| Montreal-Halifax | 890 mi. | 6 |
| Toronto-Winnipeg | 1285 mi. | 9 |
| Calgary-Vancouver | 625 mi. | 4 |
| Sudbury-Winnipeg | 973 mi. | 5 |

The relative interfering effect of a given amount of electric current in conductors situated more or less parallel to the conductors of the telephone circuit depends on several factors. First, there is that of separation; in this case the conductors carrying the disturbing currents were located within a few feet of the telephone circuits.

Second, there is the type of circuit; if the return conductor is distant from the line conductor, the intensity of the magnetic field produced by unit current in the disturbing line is very much greater than the intensity produced by the same current when the return conductor is adjacent to the line conductor. In the case of d-c. telegraph circuits, the return is through the ground and relatively distant from the line conductor. Third, there is the wave shape; if all other conditions are similar, the interference per unit current in the line conductor is proportional to the telephone interference factor of the disturbing current. In the case of high-speed telegraph circuits, the telephone interference factor is very high; for instance, the t. i. f. of the telegraph current in a four-channel multiplex-system operating duplex at 60 words per minute in each direction on each channel is about 900.

The result of all these factors is that the relative interfering effect per unit current is very high. The remedial measures used were; first, the use of a very accurately spaced system of transposing the telephone circuits, and second, the use of low-pass filters in the telegraph circuits. These functioned in such a way as to cut off the high-frequency components in the telegraph currents, and it is these high-frequency components which cause the major part of the interfering effects in the telephone circuits. The insertion of the low-pass filters introduces, in general, only a very negligible effect on telegraph transmission.

These circuits function satisfactorily in providing telephone links between adjacent regions, but the two-wire voice frequency type of telephone circuit has certain inherent limitations which become apparent when attempts are made to make use of this type of facility for establishing very long telephone connections.

These limitations are such that the existing voice frequency open-wire circuits are not entirely satisfactory for all possible connections between alternate regions. In order to provide a suitable grade of

transmission between all points in the various regions in Canada, and particularly for those cases where very long telephone connections will be involved, circuits with high inherent transmission stability and good over-all transmission qualities will be required. As it is not possible to provide direct circuits between all the regions, the circuits provided must be suitable for interconnection by means of switches in order to establish built-up connections. The transmission requirements for the design of these very long telephone circuits are materially more severe than those of much shorter lengths and, as discussed below, in many cases it has been found necessary to introduce telephone facilities of a different type (as regards design

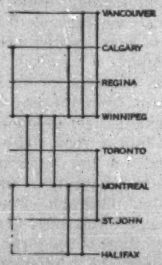


Fig. 2—Proposed Circuits in 1932

This program does not include circuits terminating in adjacent Provinces

and construction) than have been previously used. These include the use of carrier telephone systems superimposed on open-wire lines having special wire configurations, and transmission regulation arrangements.

## Proposed Long Circuits

The introduction of the circuits shown in Table I has resulted in a rapid increase in the traffic between adjacent regions and additional facilities are now required to meet the demand for service. The longer haul traffic has also increased to a point where it is now sufficient to warrant the construction of longer direct circuits between various points in Canada.

The results of a traffic study covering the number of calls per day expected in 1932 between certain of the more important points are given below:

1. Toronto-Vancouver..... 27
2. Winnipeg-Calgary.....156
3. Winnipeg-Vancouver..... 54
4. Montreal-Winnipeg.....107
5. Toronto-St. John..... 36
6. Montreal-Halifax..... 72

In order to provide for these traffic requirements in a manner most suitable from a transmission standpoint, and involving a minimum amount of switching, the fairly comprehensive network of facilities as shown in Table II has been proposed. The engineering work involved in the design and construction of these facilities is now actively under way, and in certain cases, the actual construction work has already commenced.

TABLE II

| Circuit | To be completed | Length of circuit | Type |
|---|---|---|---|
| Toronto-Winnipeg..... | 1930 | 1285 mi. | Carrier telephone |
| Montreal-Winnipeg..... | 1930 | 1600 mi. | Carrier telephone |
| Montreal-Winnipeg..... | 1931 | 1600 mi. | Carrier telephone |
| Winnipeg-Calgary..... | 1931 | 974 mi. | Carrier telephone |
| Winnipeg-Calgary..... | 1931 | 974 mi. | Voice frequency telephone |
| Winnipeg-Vancouver.... | 1931 | 1820 mi. | Carrier telephone |
| Calgary-Vancouver ..... | 1931 | 850 mi. | Carrier telephone |
| Calgary-Vancouver..... | 1931 | 850 mi. | Voice frequency telephone |

At some later date it is proposed to construct a Toronto-Vancouver circuit. This circuit will be obtained from carrier type facilities and will be 3100 mi. in length.

The circuit layout as proposed in 1932 will provide telephone connections between any two of the main toll centers shown in Fig. 2 with not more than two switches. The cities shown in Fig. 2 are the principal long-distance outlets for each province.

The engineering of these circuits involved the solution of many interesting problems of circuit design and construction methods. Engineering studies of the most economical methods of providing the required plant layout were undertaken in order to establish plans which would be most practicable for the immediate future and would also anticipate the probable requirements for some time to come. The first major problem was that of the determination of the most suitable type of construction for providing the facilities required. This resulted in a consideration of three general plans, the first of which was the construction of new pole lines throughout and the installation on these of a sufficient amount of wire to obtain the circuits required in each section. The second general method was that of stringing wire on existing pole lines with, of course, the building of a small number of new lines where the existing construction could not be used most advantageously. The third possibility was the use of carrier telephone facilities superimposed on open wires on existing pole lines where practicable, and on new construction where such new work was considered justifiable. This last consideration assumed that the carrier circuits would provide for the extensive facilities required and that the open-wire telephone circuits on which the carrier channels were superimposed could be used to advantage in providing for traffic between the shorter haul points; that is, those in the same region and, in some cases, in adjacent regions.

The detailed study of the plans outlined above, taking into account the relative transmission capabilities of the circuits derived under each method and also the relative economies involved, indicated that the most practicable plan would be that of making use of carrier telephone facilities for the longer circuits.

The results of the studies concerning the most desirable construction methods indicated the necessity of employing the best grade of outside plant facilities and wire arrangements, in order to obtain suitable transmission results. As it appeared that ultimately it would be desirable to develop the trans-Canada system on a carrier basis, at least until such time as toll cable would be warranted, and that a maximum number of carrier systems would therefore be required, it was found economical to construct the proposed facilities on the new non-phantomed arrangement. This method involves the abandonment of the phantoms and the spacing of the wires of each pair only eight inches apart. Material benefits in the form of cross-talk and noise reductions are possible with this type of construction. The use of special, improved insulators was also found to be of advantage, in that they would reduce the variations in attenuation under different weather conditions and would thus tend materially to improve the over-all stability of the circuits. This factor is of special importance at carrier frequencies where the variation in attenuation under different weather conditions may be appreciable with the normal types of toll line insulation. The use of the non-phantomed layout of course also indicated the desirability of special transposition arrangements which would provide for the maximum application of carrier facilities.

## Survey of Existing Routes

In order to determine the most advantageous routes for these circuits, a comprehensive survey of existing facilities was undertaken. It was necessary to ascertain the most suitable points in each province to be connected to this network and then by means of the data supplied by the survey to determine the most advantageous routes between these points.

The principal factors receiving consideration in this connection were the physical conditions of existing pole lines, the directness of the route between the particular points, the possibility of obtaining suitable locations of repeater points, the expense of necessary changes to the pole line and the existing circuits on the pole line in order to render it capable of long haul circuits. The determination of the condition of the various sections of the existing open-wire leads is normally made on the basis of a pole line inspection. The results of this inspection would indicate those portions of the route which would be suitable without an appreciable amount of reconditioning and would also determine those sections which might require strengthening or replacement due to poor condition, lack of uniformity or susceptibility to interference from power exposures, fire hazards or other external influences. A valuable factor in this survey work would be the possibility of scheduling the various construction items so that the work could be properly coordinated with the provision of the facilities. With the results of this survey and the knowledge of the wire loads to be carried, requirements for the size and character of the poles for the different sections could be determined, having in mind also the relative exposure to weather conditions and the factors of safety desired.

In order to obtain adequate limitation of cross-talk between carrier channels, it is essential to maintain the spacing between successive transposition poles within close limits. This requires an accurate survey of the pole line in order to determine the precise location of each pole.

A further important engineering item is the location of the various repeater points for the carrier-frequency, voice-frequency, and d-c. telegraph facilities. These points are determined by a study of certain transmission features of the circuits, the principal effects receiving consideration being the attenuation, noise, cross-talk and echoes.

Fig. 3—Proposed Route Trans-Canada Toll System showing Alternate Routes

Other factors, such as the desirability of having repeater points at locations which would be readily accessible, where adequate personnel could be obtained and where the facilities terminated or branched off to other routes, were considered. As the requirements for the location of the repeaters for carrier telephone operation are in general more strict than for voice frequency operation, the selection was made so as to provide the most satisfactory carrier layout. Coordination was then made with the indicated theoretical voice-frequency repeater points. In one or two instances this required the addition of voice frequency repeaters where they would normally not be required.

The matter of alternative routes in case of failure of a particular link was also the subject of considerable study. In some sections only one Canadian route was available; this was the case in the section between North Bay and Winnipeg. (In all cases there was a possibility of routing the calls via United States points during temporary failures due to storm conditions).

The map shown in Fig. 3 shows the route chosen and the proposed alternative routes.

## Transmission Maintenance

Due to the greater amounts of apparatus and plant facilities involved and the importance of the greater

inherent transmission variations of very long telephone circuits, the transmission maintenance of suitable over-all transmission standards requires relatively more attention than with shorter transmission systems. In order to provide adequately for these features and to assure the highest degree of efficiency and cooperation in the operation and supervision of these facilities, an extensive investigation was made of the various factors involved, and suitable procedures and arrangements planned accordingly. This investigation included among others, consideration of the following points:

1. The formulation and adoption of uniform transmission maintenance practises.
2. The allocation of responsibility for sectionalized testing and maintenance work and for over-all circuit control.
3. The organization and training of plant personnel.
4. The provision of adequate testing apparatus at all points.
5. The establishment of suitable plant communication systems for maintenance purposes.

Further consideration of the more important points in the establishment of suitable transmission maintenance arrangements are summarized in the following paragraphs:

Experience has shown the necessity of setting up rigid practises for the maintenance of transmission systems of the type proposed in this paper, and the importance of uniform treatment for the respective facilities throughout their entire length. This is of greater importance where the plant and personnel include those of different independent telephone organizations. Plans, therefore, have been made for the preparation of uniform practises which may be applied to all the regions and the establishment of suitable supervisory means for coordinating the over-all maintenance results. These practises provide for the suitable testing and maintenance of each individual part of the circuit, the individual apparatus units and the over-all circuits and systems.

The magnitude of the project and the lengths of the various circuits involved required a careful consideration of the most desirable methods of allocating the responsibilities of the testing and maintenance work so that a minimum of lost circuit time and of unsatisfactory transmission conditions would be incurred. This resulted in the division of the facilities into sectionalized units with one important office in each section designated as the control point. The personnel at this office would be responsible for and control the maintenance work necessary on the toll plant within the limits of its section length. An arrangement of this nature should, in general, simplify the maintenance problem and, furthermore, it would have the advantage of concentrating the supervisory personnel in a limited number of points. In addition, in order to supervise properly the over-all circuit performance, it was found desirable to designate certain of the important terminal offices as master control points. These offices would have the general responsibility of supervising the maintenance of the over-all circuits and would cooperate with the individual section control points in this work.

The necessity for uniformity in the transmission maintenance of the various circuits indicated the desirability of the adoption of arrangements whereby the operating personnel could be suitably trained in an understanding of their responsibilities and in the uniform interpretation and application of maintenance practises. In this connection, consideration has been given to the practicability of regional training courses for carrying out the necessary training work.

The maintenance of satisfactory over-all transmission standards requires the provision at all important points, and particularly at the control points of suitable types of transmission testing apparatus and testboard facilities. The apparatus provided must be suitable for testing quickly the line circuits and transmission systems involved, as well as the individual apparatus units; and the arrangement of the testboard facilities must be such as to allow easy access to the line circuits themselves, or the isolation of the line circuits from the office equipment.

In order to furnish suitable test communication facilities for the use of the plant forces between the control points as well as between these points and the intermediate repeater offices, it will be necessary to provide a special communication system which will allow the various control points to intercommunicate within the range over which they exercise control. A telephone typewriter system with selective control and signaling has been planned as the basic communication system for this purpose.

Another important feature in the provision of suitable testing facilities and arrangements will be the provision of pilot channel equipment associated with each of the carrier telephone systems. These pilot channels will automatically maintain the relative transmission levels of the carrier systems at the intermediate repeater points and at the system terminals within specified transmission limits. A general plan of operations for maintaining the transmission efficiency of these long circuits has been prepared for the consideration of the telephone organizations involved. It is, of course, evident that the success of an undertaking of this magnitude and importance will require the close cooperation of all the systems concerned, and their combined efforts, all directed toward the one accomplishment, that is, the provision of the best grade of telephone service. Up to the present time the progress in the project has been largely the result of the efforts of the Telephone Association of Canada, and it is anticipated that through its continued effort and guidance, this project may be successfully completed and enlarged as future conditions require.

# Two-Way Television

## Part I—Image Transmission System

BY HERBERT E. IVES,[1] FRANK GRAY,[1] and M. W. BALDWIN[1]

Fellow, A. I. E. E. Non-member Non-member

*Synopsis.—A two-way television system, in combination with a telephone circuit, has been developed and demonstrated and is now in use between the Bell Telephone Laboratories, at 463 West Street, and the American Telephone and Telegraph Company, 195 Broadway. With this system two people can both see and talk to each other. It consists in principle of two television systems of the sort described to the Institute in 1927. Scanning is by the beam method, using disks containing 72 holes, in place of 50 as heretofore. Blue light, to which the photoelectric cells are quite sensitive, is used for scanning, with a resultant minimizing of glare to the eyes. Water-cooled neon lamps are employed to give an image bright enough to be seen without interference from the scanning beam. A frequency band of 40,000 cycles width is required for each of the two television circuits. Synchronization is effected by transmission of a 1275-cycle alternating current controlling special synchronous motors rotating 18 times per second. Speech transmission is by microphone and loud speaker concealed in the television booth so that no telephone instrument interferes with the view of the face.*

* * * * *

### Introduction

DURING the past few years, since the physical possibility of television has been established, the chief problems which have received attention have been those of one-way transmission. In particular, the experimental work in radio television has had for its principal goal the broadcasting of television images, which is inherently transmission in one direction. At the time of the initial demonstration of television at Bell Telephone Laboratories in 1927,[2] one part of the demonstration consisted of the transmission to New York of the image of a speaker in Washington simultaneously with the carrying on of a two-way telephone conversation. At that time it was stated that two-way television as a complete adjunct to a two-way telephone conversation was a later possibility. It is the purpose of this paper to describe a two-way television system now set up and in operation between the main offices of the American Telephone and Telegraph Company at 195 Broadway and the Bell Telephone Laboratories at 463 West Street, New York. In principle this consists of two complete television transmitting and receiving sets of the sort used in the 1927 one-way television demonstration. In realizing this duplication of apparatus, however, a number of characteristic special problems arise, and the paper deals chiefly with matters peculiar to two-way as contrasted with one-way television.

### Physical Arrangement and Operation

The detailed description of the optical and electrical elements of the two-way television system will be more readily grasped if it is preceded by an account of the general arrangement of the parts and of the method of operation of the system from the standpoint of the user.

The physical arrangement of the two-way television system is shown by the pictorial sketch Fig. 1, and in the illustrations Fig. 2 and Fig. 3. The terminal apparatus is largely concentrated into a booth—the television booth, similar in many respects to the familiar telephone booth,—and a pair of cabinets, which contain the scanning disks and light sources. As in the 1927 demonstration, scanning is performed by the beam method, the scanning beam being derived from an arc lamp whose light passes through a disk furnished with a spiral of holes and thence through a lens on the level of the eyes of the person being scanned. The light reflected from the person's face is picked up by a group

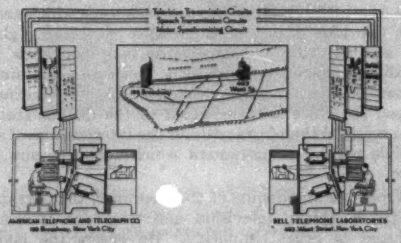


Fig. 1—Pictorial Sketch of Two-Way Television System

of photoelectric cells for subsequent amplification and transmission to the distant point. The signals received from the distant point are translated into an image by means of a neon glow lamp directly behind a second disk driven by a second motor placed below the first and inclined at a slight angle to it. The two disks, which are shown in the center cabinet of Fig. 2, are of slightly different sizes; the upper one 21 in. in diameter and the lower one 30 in. They differ from the disks used in the earlier demonstration in that in place of the 50 spirally arranged holes formerly used, they carry 72 holes whereby the amount of image detail is doubled. While with the earlier "50 line" picture recognizable

1. Members Technical Staff, Bell Telephone Laboratories, New York, N. Y.

2. *Bell System Technical Journal*, October, 1927, pp. 551-652.

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images of a face were obtainable, the aim in this new development was to reproduce the face so clearly that there would be no doubt of recognizability, and so that individual traits and expressions would be unmistakably transmitted. This doubled number of image elements necessarily requires, for the same image repetition frequency (18 per second), twice the transmission band, or approximately 40,000 cycles as against 20,000 for the 1927 image.

The only part of the television apparatus visible to

Fig. 2—The Three Major Cabinets of the Television—Telephone Apparatus

the user is the array of photoelectric cells which are in the television booth behind plates of diffusing glass. In addition to the photoelectric cells and their immediately associated amplifiers, the booth contains a concealed microphone and loud speaker. By means of these, the voice is transmitted to the distant station and received therefrom without the interposition of any visible telephone instrument which could obscure the face.

From the standpoint of the customer, the operation of the combined television and telephone system is reduced to great simplicity. He enters the booth, closes the door, seats himself in a revolving chair, swings around to face a frame through which the scanning beam reaches his face, and upon seeing the distant person, he talks in a natural tone of voice, and hears the image speak. Conversation is carried on as though across a table.

## Optical Problems

Some of the more special of the problems encountered in two-way television are primarily optical in character. The principal one is that of regulating the intensity of the scanning light and of the image which is viewed so that the eye is not annoyed by the scanning beam, or the neon lamp image rendered difficult of observation. It has been necessary for the solution of this problem to reduce the visual intensity of the scanning beam considerably below the value formerly used and to increase considerably the brightness of the neon lamp.

The method adopted consists first, in the use of a scanning light of a color to which the eye is relatively insensitive but to which photoelectric cells can be made highly sensitive. For this purpose blue light has been used, obtained by interposing a blue filter in the path of the arc light beam, and potassium photoelectric cells specially sensitized to blue light and more sensitive than those previously used have been developed. The number of these cells and their area has also been increased over those used in the earlier television apparatus so that the necessary intensity of the scanning beam is decreased.

The second half of the problem, namely that of securing a maximum intensity of the neon lamp, has been attained by the development of water-cooled lamps capable of carrying a high current. The net

Fig. 3—Interior of the Television Booth

result of the use of blue light for scanning, of more sensitive photoelectric cells, and of the high efficiency neon lamps is that the user of the apparatus is subjected only to a relatively mild blue light sweeping across his face, which he perceives merely as blue spot of light lying above the incoming image. Fig. 3 shows the interior of the television booth with the frame through which the observer sees the image of the distant person.

A second optical problem is the arrangement of the photoelectric cells required in order to obtain proper virtual illumination of the observer's face. As we have previously pointed out in discussing the beam scanning

method,[3] the photoelectric cells act as virtual light sources and may be manipulated both as to their size and position like the lights used by a portrait photographer in illuminating the face. In the present case, it is desired to have the whole face illuminated and accordingly photoelectric cells are provided to either side and above. One practical difficulty which is encountered is that eyeglasses, which often cause annoying reflections in photography are similarly operative here. For this reason, it is important that the photoelectric cells be placed as far to either side or above as possible. The banks of photoelectric cells shown in Fig. 3 are accordingly much farther removed from the axis of the booth than were the three cells used in the first demonstration. In the position which has been chosen for the cells, reflections from eyeglasses are not annoying unless the user turns his face considerably to one side or the other.

The number of cells has been so chosen as to secure a good balance of effective illumination from the three sides and it has been found desirable to partly cover the cells on one side in order to aid in the modeling of the face by the production of slight shadows in one direction.

Another optical problem is the illumination of the interior of the booth. There must, of course, be sufficient illumination for the user to locate himself, and it is also desirable that the incoming image and the scanning spot be not seen against an absolutely black background. The illumination of the booth is by orange light, to which the cells are practically insensitive, and so arranged that the walls and floor are well illuminated. In addition to the wall and floor illumination, a small light is provided on the shelf bar in front of the observer so as to cast orange light on the front wall surrounding the viewing frame. This light contributes materially to reducing the glaring effect of the scanning beam, and to the easy visibility of the incoming image.

In addition to the optical features which are visible to the person sitting in the booth, there are very necessary optical elements which have to do with the placing of the outgoing and incoming images. A practical problem which is encountered when customers of various heights use the apparatus is that the scanning beam, if fixed in its position, would strike too high or too low upon many faces. In order to direct the beam up or down as is required, a variable angle prism, consisting of two prisms arranged to rotate in opposite directions, is interposed in the path of the scanning beam. This prism, which lies directly in front of the projection lens used with the upper disk, is shown in Fig. 4 at *P*. Its rotation is controlled by a knob with a numbered dial. The exact position is determined by the operator by reference to a monitoring image which will be described below.

Another optical element, which serves two purposes, is a large convex lens lying between the receiving disk and the observing frame, shown at *L*, Fig. 4. This lens is used to magnify the incoming image to such a size that the image structure is just on the verge of visibility, under which condition the face of the distant person appears as though he were approximately 8 feet away. In addition to acting as a magnifier, this lens serves to position the incoming image to fit the height of the customer. For, by raising or lowering it by means of a knob, the operator, using the information as to the observer's height obtained from the position of the scanning beam, locates the lens so that the virtual image appears in the proper position.

### Photoelectric Cells and Associated Circuits

The photoelectric cells used in this apparatus are similar in shape to those used in the first demonstration,

Fig. 4—Optical Means for Controlling Heights of Scanning and Viewing Beams

but somewhat larger. Each cell is twenty inches long and four inches in diameter, giving it an area of approximately eighty square inches for collecting light. The anode is made in the form of a hollow glass rod wound with wire. This construction prevents the electrical oscillations that would otherwise result from mechanical vibrations of the anode. The sensitive cathode consists of a coating, covering the rear wall of the tube, of potassium sensitized with sulphur.[4] This kind of cell is considerably more sensitive than the older type of potassium-hydride cell while still having most of the sensitiveness in the blue region of the spectrum. Fig. 5 shows the response of the photoelectric cells used to the various parts of the spectrum together with the transmission of the blue filter and the brightness of the various parts of the spectrum as evaluated by the human eye. The very great efficiency of the photoelectric cells and the inefficiency of the eye to the light used are apparent.

3. *Jnl. Optical Soc. of America*, March, 1928, p. 177.

4. A. R. Olpin; *Phy. Rev.* 33, 1081, (1929).

To amplify the photoelectric current, the cells are filled with argon at a low pressure. Photoelectrons passing from the sensitive film to the anode ionize the gas atoms along their paths and thus cause a greater flow of current. The ionization of the gas does not, however, instantaneously follow sudden variations of the true photoelectric emission from the sensitive film, that is, there is a time lag in the ionization of the gas and in the disappearance of ionization. This lag results in a

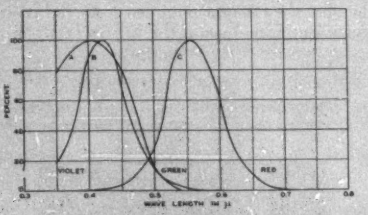


Fig. 5—*A* Relative Optical Transmission of the Blue Filter Through Which the Scanning Beam Passes

*B* Relative Sensitivity of the Photoelectric Cells to Various Parts of the Spectrum

*C* Relative Sensitivity of the Eye to Various Parts of the Spectrum

relative loss and phase shift of the high-frequency components of a television signal with respect to the low-frequency components which become serious in the wider frequency range utilized in the 72 line image. The relative loss in output from a single large photoelectric cell at high frequencies is shown in decibels by curve *A* of Fig. 6.

In the television booth, the twelve large cells mounted in the walls of the booth present an area of approximately seven square feet to collect light reflected from a

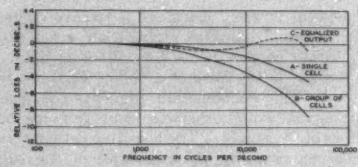


Fig. 6—Loss in Response of Photoelectric Cells at High Frequencies

subject. To secure the desired effective illumination, the cells are mounted in three groups, comprising a group of five cells in each of the two side walls of the booth and a group of two cells in the sloping front wall above the subject. The twelve cells are enclosed in a large sheet copper box, provided with doors to each group. The cells of each group are connected in parallel through the input resistance of a two stage resistance-capacity coupled amplifier similar to those previously used. This raises the level of the signal to such a point that the output of the three amplifiers may be carried through shielded leads and connected in parallel to a common amplifier.

The metal anodes and lead wires of the cells in parallel in any one group give an appreciable capacity to ground, which results in a further loss in amplitude and phase shift of the high-frequency components of the signal. The combined loss introduced by ionization of the gas in the cells and by capacity to ground is shown by curve *B* of Fig. 6. This combined loss is equalized by an interstage amplifier coupling, Fig. 7. The equalized output from the photoelectric cells is shown by curve *C*, Fig. 6.

## Two-Way Image Signal Amplifiers

The vacuum tube system used to amplify the photoelectric cell currents in two-way television is patterned closely after that used previously in one-way television, and the description here will be confined chiefly to novel features. These new features are necessary to take care of the doubled frequency band which results when the scanning is done with a 72-hole disk rather than with a 50-hole one, and to provide sufficient

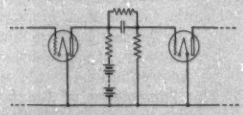

Fig. 7—Schematic of Interstage Amplifier Coupling to Equalize for the High Frequency Losses in the Photo-Electric Cells

power to operate the high intensity neon lamp which is essential to two-way television. Certain other new features have been introduced in order to simplify the apparatus and to reduce the maintenance required to keep it in good working condition.

The vacuum tubes which operate at low energy levels are the so-called "peanut" type, chosen because of their freedom from microphonic action and their low inter-electrode capacities. Protection against mechanical and acoustical interference is secured by mounting these tubes in balsa wood cylinders which are loaded with lead rings and cushioned in sponge rubber. The tubes are electrically connected in cascade by means of resistance-capacity coupling, so that the whole amplifier system is stable over long periods of time and is also uniformly efficient over the required frequency band. Grid bias for the small tubes is supplied by the potential drop across a resistance in the filament circuit; the power requirements for the low level stages of the amplifier are filled by 6-volt filament batteries and 135-volt plate batteries, all located externally where they can be checked and replaced conveniently.

The amplifier system is divided into units of convenient size as shown in Fig. 8. Associated with each of

the three banks of photoelectric cells is a two-stage unit known as the photoelectric cell amplifier; the combined output of these three units is carried to a four-stage unit known as the intermediate amplifier, output of which is of sufficiently high level to be carried outside the copper cell cabinet to the three-stage transmitting power amplifier on the relay rack. A four-stage unit known as the receiving power amplifier is also on the relay rack, and serves to amplify the signal from the other station to a level which will yield an image of satisfactory contrast when it is translated into a light variation by means of the neon lamp. The final stage of this amplifier consists of two special 250-watt tubes in parallel. These large tubes are used because their plate impedance is of the same order of magnitude as the impedance of the neon lamp, and because they will supply the necessary direct current to the neon lamp without overheating.

Fig. 8 also shows what may be termed a voltage level diagram for the whole system. Ordinates on this

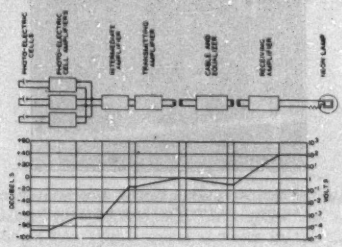


Fig. 8—Schematic Diagram of the Complete Television Channel and the Relative Voltage Levels of the Signal Along the Channel

diagram represent voltage amplitudes at the junctions between units of the system, and by themselves tell nothing at all about the power conditions in the system, since the impedances are not specified. It is interesting to observe that the signal voltage produced by the three banks of photoelectric cells has an effective value of about 50 microvolts across the 50,000 ohm input resistance; the transmitting amplifier delivers about 1 volt to the 125 ohm cable circuit, and the receiving amplifier delivers about 100 volts to the 1000 ohm neon lamp circuit. The signal current through the neon lamp has an effective value about a thousand million times greater than that of the current variation in one of the photoelectric cells.

The most outstanding contribution to the development of television amplifiers is the combination of output and input transformers whose transmission characteristics are shown in Fig. 9, *A*, and whose impedance characteristics are shown in Fig. 9, *B* and *C*. The exceptionally wide frequency range, corresponding to a ratio of limiting frequencies of 5000 to 1, transmitted by these transformers is due largely to the use of chrome permalloy, a recently developed core material having very high permeability. The improved characteristics are also the result of refinements in design which involve the use of adjusted capacities and resistances to control the characteristics at the higher frequencies. Due to the fact that each terminated transformer looks like a resistance of 125 ohms over practically the entire frequency range of the image signal, it makes no difference in the form of the over-all voltage amplification characteristic of the circuit whether the transformers are connected together

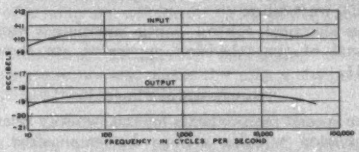


Fig. 9a—Voltage Ratio Characteristics of W-7879 Input Transformer and W-7880 Output Transformers, Each Connected Between Its Rated Impedance

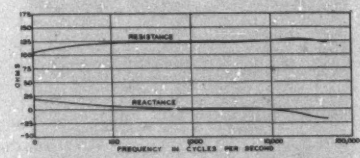


Fig. 9b—Impedance Characteristic of W-7880 Output Transformer with 1765 Ohm Resistance Load

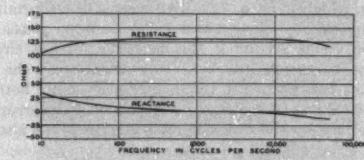


Fig. 9c—Impedance Characteristic of W-7879 Input Transformer with 20 Mmf. Capacity Load

directly or by means of the equalized cable circuit whose characteristic is shown in Fig. 10. Advantage of this circumstance is taken in providing switching means whereby each transmitting amplifier may be connected through a resistance pad to its local receiving amplifier, enabling a person to see his own image in the television booth, which is a convenience in making apparatus adjustments.

Transformers of this type must be carefully protected against magnetizing forces which might cause polarization of the core material. In order to keep the plate current of the final tube of the transmitting power amplifier from flowing through the winding of the out-

put transformer, the transformer winding is shunted by a battery and a resistance in series. The resistance is made high, so that the transmission loss due to bridging it across the circuit is small; the voltage of the battery is made equal to the potential drop across the resistance due to the plate current of the tube, so that the average voltage across both the battery and resistance, and hence across the transformer winding, is zero.

A vacuum thermocouple is connected in series with the line winding of the output transformer, serving as a level indicator for the transmitting amplifier. The level indicator for the receiving amplifier is a vacuum thermocouple in series with the grid resistance of the two 250-watt tubes.

The electrical control panels associated with one terminal of the television apparatus are shown in Fig. 11.

### Transmission Circuits

Two special requirements for the two-way television transmission circuits are to be emphasized. The first, which has already been referred to, is the wide frequency transmission band, from 18 cycles to 40,000

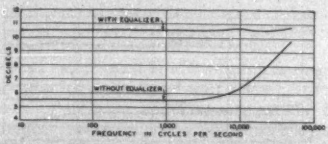


Fig. 10—Insertion Loss Characteristic of Cable Circuits which Transmit the Image Signal, Measured Between 125 Ohm Resistances

cycles, which must have a high degree of uniformity of transmission efficiency and freedom from phase distortion. The second is the necessity for *two* circuits for the television images. This arises from the fact that the two parties to the conversation must both see and be seen at all times. There can be no interruption of one face by the other, comparable with the alternation of the role of speaker and listener in telephony which permits the use of a single circuit for ordinary speech communication.

The terminal stations of the two-way television system are connected by eight underground circuits, each consisting of 13,032 ft. of No. 19 gage and 390 ft. of No. 22 gage non-loaded cable. Two circuits are used for transmitting the image signals, two for the accompanying speech, one for the synchronizing current, two are used as order wires, and one is kept as a spare. All of the circuits have identical transmission characteristics, but equalization is necessary only on the two which carry the image signals. Fig. 10 shows the insertion loss characteristic of each circuit, and also shows the insertion loss characteristic of the image circuits when the image line equalizers are included.

Although the distance between the stations is small the requirements of the television system from the standpoint of freedom from noise and other interference require that considerable care be given to the selection of the cable circuits used. All terminal connections are made through balanced repeating coils or transformers so that all of the circuits are balanced to ground. Also, in order to insure that the crosstalk between the various channels be unnoticeable the terminal equipment is so adjusted that approximately the same amount of power is transmitted by each circuit.

Fig. 11—Control Apparatus Panels Associated with One Terminal of the Television Apparatus

### Neon Lamps and Associated Circuits

After amplification, the received television signal is impressed on the grids of two power tubes in parallel to

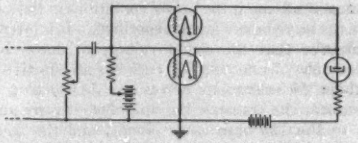


Fig. 12—Schematic of Neon Lamp Circuit

furnish current for a neon receiving lamp. The terminal lamp circuit is shown in Fig. 12. The grid bias of the two power tubes is varied by the operator to control the d-c. plate current, which replaces the original d-c. signal component suppressed at the sending end. The quality of the reproduced image is determined by the operator's control over the relative levels of the incoming a-c. signal and the restored d-c. current.

The television current from the power tubes is translated back into light by a water-cooled neon

lamp designed to operate on a large current. The structural details of the lamp are shown in Fig. 13. Heavy metal bands attach the rectangular cathode to a hollow glass stem occupying the central portion of the tube. Water from a small circulating pump flows continuously through the glass stem and cools the cathode by thermal conduction through the metal bands. To reduce sputtering of the cathode and consequent blackening of the glass walls, the front surface of the cathode is coated with beryllium. This

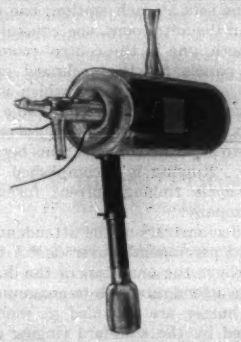

Fig. 13—Water-Cooled Neon Lamp

metal resists the disintegrating action of the glow discharge very satisfactorily and gives the lamp a prolonged life. Other metal surfaces in the tube are shielded from the discharge by mica plates; and the discharge passes from the frame-like anode to the front surface of the cathode, covering it with a brilliant layer of uniform cathode glow.

Pure neon in a plate type of lamp gives a very inferior reproduction of an image. The impedance of the lamp is relatively high and comprises both a resistance and a reactance which vary with frequency. The variation in the impedance causes a relative loss in the frequency components of the signal and also introduces spurious phase shifts. In addition, pure neon has an after-glow; the gas continues to glow for an appreciable time after current ceases to flow. This after-glow casts spurious bands of illumination out to one side of the brighter image details.

A small amount of hydrogen in the neon prevents such an after-glow; and at the same time improves the circuit characteristics of the lamp. The total impedance of the lamp is lower, making it a less influential part of the lamp circuit; and the resistance and reactance vary in such a manner that the phase shift is more nearly proportional to frequency, (a phase shift proportional to frequency causes no distortion in the reproduction of an image). Other active gases may be used with the neon to improve the operation of a television lamp, but one or two per cent of hydrogen is most satisfactory.

Since hydrogen is absorbed by the electrodes in a glow discharge, it slowly disappears from the neon during operation of the lamp. For this reason the lamp is provided with a small side reservoir of hydrogen. The lamp and the reservoir carry porous plugs immersed in a pool of mercury; and a flexible rubber connection permits the two plugs to be brought into contact at will. Minute quantities of hydrogen may be introduced into the lamp by simply bringing the two plugs into contact for a short time.

Even with this improvement the circuit characteristics of a lamp are not ideal. With power tubes it is usually desirable to include a fixed resistance in series with the lamp to prevent semi-arcing conditions. Such a resistance also makes the lamp a less influential fraction of the total circuit impedance.

### Optical Monitoring Systems

In order to insure that the incoming and outgoing images are properly positioned, no matter what the

Fig. 14—Sending and Receiving Disks, with Neon Lamps and Optical Arrangements for Image Monitoring

stature of the person sitting in the booth, and that the images shall be of proper quality, it is essential to have some means for the operator to observe and adjust these images. The optical monitoring system provided consists of an outgoing monitor and means for adjusting the scanning beam, and an incoming monitor and means for adjusting the position of the viewing lens to suit the height of the sitter.

The outgoing monitoring system is the same as that used in the one-way television apparatus which has already been described. A small neon lamp (Fig. 14, at bottom of top disk) is placed behind the sending disk but displaced several frames from the aperture

through which the arc lamp beam passes. By continuing the spiral of holes part way around it is possible to see the complete image from the auxiliary neon lamp, to which the outgoing signals are also supplied. In order to see this monitoring lamp from the operator's position, a right-angle prism and a magnifying lens are placed in front of the disk and the image is observed through an opening in the side of the motor cabinet. The task of the operator is to direct the scanning beam up or down by means of the variable angle prism until the face of the person in the booth is centrally located. This adjustment is facilitated by a wire which passes across the image and is placed at the height at which the customer's eyes should appear.

The height of the observer's eyes is an indication of the position which should be taken by the large magnifying lens *L*, and the operator, after having properly placed the scanning beam, reads the scale on the variable angle prism dial, and then sets the magnifying lens by turning its controlling knob to the same number. When both adjustments are complete, the person in the booth will not only be properly scanned but will be in the best position to see the image.

In order to monitor the incoming image, an optical arrangement is adopted by means of which light from the water-cooled neon lamp is taken off at the side and reflected through the disk and thence reflected again, as shown in Fig. 14, (top of bottom disk), through a second, lower, observing hole on the side of the motor cabinet. Because of the small area of the side view of the neon lamp, a lens system is inserted which focuses the image of the lamp at the place to be occupied by the pupil of the operator's eye. When the eye is properly placed, the whole of the lens area is seen filled with light and exhibits the incoming image.

In addition to the monitoring means just described, an additional view of the incoming image is provided by means of a 45-deg. mirror which is carried on the back of a movable shutter which is shown at *S* in Fig. 4. This shutter carries an illuminated sign on the side turned to the customer with the inscription, "Watch this space for television image." The shutter with its sign covers the image until the adjustments just described are made, when it is dropped out of sight. While it is in place, the operator is provided with an additional monitoring image reflected from the 45-deg. mirror. This view is, of course, in every respect identical with that which the customer sees.

The function of the incoming monitoring system is primarily to enable the operator to set the electrical controls to give the proper quality of image. He also has another task which is that of properly framing the image. This he can do by turning the framing handle, which is described elsewhere, while watching the image from the mirror. The framing operation is preferably performed not on a person sitting in the booth but upon some suitable object such as a mirror located upon the rear door of the booth. In order to make this framing adjustment, the operators at the two terminals set their scanning beam dials to predetermined positions such that the scanning beams place the framing mirrors at the lower edge of the scanning rectangles; the phases of the incoming disks are then shifted until the images of the mirrors are seen properly located in the incoming monitors.

## Signaling System

In order to coordinate operations at the two terminal stations, an order wire system is provided. There are four telephone sets at each station; one on the attendant's desk in the ante-room, one concealed inside the television booth, one in the control room, and one at the control panels for the technical operator, who operates the small switchboard which is part of the system. Two of the underground cable circuits connect the two switchboards, so that there may be not more than two separate conversations between stations at one time. Ringing is accomplished by means of standard 20-cycle ringing current furnished by the telephone company.

During a demonstration, the attendants' telephones are connected permanently over one of the cable circuits. To relieve the operators of the duty of ringing each time the attendants wish to communicate, a push button and buzzer are provided at each attendant's desk, operated by the standard ringing currents simplexed on the synchronizing circuit. This arrangement leaves the operators free to manipulate the television apparatus.

The two order wire circuits are each simplexed to provide two additional circuits which operate signal lamps indicating to both operators when either chair in the television booths is occupied and turned in position.

## Conclusion

The primary objects in developing and installing the two-way television system have been two. The first was to obtain information on the value of the addition of sight to sound in person to person communication over considerable distances. The second was to learn the nature of the apparatus and operating problems which are involved in a complete television-telephone service. While the installation is entirely experimental, it is being maintained in practically continuous operation for demonstration to employees and guests of the telephone company, and interesting data are being gathered on all aspects of the problem.

It may be said without fear of contradiction that the pleasure and satisfaction of a telephone conversation are enhanced by the ability of the participants to see each other. This is, of course, more evident where there is a strong emotional factor, as in the case of close friends or members of the same family, particularly if these have not been seen for some time.

Were the television apparatus and required line facilities of extreme simplicity and cheapness it would be

sate to predict a demand for its early use. At the present time, however, the terminal apparatus is complex and bulky, and requires the services of trained engineers to maintain and operate it. In addition to the cost of the terminal apparatus there is the unescapable item of a many-fold greater transmission channel cost. Because of the wide transmission bands required for the television images, the inherent necessity for a television channel in each direction, and the extra channels for synchronizing and signaling, the total transmission facilities used in this demonstration are those which could, according to current practise, carry about fifteen ordinary telephone conversations. It is to be expected, of course, that development work will result in some increase in the efficiency of the transmitting channels and in simplifications of the terminal apparatus. It is conceivable, therefore, that our present conception of the cost of the whole system may ultimately be materially changed.

## PART II—SYNCHRONIZATION SYSTEM

By H. M. Stoller[5]

Member, A. I. E. E.

### General Requirements

Television transmission requires not only synchronization of the transmitting and receiving equipment but

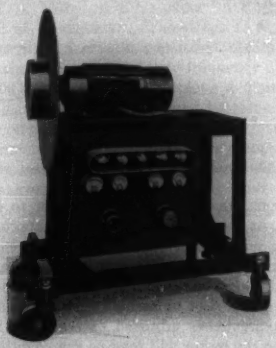

Fig. 15—New Television Motor and Vacuum Tube Control Circuit

such synchronization must be held to a narrow phase angle so that the scanning disks at the transmitting and receiving end will never depart more than a small fraction of a picture frame width from the desired position.[6] In the 1927 demonstration, 2125-cycle synchronous motors were employed with supplementary d-c. motors to facilitate starting. This plan required the use of vacuum tube amplifiers of large size in order to supply sufficient power to the synchronous motors.

Such high-frequency synchronous motors, however, are inefficient and expensive, so that when designing the new system it was desired to solve the problem of synchronization with simpler and cheaper equipment and in a manner which would require less attention in starting. It was particularly desired to employ a motor which could be operated directly from the 110-

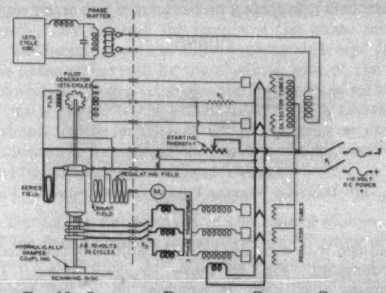


Fig. 16—Schematic Diagram of Control Circuit

volt lighting circuit without any auxiliary *A*, *B*, or *C* batteries for the control equipment.

### Description of Motor

Fig. 15 shows a photograph of the new television motor and its associated control equipment.

The motor is a four-pole, compound-wound, d-c. motor with the following special features added:

1. An auxiliary regulating field, the current through which is controlled by the vacuum tube regulator.
2. A damping winding on the face of the field poles to prevent the field flux from shifting (Fig. 17).
3. Three slip rings are provided at points 120 electrical degrees apart for furnishing three-phase power to supply plate and filament voltage for the regulating circuit.
4. A pilot generator of the inductor type is built into the motor frame and delivers a frequency proportional to the motor speed for actuating the control circuit.
5. A hydraulically damped coupling is provided between the motor shaft and the scanning disk. (Fig. 18).

The motor frame was made from a standard 36 tooth stator punching by cutting out three teeth per pole, thus forming four polar areas of six teeth each. The shunt, series, and regulating fields enclose the entire polar areas. The damping winding consists of insulated closed turns of heavy copper wire distributed over the pole faces in the slots as shown in Fig. 17. It will be noted that this damping winding has no effect upon the flux through the poles as long as the flux density over the polar surface does not shift. In other words, the damping winding permits the total flux of the motor to

5. Apparatus Development Dept., Bell Telephone Laboratories, New York, N. Y.

6. These requirements are more fully discussed in a previous paper of the A. I. E. E. Journal, Vol. 46, p. 940, 1927.

increase or decrease as required by the regulating circuit but will oppose any tendency of the flux to shift back and forth across the pole face. As will be explained later on, this feature is essential in order to prevent hunting or instability of the image.

The hydraulically damped coupling between the motor shaft and the scanning disk is also essential in order to avoid hunting. It employs flexible metal bellows filled with oil and connected by a small pipe

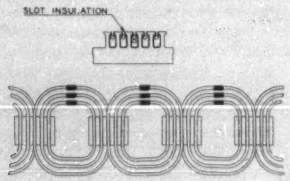


Fig. 17—Damping Winding Preventing Shifting of Field Flux

equipped with a needle valve for adjusting the amount of damping. Fig. 18 shows its construction. The scanning disk itself is centered on a ball bearing which allows the disk to rotate with respect to the shaft within approximately ± 5 degrees mechanical movement.

## Control Circuit

Fig. 16 shows a schematic diagram of the control circuit. When the motor is operating at full speed the

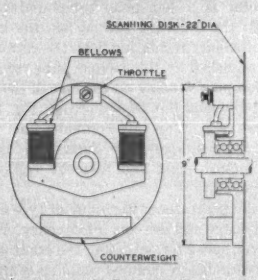


Fig. 18—Hydraulically Damped Coupling to Prevent Hunting of Motor

pilot generator delivers approximately 1 watt of power at 300 volts, 1275 cycles to the plates of a pair of push-pull detector tubes. The grids of these tubes are supplied with an e. m. f. of the same frequency from an oscillator or other source of power having a sufficiently constant frequency. The amount of power required for this grid circuit is only a few thousandths of a watt. The detector tubes rectify the plate voltage producing a potential drop across the coupling resistance $R_1$. If the plate and grid voltages are in phase, so that the grids of the tubes are positive at the same instant that the plates are positive, the plate current will be a maximum. If the grid voltage is negative when the plate voltage is positive the plate current is practically zero, so that the magnitude of this current is a function of the phase relationship between the grid and plate voltages as shown in Fig. 19.

The voltage drop across the coupling resistance $R_1$ is applied to the grid circuits of three regulator tubes. These tubes derive their plate voltage supply from a three-phase transformer fed with power from the three slip rings provided on the motor. These tubes act as a rectifier whose output is controlled by the potential impressed upon the grids from the coupling resistance $R_1$. The current of the regulator tubes is passed through the regulating field provided on the motor. This field is in a direction to aid the shunt field and series fields of the motor.

The operation of the circuit is as follows: In starting switch $S_1$ is closed which applies direct current to the shunt field and armature circuits of the motor. The motor accelerates as an ordinary compound wound motor. Switch $S_2$ is then closed applying three-phase

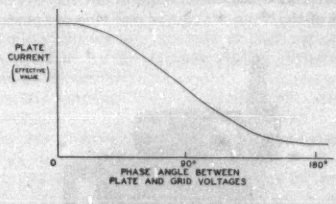


Fig. 19—Phase Detector Tube Characteristic

power from the slip rings of the motor to the transformer. As the speed of the motor approaches the operating point, the beat frequency between the pilot generator and the oscillator will cause beats in the current through the regulating field which are visible on the meter $M_1$. Let us assume that the field rheostat has been previously adjusted so that with the shunt field alone the motor will tend to run slightly over the desired operating speed. When the exact operating speed is obtained, the beat frequency in the regulating field will be zero and as the motor tends to accelerate, the phase relationship between the pilot generator and the oscillator will reach a point tending to give maximum strength to the regulating field. When this point is reached, the acceleration of the motor will be checked by the increased field and the speed will tend to fall until the phase of the pilot generator with respect to the oscillator has shifted sufficiently so that the regulating field current is reduced to an equilibrium value, after which the motor continues to run at constant speed in accordance with the frequency of the oscillator.

Operating tests on the circuit show that the motor will hold in step over line voltage ranges from 100 to 125 volts and will be self-synchronizing over somewhat narrower voltage limits. Thus, under normal conditions all that is necessary from an operating standpoint is to close the switch and wait for the motor to pull into step.

### Control Oscillator

The control oscillator is a standard type of vacuum tube oscillator having a frequency precision of the order of 1 part in 1000, when delivering the negligible output of 0.005 watt to the grid circuit of the detector tubes. This frequency is delivered directly to the motor circuits at one end of the line and is transmitted over a separate cable pair to the control circuits at the other end of the line. It was found that the detector tubes would operate successfully over a considerable variation in power level, provided the minimum oscillator output was sufficient.

An interesting alternative method was developed in which the synchronizing channel between stations may be omitted entirely, but this method was not used in the present system as the additional cost was not justified. The method, however, is described as it may prove of value if television transmission over long distances is considered.

Mr. W. A. Marrison in his paper "A High Precision Standard of Frequency," *Proceedings I. R. E.*, July, 1929, described a crystal controlled oscillator which would maintain a precision as to frequency of 1 part in 10,000,000. This oscillator employs a quartz crystal as its primary means of control and by means of secondary circuits, the natural period of the crystal, which is approximately 100,000 cycles, may be stepped down to lower frequencies which are more convenient for such purposes as motor control.

By this means, a frequency of the desired value may be obtained with a precision so great that the speed of the scanning disks under control of the above described circuit will be so nearly perfect that no synchronization channel at all is required. For example, if the period of observation of the television image is 5 minutes, the scanning disk will make 5300 revolutions when operating at a speed of 1060 rev. per min. Assuming a precision of control of 1 part in 10,000,000, the maximum error during the 5 minute interval will be 5300 divided by 10,000,000 or about 1/2000 of 1 revolution. Expressed in degrees on the periphery of the disk, this is equivalent to approximately 1/6 of 1 degree or since the width of the television image with 72 holes in the scanning disk is 5 degrees, the image will drift 1/30 of a frame width during the 5 minute interval If the speed of the scanning disk at the other end drifts an equal amount in the opposite direction, the displacement of the television image will be only 1/15 of a frame width, which is a tolerable amount of drift.

From a practical standpoint, however, it is apparent that the additional cost of very precise independent oscillators would be greater than the cost of providing the synchronization channel, except possibly for transmission over long distances.

### Framing

Referring to Fig. 16, it will be noted that a phase shifter is provided between the oscillator and the input terminals to the control circuit. This phase shifter is designed with a split phase primary member producing a rotating magnetic field. The secondary member is single phase and is mounted on a shaft provided with a handle. By rotating the handle of the phase shifter in the desired direction, the frequency delivered from the phase shifter will be the algebraic sum of the frequencies of the oscillator plus the frequency of rotation of the armature of the phase shifter. It is, therefore, a simple matter for the operator at the receiving end to momentarily increase or decrease the control frequency and thus bring the picture into frame.

### Conclusion

During the development of the control system, one of the first difficulties encountered was hunting of the controlled motor. The problem of hunting, of course, becomes more difficult of solution the greater the precision of speed regulation desired and the greater the moment of inertia of the load connected to the motor, the latter statement applying only to controlled systems of the synchronous type. Since the moment of inertia of the scanning disk is large relative to that of the motor armature, it is seen that the conditions for securing stable rotation would be unfavorable in both the above mentioned respects if the scanning disk were mounted directly on the motor shaft. The hydraulically damped type of coupling above described was, therefore, inserted between the motor shaft and the scanning disk. It was found, however, that hunting still occurred. A further analysis of the problem showed that the axis of the field flux of the motor was shifting back and forth across the pole faces. The damping winding shown in Fig. 18 was then added with a marked improvement. It was also observed that a strong series field on the motor assisted in securing stability and it was, in fact, necessary to employ all three expedients to secure satisfactory performance. In the system as finally developed the television image, if disturbed by a momentary load such as the pressure of the hand against the disk, would come back to rest within approximately one second, there being two oscillations during this interval. In actual operation, it was found that the normal fluctuations in line voltage occurring on the commercial power supply produced no transients of sufficient magnitude to cause any objectional instability in the received image.

In conclusion, it should be pointed out that this type of control system could be equally well employed with larger motors for other applications requiring precise speed regulation. While the circuit described

is applicable only to a d-c. motor, a similar system may be applied to an a-c. motor substituting a saturating reactor in place of the regulating field winding in the manner described by the author in his paper[7] presented before the Society of Motion Picture Engineers, September, 1928.

## PART III—SOUND TRANSMISSION SYSTEM

By D. G. Blattner[8] and L. G. Bostwick[8]
Associate, A. I. E. E. Non-member

From the very beginning the ultimate goal of the communication engineer has been to annihilate distance and establish between remotely located parties the effect of face to face communication. Means for accomplishing this goal must of course involve the reproduction at some particular point of both visual and aural effects originated at another and it goes without saying that the two types of effects must be mutually coordinated if the result is to be of the best.

In the design of a sound transmission system to be correlated with a visual system, the requirements as to perfection of results desired are no more stringent than for other high grade sound reproducing systems[9] that have been described in the literature from time to time. Rather in this case the peculiarities of the system are largely those incidental to the adaptation of old technique to meet new conditions.

The principal limitation of the sound system imposed by the visual system is that the use be relieved of all necessity of holding a telephone in close proximity to the head. Such a limitation is highly desirable in order to secure the most natural pose of the features and the most satisfactory scanning. Obviously, the best way of meeting this limitation is by the use of telephone instruments of the type adapted for picking up and reproducing sounds at a distance. The use of such instruments has the further advantage that they can be located near the vision screen and so reproduce any peculiarities in tone quality that would result if the speaker were actually located at the position of the image. Of course, the sharpness of this perspective effect obtained is influenced by the loudness of both the original and the reproduced sounds but the matter of location of instruments is also very important.

It would thus seem that the use of distant pick-up and distant projecting instruments offers certain rather fundamental advantages but it is also true that it presents certain other disadvantages. One of the disadvantages is that the distant pick-up microphone gives less output than a close-up device because of the reduced sound pressure on the diaphram; also a sound producing device to give suitable reception at a distance must be supplied with a higher transmission level than would a close-up instrument. It thus becomes necessary to provide for obtaining greater gain in transmission and greater electrical power capacity than would be required were the instruments held close to the head. The use of the more elaborate transmission facilities is in itself disadvantageous but it also tends to increase the feed-back from the loud speaker to the microphone, also the effect of any noise at the microphone position or at the listening position tends to interfere more seriously with the successful conduct of conversation. In the design of the two-way television system under discussion it was felt that it would be possible to overcome these technical objections to the distant type instruments and that the advantages mentioned would justify any measures necessary to do so.

The question of instruments was solved by the use of the Western Electric 394 condenser type transmitter[10] and a dynamic direct radiator loud speaker. The transmitter is one of the type generally used for phonograph and sound picture recording and for other purposes where good quality, high stability, and quietness of operation are essential. The direct radiator type of loud speaker was used instead of the usual horn type because of the limited mounting space available. It consists of a dynamic structure with a rigid duralumin diaphram about 3 in. in diameter flexibly supported at the edge and radiating directly into free air. While such a structure is not highly efficient and permits of only a small sound power output these considerations are of secondary importance in this case. The instruments were located in the front wall of the booth about 2 ft. from the position of the user and adjacent to the viewing screen in order to enhance the perspective as described above, the microphone being above and the loud speaker below as shown in Fig. 20. These instruments, in this particular case, were connected into a 4-wire circuit although in certain cases it might be desirable to use a 2-wire circuit. Such a change would of course be entirely feasible. The remainder of the apparatus used consisted of amplifiers located at the transmitting end of each channel and an attenuator at the receiving end, the two ends being connected by means of a loop of approximately 3 miles of non-loaded non-equalized cable. The amplifiers and the attenuators were each readily adjustable so that the sounds of different speakers could be reproduced at the optimum loudness. Observation of the performance of the system was made possible in each of the control rooms by means of a monitoring head type receiver bridged across the mid-point of an attenuator tying the two channels together. The attenuation used in the monitoring circuit was such as to give no audible feed-back in either booth. The results obtained with this step-up were considered satisfactory from the standpoint of

7. S. M. P. E. *Transactions*, Vol. 12, No. 35, p. 696.

8. Telephone Engineers, Bell Telephone Laboratories, New York, N. Y.

9. *Public Address Systems*, by J. P. Maxfield and I. W. Green in A. I. E. E., Feb. 14, 1923; *High Quality Recording and Reproducing of Music and Speech*, by J. P. Maxfield and H. C. Harrison, A. I. E. E., Feb. 1926.

10. E. C. Wente in *Physical Review*, May 1922.

both volume and quality. Ready recognition of familiar voices and the association of the source of the reproduced sounds with the image were the usual occurrence. Fig. 21 shows in block form the complete circuit set-up and Fig. 22 shows the combined response frequency characteristic of the microphone, amplifier, and loud speaker. The ordinates of this curve represent variations in sound pressure from the loud speaker for constant pressure on the transmitter diaphram. These data were obtained with the loud speaker located in a heavily damped room. The measurements were made on the sound axis at a distance of 2 ft., representing the relative position of the observer under conditions of actual use.

In setting up such a system the chief consideration is in regard to the acoustic feed-back from the loud

Fig. 20—Microphone and Loud Speaker in Position Above and Below Television Scanning and Viewing Aperture

speaker to the microphone and in this connection the design of the booth is an important factor. The booth must necessarily be so shaped that the user, looking at the viewing screen, can be satisfactorily scanned and the light reflected from the scanned areas will strike the banks of photoelectric cells required for the reproduction of the visual likeness. This requires that the person scanned be located in close proximity to the scanning disk and to the photoelectric cells as well as to the microphone and loud speaker. Such an arrangement is objectionable from an acoustic standpoint because in the present state of development the cells are necessarily large and poor absorbers of sound. They thus tend to cause part of the sound output from the loud speaker to reflect back into the microphone. If the sound so reflected or fed-back is equal or greater in magnitude than the original sound picked up and is of the proper phase relation, the system will "sing" and become of no practical use. A further effect of the design of the booth is that, as a closed cavity, it tends to cause sounds of a certain pitch range to be accentuated. To reduce these effects as far as possible, the television booths were made as large as other considerations would permit and all surfaces were covered where

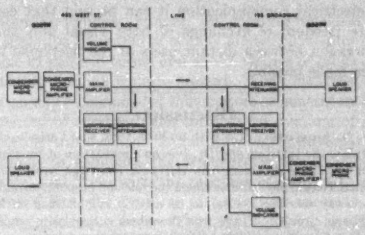


Fig. 21—Circuit Diagram for Sound Transmission System for Two-Way Television

possible with acoustic absorbing material. They have a floor area of about 35 sq. ft. and are about 8 ft. high. Because of the increased transmission required for the proper interpretation of sounds in the presence of noise, the booths were made of heavy masonry material to insulate the user and the microphone from the noise incidental to the rotating parts of the television apparatus. It was thus necessary to project the scanning beam and to view the illuminated image through a

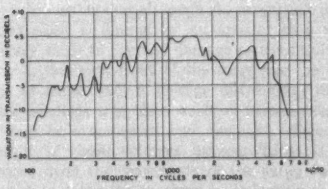


Fig. 22—Response Frequency Characteristic of Microphone, Amplifier and Loud Speaker

window located in the front wall. The microphone and the loud speaker were fitted into this wall, which was then covered over with a thin screen to improve the appearance as shown in Fig. 3. These means effectively reduced the noise in the booth to an unnoticeable amount and reduced reflection effects to the extent that the voice of the average speaker talking in a conversational manner could be reproduced at a loudness best suited

to the general effect. The optimum loudness seemed to be about the same as would be obtained from the speaker direct at a distance of 10 ft., the apparent distance between the image and the observer. At this loudness the gain of the amplifiers was 12 db. less than that required to cause singing.

While the system demonstrated was operated over a distance of only a few miles, it will be appreciated that the same facilities might have been used over much greater distances. Thus for the first time in the history of electrical communication it can be said that complete freedom of exchange of both visual and aural expression between distant users of the telephone has been made possible.

## Discussion

**N. S. Amstutz:** It is with no little thrill that I arise to congratulate the Institute and Dr. Ives on a realization of the vision of one of those dreamers who thirty-six years ago wrote about "Visual Telegraphy" and assumed the role of a prophet, outlining a two-way working system to be used in combination with a telephone circuit.[1] There was described a television sending circuit, a television receiving circuit, a speech transmission circuit and a motor synchronizing circuit. The one-way television circuit and scanning disk device of Nipkow was described in detail, among a number of other proposals. The simultaneous sending and receiving of television currents was by means of two separate cylinders directly connected to a synchronous motor, each cylinder carried a group of openings arranged spirally.

It is indeed a great personal satisfaction to have the dreams of yesteryear come true and this opportunity is taken to congratulate Dr. Ives along with other workers, such as Jenkins at Washington, Alexanderson at Schenectady, and Baird of London, England, all of whom, thanks to sensitive light responsive devices, neon lamps, carrier currents, ultra precision apparatus, adequate financing and technical staffs, are hastening the day when television will not only be spectacular but harnessed to the service of man.

Dr. Ives, in his address referred to television as having been "in the air" for a long time, as far back as the Arabian Nights. Conjecture reverts to an incident described in Dr. Guthries "General History of the World" 1764, Vol. VII pages three and four in which portraits were made and sent in some mysterious manner during the reign of the twenty-sixth califf of the house of Al Abbas, circa A. D. 1037. This is referred to as follows "Avicenna, was obliged to fly to Forjan, where Washmakin reigned. Upon this, Mahmud, having got one of his portraits, ordered a great number of copies of it to be made and dispersed all over the east, that Avicenna might be seized." * * * "Washmakin knew him, by one of his portraits which had been sent him by Sultan Mahmud." The engineers of today may well wonder how the feat described above was accomplished.

1. "Electricity," (New York) Feb. 28, 1894, pp. 77-80, and March 14, 1894, pp. 110-111.

# Effects of Lightning Voltages on Rotating Machines and Methods of Protecting Against Them

BY F. D. FIELDER[1] and EDWARD BECK[1]
Associate, A. I. E. E. Member, A. I. E. E.

*Synopsis.—Rotating machines directly connected to overhead lines are subject to damage from lightning surges. Many methods of protection against such damage are possible, several of which are discussed in this paper. Laboratory experiments have been made to show the normal distribution under various steepnesses of waves, and the improvement of unsatisfactory distributions by means of condensers or lightning arresters connected to various parts of the windings has been studied.*

THE purpose of this paper is to discuss means of protecting rotating machines directly connected to overhead lines from damage by lightning voltages. In order to select proper methods of protection, it is necessary to determine the distribution of surge voltages in the windings of machines under various cases of applied voltage and with different methods of protection. An investigation of this problem has been made and is described in this paper.

## The Problem

There are two problems involved; one is the limitation of the surge voltages which may be impressed on the insulation between the windings and ground to a value less than its puncture voltage; the other is the limitation of the voltage impressed on the insulation between turns to a safe value. The voltage impressed between windings and ground depends principally upon the magnitude of the transient voltage which reaches the machine through the overhead line; the voltage impressed between turns of the winding depends on both the magnitude and wave front of the incoming transient and upon the distributed capacity and inductance of the windings. The protection of the machine against these voltages can be accomplished by several methods; the magnitudes of the incoming surges can be limited by properly applied lightning arresters; the wave-fronts of the incoming surges can be modified at the terminals of the machine by the introduction of lumped inductance or capacity, or both, in the circuit ahead of the machine; or the voltage distribution in the machine can be altered by the insertion of external apparatus at various points in the winding. These methods will be discussed at greater length later in the paper.

## Present Practise

On the whole it has been true in the past that no special pains have been taken to protect rotating machines directly connected to overhead lines. It is, however, generally recognized that it is more difficult to protect a machine of this kind against damage by surge voltages than a transformer, since, for structural reasons, the insulation used in generators or motors is not as resistant to impulse voltages. In rotating machinery, the space for insulation in slots is limited; it is impracticable to pad end turns; and as yet the use of oil as an insulating medium is quite limited. For these reasons it is usually recommended that motors or generators be connected to overhead lines through the medium of an insulating transformer. In many cases, however, it is desirable to eliminate the transformer for economic reasons, and then, with the machine connected to an overhead line, the problem of protection becomes of considerable importance. The usual lightning arrester protection given to transformers has been inadequate in some cases of machine protection. Because of the unequal distribution of the surge voltage in the windings, if it enters them with a steep front, the trouble has usually consisted in breakdown of insulation between turns or coils rather than from windings to ground. A lightning arrester limits the magnitude of the surge voltage to ground, thereby preventing insulation failures to ground, but it exerts little if any effect on the steepness of the wave-front. The voltages which will exist across the insulation between turns is determined by the crest voltage of the applied surge, by the length of time it takes to reach this crest value, and by the distributed capacity and inductance of the windings. Hence it is possible that although the magnitude of the incoming surge is limited by an arrester to a value sufficiently small to prevent damage to the insulation to ground, the wave-front of the surge may be steep enough to cause such a voltage distribution in the machine windings that the insulation between certain turns may be overstressed and damaged. Since the magnitude of these voltages between turns is also dependent upon the magnitude of the surge voltage permitted to enter the machine, a reduction in this entering surge voltage will reduce the stresses on the windings. It has been recommended, therefore, that in applying arresters to machines directly connected to overhead lines, arresters of the lowest possible rating be applied in order that the surge voltages shall be limited to the greatest possible degree. In applying arresters to transformers, it is usually the practise to apply arresters of ratings sufficiently high to withstand possible system overvoltages or unbalance of voltage to ground. Where transformers are concerned such protection is adequate, but in the case of rotating machines

1. Both of the Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.*



30-103

the margin of safety against damage by lightning is often not sufficient. Therefore, it has been recommended in many cases that when arresters are applied to such machines, they be chosen to withstand only the probable, and not the possible, maximum circuit voltages, and that the risk of an occasional arrester failure be run and accepted rather than the risk of damage to a machine. So, for instance, arresters designed for solidly grounded neutral circuits have for the sake of the added protection against lightning thus secured, been applied to machines feeding, or fed from, ungrounded or poorly grounded systems, but with full recognition of the fact that if the voltages to ground become displaced, (as they readily may except on well grounded systems), an arrester may be damaged and require replacement. This is done on the basis that the cost of replacing a lightning arrester is small compared to the economic loss involved in a damaged machine. On the whole, this practise has shown quite satisfactory results; it still leaves some room for improvement however, in that by the use of auxiliary means, the stresses in the windings can be reduced, and the likelihood of damage to the protective equipment, from circuit voltages exceeding the arrester ratings, avoided.

As pointed out in the foregoing, the danger of damage resides principally in the possibility of large voltage stresses between turns caused by non-uniform distribution in the windings when a surge enters. When the surge voltage first enters the machine, the potentials developed across various parts of the windings are determined by the electrostatic field conditions in the windings; in other words, by the relations of the distributed capacities. As the surge penetrates further into the windings, these conditions change; hence, the voltage conditions also change; and it is not until surge current flows throughout the windings that the inductance of the windings plays a major part in the voltage distribution. The theory of the voltage distribution has been described in various papers.[1, 2]

## Experimental Tests

In order to investigate the potentials to which machine windings may be subjected when surges of various shapes enter, a series of tests was made in the High Voltage Laboratory at Trafford City on a commercial rotating machine. These tests were made on a standard 5000-kv-a., 4000-volt, three-phase, 60-cycle, 900-rev. per min., synchronous condenser. The machine had two parallel groups of windings per phase, each group containing eight coils, with five turns per coil. Well insulated taps were brought out from each of the eight coils, as well as from each of the five turns of the first line-side coil. Surges of various wave-fronts were applied to the windings and cathode ray oscillograms were obtained at each tap.

Fig. 1 shows the method by which the surges were applied to the windings. The main condenser bank was charged to a constant voltage, and then tripped by a three-point gap with the same impulse which initiated the cathode beam of the oscillograph. Then, for purposes of oscillograph synchronization, the surge was passed through a 500-foot cable to the terminal of the generator winding. A linear timing system was used, with a single sweep of the cathode beam across the film initiated by a tap near the beginning of the cable. The wave-front of the applied surge was controlled by a small inductance connected between the bank of condensers and the cable. A surge impedance at the generator end prevented cable reflections. Voltages at the various taps of the winding were measured by capacity potentiometers, directly connected to the oscillograph. Two potentiometers made it possible to measure differences between taps wherever desirable.

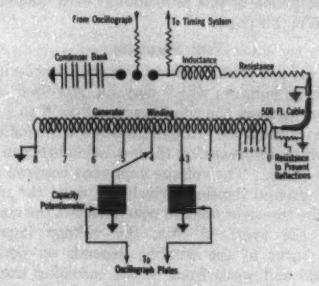


Fig. 1—Test Circuit Diagram

In the analysis of the results, two groups of curves are used. The first group consists of a careful replotting of the actual wave obtained from each tap; these curves are merely copies of the oscillograms on a percentage basis. The second group of curves is derived from the first group by considering the conditions at any definite time. For example, where 100 per cent is taken as the crest value of the applied voltage wave, the first curve shows the per cent voltage to ground for each tap. If one particular instant is considered,—say at the time corresponding to one microsecond after the surge first reaches the windings,—it will be seen that a certain distribution obtains at this time. This distribution is most readily shown by plotting per cent voltage to ground against coil tap or per cent of the winding. One microsecond later, as may be seen by considering the curves at two microseconds, the distribution has changed. A family of curves adequately describing the distribution at various times is thus obtained by progressing along the time scale of the first group of curves. Since this method shows the results more quickly and more completely, it will be used in this paper for all tests. In considering the results, it is

1. For references see Bibliography.

evident that the upper envelope of the curves indicates the maximum voltage to ground; also, the slope of these curves indicates the stress in any coil, the greatest slope showing the worst condition for any particular test. The amount of voltage stress across any coil is determined from the curves showing per cent of voltage,

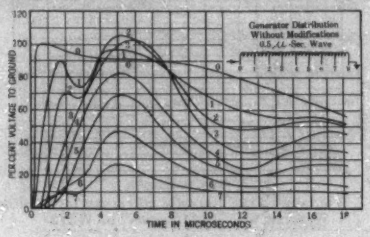


FIG. 2—VOLTAGE—TIME RECORDS OBTAINED ON UNMODIFIED WINDING, WITH ½-MICROSECOND WAVE

plotted against coil taps or per cent of winding by considering the voltage difference across the taps of the coil at any instant.

Two waves were used for most of the tests; one was a wave with a rapid rise which increased from zero to crest value in one-half microsecond; the other wave, obtained with a small inductance in the circuit, rose to crest value in approximately two microseconds. In the light of recent data on the shapes of actual lightning surges, it appears that the wave-fronts of the majority of lightning surges which reach apparatus are not so steep as those applied in these tests; hence the tests, (particularly those made with the one-half microsecond wave-front), probably represent more severe conditions than will be experienced in practise. To show further the effect of the change in equivalent frequency a third wave was applied to the unmodified winding. This wave rose to crest value in twelve microseconds. To show comparative results which hold for any applied voltage, curves are plotted on a per cent voltage-to-ground basis. Actually, the wave used had a maximum value of 6300 volts. All waves decreased from crest value to an average of 60 per cent after 20 microseconds with the generator connected.

## NOTATION

The generator taps were numbered arbitrarily 0, 1, 2, 3, 4, 5, 6, 7, 8, from line end to ground, 0 being the line side and 8 the actual ground connection. Taps on the first five turns of the first coil were numbered, 0.2, 0.4, 0.6, and 0.8. The oscillograms showed a fairly uniform distribution on these first turns, so they were plotted separately only whenever high stresses were obtained.

## UNMODIFIED DISTRIBUTION

The first problem was to determine the voltage distribution throughout the unmodified winding for the various waves under consideration. Fig. 2 shows the replotted oscillograms for the one-half microsecond wave, and Fig. 3 shows four typical oscillograms. Fig. 4 shows the results again replotted with the winding as abscissa. The worst stress occurs across the first coil shortly after the wave strikes the winding, and amounts to 80 per cent of the applied voltage. This stress is rapidly relieved, for only 0.2 of a microsecond later, this stress has been reduced to 60 per cent. One microsecond after the application of the surge the stress across the first coil becomes 30 per cent. The greatest voltage to ground is obtained after about five microseconds, and amounts to 106 per cent of the impressed voltage. It occurs between the second and third coils from the line end.

The voltage which exists (in these tests) across any particular coil, is determined from either the curves of Fig. 4 or those of Fig. 2, considering the differences in voltage to ground existing at the ends of the coil at any instant. Typical curves of the voltage stresses existing

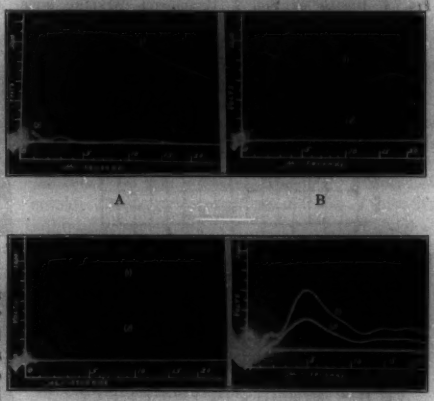


FIG. 3—FOUR TYPICAL OSCILLOGRAMS, OBTAINED ON UNMODIFIED WINDING, WITH ½-MICROSECOND WAVE

A. 1. Applied voltage wave (0-8)
2. Voltage difference across first turn (0-.2)
B. 1. Voltage from tap 2 to ground (2-8)
2. Voltage difference across third coil (2-3)
C. 1. Voltage from tap 3 to ground (3-8)
2. Voltage difference across fourth coil (3-4)
D. 1. Voltage from tap 6 to ground (6-8)
2. Voltage difference across seventh coil (6-7)

across coils are shown in Fig. 5 for Coils 1 and 4, plotted in terms of per cent of kv. applied to the total winding against time measured from the instant the applied surge strikes the line end (Tap 0) of the winding. Similar curves may be plotted for any coil under this test condition or those recorded in Figs. 6, 9, 10, 11, 12, or 13.

These curves may be translated into actual potentials. For example, consider a 22,000-volt machine with solidly grounded neutral; the normal working voltage per phase is then 12,700, and with eight coils, the voltage per coil would be 1600. Now suppose an arrester installed at the machine terminals to ground, which would limit the magnitude of the applied lightning

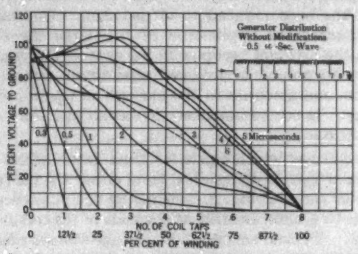


FIG. 4—REPLOT OF FIG. 2, UNMODIFIED WINDING WITH ½-MICROSECOND WAVE

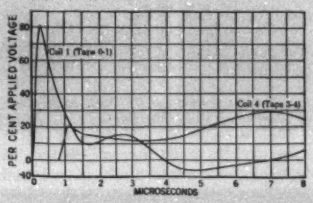


FIG. 5—TYPICAL VOLTAGE STRESSES ACROSS COILS FOR CASE SHOWN IN FIGS. 2 AND 4

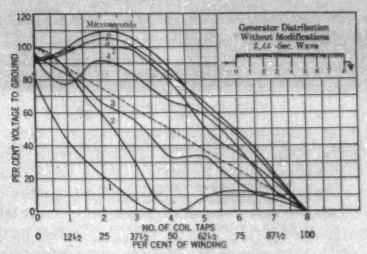


FIG. 6—REPLOT OF OSCILLOGRAMS, UNMODIFIED WINDING WITH 2-MICROSECOND WAVE

voltage to 3.5 times the normal working voltage,—a ratio which generally obtains with the commercially available arresters of this class,—or a surge voltage corresponding to an equivalent 60 cycle r. m. s. value of about 44,000 volts. If the applied surge rises to this value in 0.5 microseconds, Fig. 5 shows that the maximum voltage stress across coil No. 1 will be 80 per cent of 44,000 or 34,000 volts r. m. s.; in other words $\frac{34,000}{1600}$ or 21 times normal, whereas with uniform

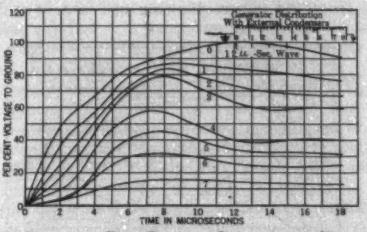


FIG. 7—VOLTAGE—TIME RECORDS OBTAINED ON UNMODIFIED WINDING WITH 12-MICROSECOND WAVE

distribution in the windings the stress on the coils would be 12.5 per cent of 44,000 or 5500 volts, or 3.5 times normal for an exceedingly short period of time. As announced before the Institute last October and Jan-

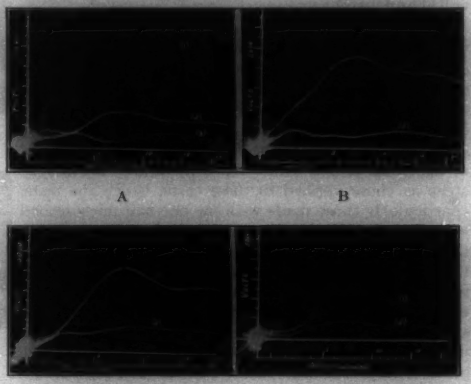


FIG. 8—FOUR TYPICAL OSCILLOGRAMS, OBTAINED ON UNMODIFIED WINDING, WITH 12-MICROSECOND WAVE

A. 1. Applied voltage wave (0-8)
2. Voltage from tap 6 to ground (6-8)
3. Voltage difference across first coil (0-1)
B. 1. Voltage from tap 2 to ground (2-8)
2. Voltage difference across third coil (2-3)
C. 1. Voltage from tap 3 to ground (3-8)
2. Voltage difference across fourth coil (3-4)
D. 1. Voltage from tap 5 to ground (5-8)
2. Voltage difference across sixth coil (6-7)

uary lightning arrester developments now in progress indicate that these voltages may in the future be further reduced in the ratio of approximately 2.5/3.5.

The results obtained with the two-microsecond wave show a less severe initial distribution, Fig. 6. The

greatest stress again occurs on the first coil, but this time it is only 40 per cent of the applied wave. Nearly as great are the stresses obtained later: 30 per cent over coil 3 after two microseconds, and 25 per cent over the last coil, 8, after about five microseconds. The maximum voltage to ground due to internal resonance is 108 per cent of the applied voltage at six microseconds.

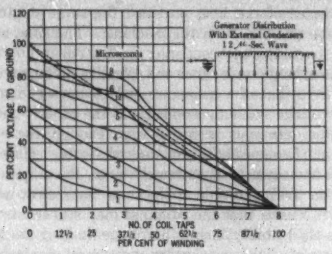


FIG. 9—REPLOT OF FIG. 7 UNMODIFIED WINDING WITH 12-MICROSECOND WAVE

The effect of a considerably slower wave rising to crest value in 12 microseconds was studied. The curves, like the theory, indicate that the distribution would be more uniform with slower waves; so this was checked. The modification in this case was obtained by inserting a condenser at the generator end of the cable in much the same way as the front can be modified in practise. Fig. 7 shows the oscillograms replotted, Fig. 8, four typical oscillograms, and Fig. 9, the distribution curves for the winding. It will be seen that the stresses are

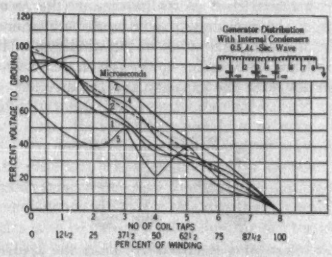


FIG. 10—REPLOT OF OSCILLOGRAMS, WINDING EQUIPPED WITH INTERNAL CONDENSERS, WITH ½-MICROSECOND WAVE

comparatively small, in no case exceeding a maximum of 20 per cent across any individual coil.

The point to which the modification of the wave must be carried for a satisfactory distribution depends upon the natural frequency of the generator, for if the impressed wave has an equivalent frequency less than the natural frequency of the machine, little distortion of the distribution is possible.

## DISTRIBUTION MODIFIED BY DISTRIBUTED CAPACITORS

In accordance with theory it follows that the addition of small capacities connected to points in the winding would improve the voltage distribution obtained with steep fronts. Accordingly several condensers varying from 0.001 to 0.005 $\mu$ f. capacity were connected from the line to the coils. Instead of taking oscillograms of each of the many possible combinations, the effects of each combination were observed on the oscillograph screen. At first, condensers were connected to each

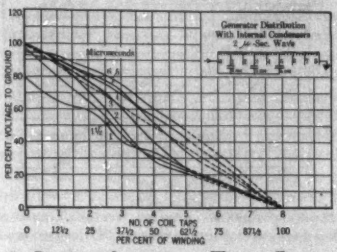


FIG. 11—REPLOT OF OSCILLOGRAMS, WINDING EQUIPPED WITH INTERNAL CONDENSERS, WITH 2-MICROSECOND WAVE

tap, but it was later found that practically as good correction was obtained with fewer condensers; this, of course, means fewer taps in a machine actually protected in this manner. The final arrangement employed three condensers: one of 0.004-$\mu$ f. capacity,

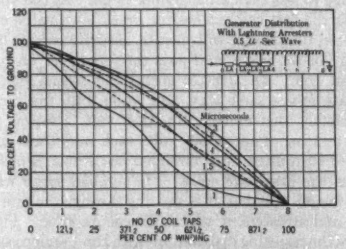


FIG. 12—REPLOT OF OSCILLOGRAMS, WINDING EQUIPPED WITH INTERNAL LIGHTNING ARRESTERS, WITH ½-MICROSECOND WAVE

connected between the high side and the first coil (Tap 1); one of 0.004-$\mu$ f. capacity connected between the high-voltage side and the third coil (Tap 3); and one of 0.002-$\mu$ f. capacity connected between the high-voltage side and the fifth coil (Tap 5).

Fig. 10 shows the results obtained with the ½-microsecond wave and these condensers. The curves show that with a maximum stress of less than 25 per cent on any coil at any time and voltage to ground always less than the applied surge; high-voltage concentrations have been eliminated. In comparison with the original

curve, this curve suggests another way of explaining the improvement; that is, the auxiliary condensers pass the surge to the lower coils before it could pass through the winding itself, thus relieving the concentration over the first coils. Fig. 11, obtained with the two-microsecond wave, approaches a perfect distribution, and shows far better characteristics than were obtained with the unmodified winding. For this wave, the maximum

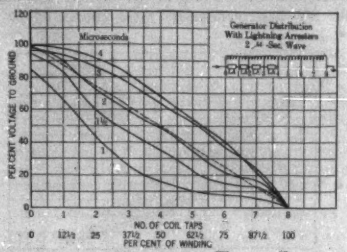


Fig. 13—Replot of Oscillograms, Winding Equipped with Internal Lightning Arresters, with 2-Microsecond Wave

stresses compared with a value of 12.5 per cent which would result from perfect distribution are only slightly greater than 15 per cent for all coils.

### Protection Against Uneven Distribution by Means of Shunt Lightning Arrester Units

In this case, small arrester units were placed across the coils having the greater stresses, thus limiting the voltage to less than a dangerous value. As the voltage across the first coil reaches the breakdown value of the arrester, the arrester will operate, absorb a portion of the energy of the wave, and pass the remainder on to the second coil. An arrester across the second coil will operate in the same way, and so on until the surge is completely distributed. In this test arrester units with a rating of about 600 volts each were used, and a good distribution was obtained with this protection across the first four coils. The applied surge was of such magnitude that after passing through the first four coils and arresters, it was no longer harmful. Fig. 12 shows the resulting distribution with the ½-microsecond wave representing considerable improvement over the original distribution. The greatest stresses were only slightly above 20 per cent. With the two-microsecond wave, (Fig. 13), similar results were obtained. On the whole, the results obtained with the lightning arresters were as good as those obtained with the internal condensers, and show stresses and voltage to ground of approximately the same values.

The tests described in the foregoing show that the voltage distribution in the machine windings can be made practically uniform by several methods.

### I. Changing the Shape of the Applied Wave

If the wave-front of the applied surge has a sufficiently gradual rise, the distribution will be quite uniform as shown in Figs. 7 and 9. As shown by these figures the wave-front of the incoming surge can be sloped off by the insertion of capacity between the machine terminals and earth. This capacity, together with the surge impedance of the line, provides a circuit in which it will take a definite time to charge the condenser up to the full voltage of the incoming surge through the surge impedance of the line, provided the surge originated at some distance from the machine. The time necessary to charge the condenser is dependent upon the values of surge impedance and capacity The circuit is similar to that of a resistance and condenser in series, with voltage suddenly applied. If the capacity at the machine terminals is made large enough, the wave-front can be sloped off to any desired degree. However, unless the capacity is extremely large, this imposes no limit on the magnitude of the surge impressed, which, in turn, means that the windings may still be stressed above their ability; hence, a voltage limiting device in the form of a lightning arrester or gap must also be introduced. The rate of voltage rise up to the beginning of the discharge of the arrester is then determined by the magnitude of the applied surge, the capacity placed at the machine terminals, and the surge impedance of the line, if the surge originated at a distance. In the case of high-voltage surges of steep front, the time in which the voltage reaches the limit imposed on it by the arrester,—that is the wave front preceding arrester discharge,—may be very short. Hence, although the voltage impressed on the machine is limited, the time to reach its crest may be short, and uneven distribution result. To preserve uniform distribution and low magnitude, it is desirable that the time in which the voltage applied to the machine rises to its maximum (the terminal voltage of the lightning arrester used) be long enough to give uniform distribution in the windings. This is accomplished by resorting to the use of a choke coil in conjunction with the capacity and the arrester. The

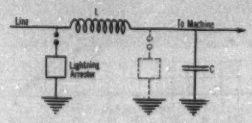


Fig. 14—Protective Equipment to Limit the Magnitude and Steepness of Surge Voltage Applied to Machine

circuit is as shown in Fig. 14. The use of such an inductance has a further advantage in that the sloping off effect of the condenser is then active, even for surges originating near the machine. The incoming surge first strikes the arrester which limits its magnitude to a definite value. The lightning arrester voltage then passes through the choke coil to charge the condenser. Thus, regardless of the magnitude of the incoming surge the voltage available for charging the condenser is

always substantially the same. The time necessary to charge the condenser up to its maximum potential is determined by the period of the circuit consisting of the inductance of the choke coil and the capacity of the condenser. The theory of this will not be discussed here; it can be found in various papers and text books.[3,4,5] Briefly stated, an approximation of the actual (sufficiently accurate for our purposes) is that the period of this circuit is $2\pi\sqrt{LC}$ and the time required to reach the maximum charge is one-half of the period, or roughly $3\sqrt{LC}$. The voltage to which the condenser may theoretically be charged is $2e$, where $e$ is the applied surge voltage,—in this case the voltage permitted by the lightning arrester. Certain investigations made by means of surge generators and cathode ray oscillographs indicate that in the type of circuit shown in Fig. 14, the condenser voltage may overshoot 50 per cent; that is, may reach $1.5e$. This can be reduced by shunting the choke coil by a suitable resistor; or can be prevented by the application of a second lightning arrester at the condenser. By this combination of devices, then, the magnitude and wave-front of the voltage applied to the machine can be fixed for the steepest possible lightning surge by selecting the magnitudes of $L$ and $C$ to give the desired wave front. The desired effect can be approached by the use of an arrester and capacity without the choke coil; but here the rate of rise of voltage preceding the arrester discharge is governed by the magnitude of the incoming lightning surge, and will therefore vary. Unless the capacity is very large this may cause non-uniform distribution. Consequently the use of an inductance in combination with the capacity is preferred.

In the application of the equipment described in the foregoing, the amount of inductance that may be used in the choke coil is usually limited by the reactance that may be placed in series with the machine. Often the current limiting reactor, if one is employed, can be used as the choke coil, except in some cases when its insulation and turn spacing may require special attention. In such cases, the required capacity is at once determined. For instance, suppose it is desired to protect a 60-cycle generator whose characteristics are such that an applied surge which rises to its crest in not less than ten microseconds will give a safe distribution, and that with this is to be used a current limiting reactor of one ohm in each phase; the inductance of this reactor is then 2.65 millihenrys. The capacity required to slope an abrupt incoming surge off to a 10-microsecond front is then 0.0042 $\mu$f. With such a combination of arresters, choke coil, and capacity, the magnitude of the surge applied to the machine windings will be limited to the terminal voltage of the arresters which is below the danger value for the insulation of the machine windings to ground. To this it will rise in approximately 10 microseconds, thereby providing a uniform distribution and safe magnitude of voltage.

## II. The Use of Cable Between the Machine and the Overhead Line

It is well known that when an overhead line terminates in a cable, surges traveling in the overhead line when they penetrate the cable undergo considerable change because of the relation of the surge impedances of the cable and the overhead line. The surge that enters the cable is much reduced, (for the usual cases to about 20 per cent of the magnitude it had in the line), and its front is correspondingly sloped off. If the cable is long, attenuation further slopes off the front of the surge and reduces its crest; a long cable will therefore exert considerable beneficial effect. In short cables, however, successive reflections of the surge gradually raises its voltage in steps until it exceeds the magnitude of the original surge in the line.[3,4] It is questionable whether cables of the length usually employed have sufficient protective effect to safeguard the machine in the case of severe lightning transients; particularly since lines of the relatively low voltages usually involved are generally overinsulated, or supported on wood poles, so that their flashover voltages are high and therefore the magnitude of the surges which can produce voltage in the cable is also great.

## III. Condensers Tapped to Points of the Winding

As was to be expected from theory, the tests showed that the voltage distribution in the windings can be made sufficiently uniform to be safe by shunting portions of the windings by employing small capacities. These capacities may be either external to the machine or built in it. They may be of relatively low voltage rating, and the leads to them may be small, although they must be insulated for the working voltage which exists at the point where they are tapped to the windings. Where shunt capacities are used, a lightning arrester should be applied to the terminals of the machine to limit the magnitude of the lightning voltages applied to the windings.

There are theoretical possibilities in the design of stator windings with shielding so introduced that the voltage will be distributed uniformly. Whether or not these are economically practical remains to be seen.

## IV. Lightning Arresters in Shunt with Portions of the Winding

In a manner similar to Section III, the distribution may be made uniform by shunting portions of the winding by lightning arresters whose voltage rating corresponds to the working voltage which will exist across their terminals. These arresters prevent the building up of dangerous voltages across the windings with which they are in shunt. The arresters may be either external to the machine, or built in it; and again, the leads to them may be small, but must be insulated for the working voltage which exists at the point where they are tapped to the windings. The tests indicate that

relatively few arresters in shunt with a few sections of the winding at the line end will alter the distribution sufficiently; however, if lightning arresters are placed in shunt with parts of the winding throughout its entire length, the arrester usually applied to the machine terminals may be dispensed with.

In the above discussion it has been assumed that the neutral of the machine is grounded. If the neutral is free or grounded through resistance, the above data on distribution will, in general, still hold. Where the neutral is free or grounded through a high resistance, it is to be recommended that a lightning arrester be applied from the neutral point to ground; otherwise high voltages to ground may appear at the neutral because of reflections.

There are thus several methods by which a rotating machine connected to overhead circuits may be protected against lightning:

1. Interposing an insulating transformer protected by lightning arresters between the machine and the overhead line. (This is common practise today, particularly in those locations where lightning conditions are severe.)

2. Combinations of inductance, capacity, and arresters connected in the machine circuits. (This provides effective protection at a moderate cost, and in the authors' opinion is to be preferred to the use of capacity without inductance. In considering the construction of a certain large 22,000-volt synchronous condenser for direct connection to an overhead line, the cost of such protective equipment was estimated at approximately 15 per cent of the cost of the machine. This includes the cost of a reactor, which if already required for current limiting purposes, should be compensated for in the cost of the protective equipment.)

3. Shunting parts of the winding by capacities with arresters applied to the machine terminals. (This method is equally effective. It may require some modification of machine design in order to bring out the leads to the condensers.)

4. Shunting parts of the winding by lightning arresters. (This is another effective method resembling Method 3. It has the advantage of possibly permitting the elimination of the arresters now usual at the machine terminals, but also may require modification of the machine design.)

5. Application of arresters to the machine terminals only. (This has no effect on the voltage distribution in the windings, and the arresters, if so applied, should have the lowest possible rating. It may be considered an expedient; the previously described methods are to be preferred from the standpoint of protection.)

6. Interposing a length of cable between the machine and the overhead line. (Short lengths of cable will exert little beneficial effect, long ones may. Other methods are preferable.)

7. Machines with specially shielded windings, with arresters applied to the machine terminals. (This requires more or less sweeping changes in design which at the present writing do not appear economically practical.)

The present tendency in machine design is to avoid the necessity of tapping the windings which would require that additional leads be brought over or through end turns and to avoid installing in the end winding space supplementary devices not inherently necessary to the proper operation of the machine. For this reason it is thought preferable to introduce protective measures entirely external to the machine, by the method described in I.

In the application of any of the above methods except 1, each case should receive special consideration, as the characteristics of the protective equipment must be fitted to the characteristics of the machine involved.

## Appendix

The purpose of this Appendix is to present in graphical form, so far as possible, the behavior of a lightning transient when it strikes a machine or the protective equipment installed at the machine terminals. It is

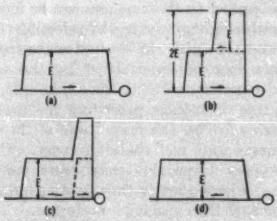


Fig. 15—Surge Voltage which will Appear at Machine Terminals if it is Unprotected

(a) Incoming traveling wave of voltage $E$
(b) and (c) Approximately $2E$ appears to ground at the machine for for the duration of the surge
(d) The reflected wave passes back into the system

not intended that this shall be a rigid analysis calculated on the basis of the actual shape of lightning transients as they have been measured, nor on the actual shape of the voltage waves that appear across lightning arrester terminals. This would involve complications unnecessary for our purpose, which is to present in as simple a manner as possible the behavior of the voltages at the protective equipment. Consequently it is assumed that the lightning transient impressed on the apparatus is of a simple shape, practically rectangular; that is, with an abrupt front, a flat top, and an abrupt tail. It is also assumed that the lightning arrester terminal voltage is of this same shape. Actually these conditions do not exist, but for the sake of simplicity, they are assumed. The fundamental picture which the authors wish to present is most easily drawn and visualized by this means. Actual cases may be analyzed step by step in a similar manner. Much of the material presented is not new; it can be found in text books. But it was

thought to be of some value to present that which is pertinent to the subject of the paper.

With this apology, let us consider the case of Fig. 15,—a traveling wave approaching an unprotected machine. It is well known from theory and experiment that when surge voltages reach an open end or the high surge impedance of a winding they will virtually double.

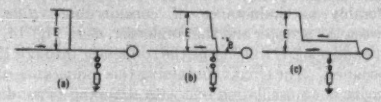


FIG. 16—SURGE VOLTAGE WHICH WILL APPEAR AT MACHINE TERMINALS IF IT IS PROTECTED BY A LIGHTNING ARRESTER

(a) Incoming traveling wave of voltage $E$
(b) Arrester limits the transient voltage to $e$
(d) The voltage which reaches the machine is $e$

Hence, if the machine is unprotected, the voltage applied to the machine windings is practically $2\,E$, the voltage distribution in the windings will be determined by the time it takes the voltage to increase from zero to $2\,E$, and the magnitudes of these distributed voltages are determined by $2\,E$.

If the machine is protected by a lightning arrester, the conditions are as in Fig. 16. If the distance between the arrester and the machine is great, the voltage at the machine may reach twice the arrester voltage; that is, $2\,e$, by reflection in a manner similar to that

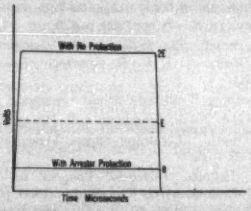


FIG. 17—VOLTAGES WHICH WILL APPEAR AT THE MACHINE TERMINALS IF UNPROTECTED AND IF PROTECTED BY A LIGHTNING ARRESTER

shown in Fig. 17. This will, however, be modified if there are present busses, taps, and other lines. If the arrester is installed close to the machine, the voltage impressed on the machine is $e$, the distribution in the windings is determined by the time it takes the voltage to rise from zero to $e$, and the magnitude of these distributed voltages is determined by the value of $e$.

Let us now consider the application of a condenser alone at the machine terminals, as in Fig. 18. With a traveling wave approaching the condenser through the surge impedance of the line, the condenser will slope off the wave-front. If there were no protective equipment at all, the incoming wave would double by reflection to $2\,E$, as in Fig. 15; hence the voltage applied to the condenser through the surge impedance is $2\,E$, to which voltage the condenser will ultimately charge if the surge is of sufficient duration. Considering for the moment the equivalent circuit, the condenser voltage at any time $t$ microseconds after the voltage is applied is

$$e_c = 2\,E\,(1\,\epsilon^{-t/T}) \qquad (1)$$

$T = R\,C = Z\,C$ = the "time constant" of the circuit. $Z$ is assumed 500 ohms, $C$ is the capacity in microfarads, and $t$ and $T$ are expressed in microseconds.

Fig. 19 shows the charging of the condenser. In

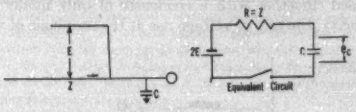


FIG. 18—MACHINE PROTECTED BY A CONDENSER ONLY, AND EQUIVALENT CIRCUIT

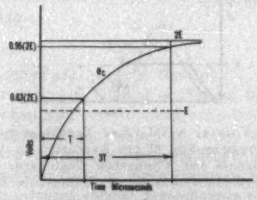


FIG. 19—CURVE SHOWING THE CHARGING OF THE CONDENSER

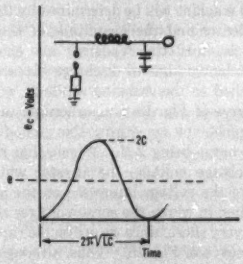


FIG. 20—VOLTAGE AT MACHINE TERMINALS FOR CIRCUIT INDICATED IN FIGURE, ASSUMING NO DAMPING

$T$ microseconds, $e_c$ will equal 0.63 ( $2\,E$ ) and in $3\,T$ microseconds $e_c$ equals 0.95 ( $2\,E$ ); hence to all practical purposes it may be said that $e_c$ will become equal to $2\,E$ in $3\,T$ microseconds.

The condenser will slope off the wave, but will not reduce its crest below $E$ unless $C$ is so large that the condenser will be charged to less than $E$ when the duration of the surge is passed. To achieve a reduction in voltage comparable to that of a lightning arrester if a long and high surge occurs, the value of $C$ must be great.

The distribution in the windings, if $e_c$ reached $2\,E$, is determined by $3\,T$, and the magnitude of these distributed voltages is determined by the maximum $e_c$, in this case $2\,E$. Thus, although the voltage distribution may be good, the magnitudes of the voltages impressed may be higher than the insulation can withstand.

It would be desirable to limit the magnitude of the voltage impressed on the machine, and to fix the time constant of the protective circuit used so that $3\,T$ will be large enough to assure a uniform distribution. The voltage can be limited by an arrester, but if an arrester is used, together with a condenser of only moderate capacity, the rate of voltage rise at the terminals of the

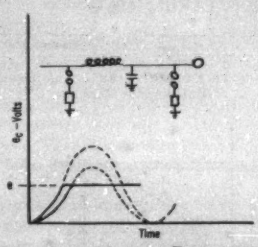


FIG. 21—VOLTAGE AT MACHINE TERMINALS FOR CIRCUIT SIMILAR TO THAT OF FIG. 20, BUT EMPLOYING AN ADDITIONAL ARRESTER ACROSS THE CONDENSER TERMINALS; ASSUMING BOTH NO DAMPING AND SUFFICENT DAMPING TO HOLD $e_c$ TO 1.5 $e$.

arrester and machine will be determined by the capacity of the condenser and the magnitude of the incoming surge; that is, until the condenser has charged to a voltage sufficiently high to discharge the arrester, the voltage applied to the machine windings will increase along the curve of Fig. 19, *i. e.*, according to Equation (1), the applied voltage during this period preceding arrester discharge being $2\,E$. When $e_c$ has risen to the arrester discharge voltage, the arrester will limit the magnitude of the voltage impressed on the machine to $e$; but the time in which the surge voltages rise from $O$ to $e$ may be very short, since we are on the rapidly rising part of the curve of Fig. 19. Thus, although the voltage has been limited by the arrester, the time to reach the crest may have been very brief; and although the surge crest has been limited, the voltage distribution in the windings may be bad. For this reason it is desirable that matters be arranged so that the voltage is first limited to $e$ by the arrester, and that it will be this voltage $e$ which charges the condenser at such a rate that $3\,T$ is sufficiently long to give uniform distribution.

This is accomplished by interposing an impedance,—preferably an inductance of considerable value,—between the arrester and the condenser, as in Fig. 14, so that $e$ and not $2\,E$ will charge the condenser through this impedance. The circuit containing this inductance and capacity is an oscillating one with damping depending upon the surge impedance of the line and the impedance of the arrester connected to the line. Let us suppose it is undamped and that no auxiliary arrester is connected across the condenser terminals; the condenser voltage will then oscillate about the voltage $e$, as in Fig. 20, possibly reaching a value to ground of $2\,e$. Its period will be $2\,\pi\,\sqrt{L\,C}$, and the time required to reach $2\,e$ will be half of this, or roughly $3\,\sqrt{L\,C}$. By this device, then, the magnitude and front of the surge can be controlled. In practise, the condenser voltage is not likely to overshoot to $2\,e$; generally there exists sufficient damping to prevent rises to more than $1.5\,e$, as indicated by certain controlled surge tests. Increases above $e$ can be entirely prevented by the use of an additional arrester across the condenser terminals as in Fig. 21.

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## Discussion

For discussion of this paper see page 1607.

# Voltage Oscillations in Armature Windings Under Lightning Impulses—I

E. W. BOEHNE*

Associate, A. I. E. E.

*Synopsis.—Experience has shown that rotating machinery connected directly to overhead lines is more vulnerable to surges than many other types of apparatus. This fact together with a desire on the part of some to connect important units to the line in this manner, has necessitated a study of the protection problem. Such a study is here described, showing oscillograms taken when steep voltage surges were applied to machine windings, measuring internal voltages to ground which are 200 per cent of the voltage allowed by the terminal lightning arrester. A simple traveling wave analysis of these oscillations is developed, which has successfully explained the peculiarities of over 400 oscillograms taken under various terminal conditions. Practical methods of eliminating the oscillations with neutral impedance are outlined in the light of the theory developed, and oscillographic evidence supporting their reliability is given. A generalized theory of neutral protection is proposed. The importance of wave-front, surge impedance of incoming line, arrester resistance, and other factors is discussed. Methods for protection of the turn insulation and the insulation to ground of such machines are suggested, showing that the lightning arrester only limits the potential of waves entering the machine and cannot control oscillations which may take place within the machine. The advantages of thyrite as a neutral resistor are pointed out in connection with the short-circuit protection, telephone interference, and lighting protection problems of such machines. In Appendix A the test circuits and methods used in the laboratory are discussed in relation to actual field conditions.*

## Introduction

THE peculiar response of synchronous machinery to transient surges has been realized for some time as a cause of frequent failures of machines connected directly to overhead lines.

One of the fundamental reasons why these transient surges cause so much trouble in electrical apparatus is because they require a definite time to travel a given distance. On an open line a surge travels at the velocity of light, which accounts for the fact that while one point on the line may be at normal line potential at a given instant, another point only a short distance away may be at 100,000 volts at the same instant. In machine windings where these physical circuits of length are concentrated in a frame of iron, the two points in question may be electrically some distance apart while physically there may be only an inch or less insulation between them. Furthermore, these surges obey definite laws of reflection at any discontinuity of circuit giving rise to additional stresses in many cases.

There are several principles which may be followed in reducing these abnormal potentials. One is shielding. Another is to introduce a change in the circuit actuated by the surge itself, having the effect of counterbalancing these abnormal potentials. Another method is that of eliminating the discontinuities of circuit so as to avoid increased stresses due to reflection. In many cases the use of one or more of these forms of protection is possible and necessary for the safety of the insulation of machine windings. This fact is the basis of the paper.

In order to understand how to protect rotating machinery from transient surges it is essential to know how machine windings respond to surges. An investigation with this objective has been made and will be outlined here.

## Object

The object of this paper is threefold:

(1) To explain the internal oscillations in machine windings when subjected to steep wave fronts. It is shown by a cathode ray oscillograph study, followed by theoretical considerations, that the highly oscillatory internal voltages rising in some instances to 200 per cent of the terminal voltage, are primarily due to successive reflections of a traveling wave in the machine winding.

(2) To show that the oscillations may be eliminated by connecting between the neutral of the machine and ground, a resistance equal to the characteristic surge impedance of the machine winding.

(3) To present an analysis of the protection of the insulation between turns of machine windings and to ground. It is shown that the voltage stress between turns may be reduced by shielding or by placing a capacitor in parallel with an arrester unit.

## Oscillograph Investigation

A cathode ray oscillograph investigation forms the foundation of the study and resulting theory presented in this paper. Three machines were tested ranging from a small 2200-volt induction motor to a 24,000-volt synchronous condenser and all were found to perform in a similar manner under artificial lightning surges. The lightning generator used for the tests was designed to represent electrically an equivalent transmission line of definite surge impedance delivering a given wave. It is felt that this phase of the study is of considerable importance and a detailed analysis and discussion is given in Appendix A, where it is proved that the test circuit used is an accurate representation of transmission line traveling wave conditions.

*A-C. Engg. Dept., General Electric Co., Schenectady, N. Y.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

## Oscillogram Characteristics

All of the oscillograms shown in the paper are oscillograms of voltage to ground with respect to time. Each oscillogram is titled with a figure, the key to which is as follows:

A single phase of a machine winding is represented by the rectangle shown in each diagram. In all cases the traveling wave approaches from the left. The point at which the voltage is measured is indicated by an arrow on the winding with the corresponding percentage from line terminal indicated below the arrow. The condition of the opposite end of the winding is important and is given in the usual notation. Hence, Fig. 1 is an oscillographic record of what takes place in the winding of a 24,000-volt machine when a steep wave is applied to its line terminal and the opposite end grounded. The equivalent surge impedance of the lightning generator was very small for these tests. The voltage in all cases is scaled in per cent of the wave which enters the machine winding, this being defined as the applied wave. It will be seen later that this is equivalent to the arrester voltage. The abscissa is time, the reference point in each case being taken at the moment the wave reaches the line terminal of the machine. Similarly, Fig. 2 is the record when the neutral of the same winding is open, the same wave being applied as in Fig. 1. In these tests the rotor was removed and only a single phase of the machine was tested.

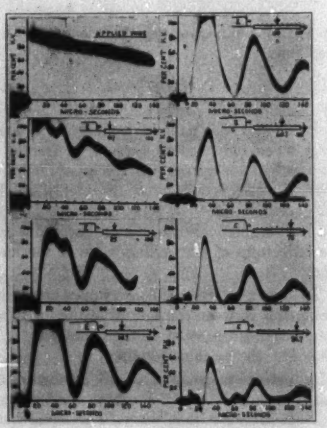

Fig. 1—Oscillations in the Winding of a 24,000-Volt Machine with the Neutral Grounded

A study of these oscillograms will be made here by listing some of the outstanding relations which are apparent.

(1) The maximum voltage with the neutral open is twice that of the neutral grounded.

(2) The frequency of the oscillations with the neutral grounded is twice that of the neutral open.

(3) The time delay of any appreciable voltage rise increases in proportion to the distance from the line terminal at which the voltage is measured.

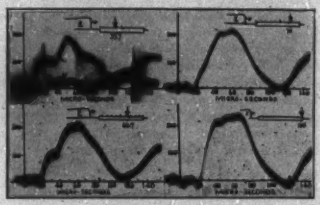

Fig. 2—Oscillations in the Winding of a 24,000-Volt Machine with the Neutral Open

(4) This time delay is the same with the neutral open or grounded.

(5) The voltages oscillations measured at various points in the winding with either the neutral open or grounded are substantially "in phase."

(6) A certain flat top characteristic is evident in many of the oscillograms, it being predominant near the neutral of the open neutral winding and near the line terminal of the grounded neutral winding.

(7) All records are distinctly unidirectional.

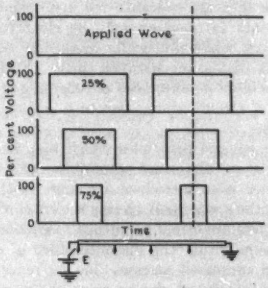


Fig. 3—Calculations of Voltage at Various Points of a Finite Line with the Neutral Grounded

## Explanation of Oscillograms

It will be shown that the voltage oscillations bear a marked similarity to those which would occur on a short length of transmission line, when subjected to a similar transient force. Consider the simple case of a suddenly applied voltage to the short line shown at the bottom of Fig. 3. First, when the far end is grounded.

At time $t = 0$ the switch is closed and a voltage

wave, $E$, will travel out on the line at a velocity depending upon the inductance and capacity of the line per unit length in the well known relation

$$v = \frac{1}{\sqrt{LC}} \tag{1}$$

When the voltage wave reaches the grounded terminal it will reflect with change of sign and return as a negative wave to the source at the same velocity. On

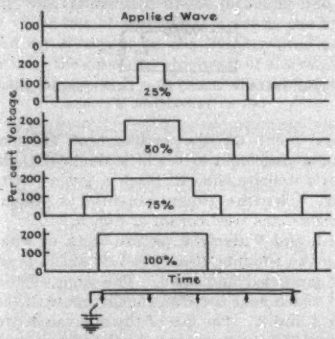


Fig. 4—Calculation of Voltage at Various Points of a Finite Line with the Neutral Open

reaching the source it will again find a grounded condition and reflect with a change of sign and repeat the operation indefinitely. Assuming no attenuation or distortion of the wave, and realizing that the potential at any point on the line is the algebraic sum of the resulting waves, it is easily seen that the voltages to ground which would be recorded by an oscillograph placed along the line would be as shown in Fig. 3.

Now consider the case where the far end of the line is open. When the voltage wave reaches the open neutral it reflects without change of sign and returns on the line, everywhere doubling the voltage to ground. On reaching the source it reflects with change of sign and returns negatively to the open end, reflecting again without change of sign and returning to the source to complete the cycle of its oscillation. Note that this time the wave had to travel twice as far to complete one cycle. Fig. 4 shows what the oscillograph would measure at various points along the line in the above example.

Making a study of Figs. 3 and 4 it is found that each of the seven characteristics which were tabulated in the study of the oscillograms of Figs. 1 and 2 is distinctly true in this case of a simple finite transmission line. These seven characteristics may be considered as criterions of traveling wave phenomena.

This analysis forms a basis for the theory that each phase of a generator winding functions as a finite transmission line to traveling surges arriving at its terminals. It will be noted by inspection that the distortionless calculations of Figs. 3 and 4 form the envelope of the corresponding voltages of Figs. 1 and 2, the latter showing the effect of such factors as losses and series capacity in distorting the wave. The transmission line constants of the generator winding will be discussed later.

As previously pointed out the oscillograms were taken on a single phase. Generally lightning surges involve all three phases. The phase voltages may be divided into two groups, a group which represents the average voltage to ground of all three phases and a group which represents the inequalities in voltage to ground as between the different wires. The first component is really a zero phase component and is practically unaffected by the presence of the rotor. The other group will in general be affected by the presence of the rotor.

The test results given in the paper and the resulting conclusions apply primarily to the first group, although even in this group we may expect small differences in results between the single-phase tests with the rotor

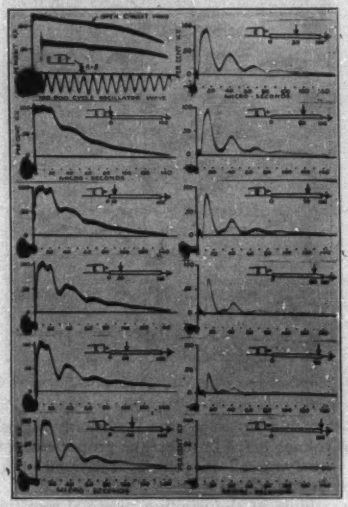

Fig. 5—Tests on 6600-Volt Winding, Neutral Grounded

removed and the first group mentioned above especially in machines of two-thirds pitch. A number of tests with all three phases connected showed that these differences were small in the machines tested.

## Oscillographic Data

A 6600-volt steel mill motor was then tested, the object being:

(1) To verify the proposed traveling wave theory for machine oscillations.

(2) To obtain additional constants of the transmission line properties of the new windings to be tested.

(3) To test certain methods of eliminating the oscillations which presented themselves in the light of the theory proposed.

The lightning generator for these tests was designed to represent a transmission line of 250 ohms surge impedance delivering a very steep wave. (See Appendix A.) The criterion for such a line is that when a resistance equal to 250 ohms is placed across the open end, the terminal voltage will be half of the open circuit wave. Such a relation is shown in the upper left hand corner of Fig. 5.

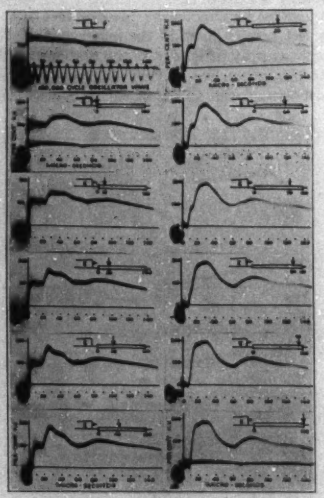

Fig. 6—Tests on 6600-Volt Winding, Neutral Open

When such a circuit is used it not only furnishes the proper voltage wave but also the proper current wave, hence satisfying all the energy relations of a transmission line traveling wave.

The voltage at the winding terminal resulting from such a traveling wave is the drop across the resistance $Z_g$, (see Appendix A) of the circuit shown in Fig. 7, that is

$$E_g = 2E\left(\frac{Z_g}{Z_1 + Z_g}\right) \qquad (2)$$

where $2E$ is the open circuit wave, $Z_1 = 250$ ohms = the surge impedance of the incoming line, and $Z_g = 800$ ohms = surge impedance of the machine winding as measured by the oscillograph. $E_g$ in the above equation is considered as 100 per cent and all voltages are referred to this as a base. It is the wave which actually enters the winding.

In order to give all oscillograms a definite reference point for which to consider $t = 0$, a special circuit arrangement was resorted to which recorded this

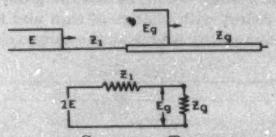


Fig. 7—Equivalent Circuit of Transmission Line Meeting a Generator Winding

reference point on the oscillograms automatically. Such an arrangement leaves little doubt that the wave requires a definite time to reach a given point in the winding. The true ground potential is shown in the lower right-hand oscillogram of Fig. 5.

Figs. 5 and 6 give the picture story of what takes place in the winding of a 6600-volt machine with the neutral grounded and open. The same relations are evident which were listed in connection with the study of Figs. 1 and 2. The use of the equivalent transmission line of 250 ohms accounts for the minor peculiarities

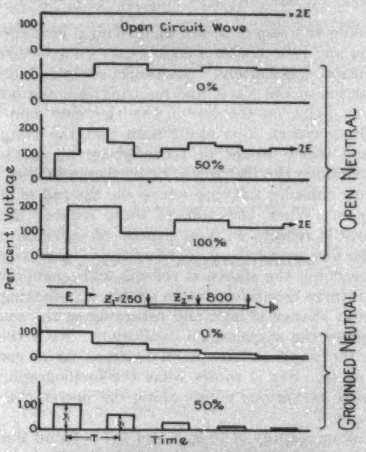


Fig. 8—Calculated Voltages in 6600-Volt Winding

of these oscillograms as shown by comparing with the calculated voltages for a few points in the winding as shown in Fig. 8. There is excellent agreement with the recorded voltages. Consider, for instance, the voltage measured at the line terminal when the far end is open. It shows distinctly that the wave returned to the line

terminal on the 800-ohm winding and found a surge impedance of 250 ohms. The resulting voltage at the line terminal would be:

$$E_g \left\{ \frac{3\,(250) + 800}{250 + 800} \right\} = 1.476\, E_g \qquad (3)$$

where $E_g$ is the wave which entered the winding.

This means that part of the wave was again reflected in the winding negatively while part, namely 0.476 per cent, was transmitted to the incoming line, not to return. This loss of part of the wave to the line each time the wave returns to the line terminal accounts for much of the apparent damping of the oscillations. This is best shown in Fig. 8, these voltages being calculated on the basis of no loss or distortion in the generator winding. The exact expression for this damping due to the junction loss is shown as Equation (39).

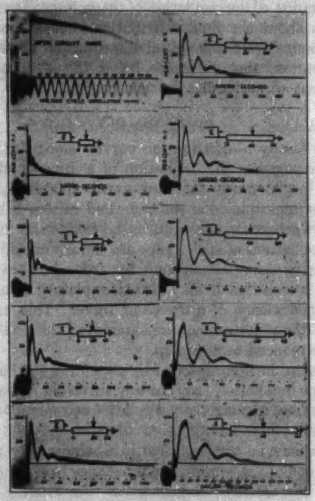

Fig. 9—Test on Fractional Lengths of 6600-Volt Winding—Neutral Grounded

By studying the development of the voltage oscillations on a finite transmission line as shown in Figs. 3, 4, and 8 it will be seen that the period of oscillation in all cases was a direct function of the length of the line, the velocity of wave being fixed. Hence it follows that if a winding behaves as a transmission line, by testing fractional lengths of the winding there should result a linear relation between the period of oscillation and the length of winding tested. Such tests were made on the 6600-volt machine and the oscillograph record is shown in Fig. 9 for the grounded neutral and Fig. 10 for the open neutral. In Fig. 11 the relations between the period of oscillation and length of winding tested, as plotted from Figs. 9 and 10, are shown to be practically linear as the theory indicates. This constitutes an additional proof that such oscillations are due to a reflection phenomenon.

Another test which forms a proof of the proposed theory and also lays the foundation of a practical method of eliminating the oscillations, is based upon the transmission line principle that if a resistance equal to the surge impedance of a line be placed at the end of the line to ground, that any wave arriving at this end will be completely absorbed and there will be no reflection to produce an apparent oscillation on the line.

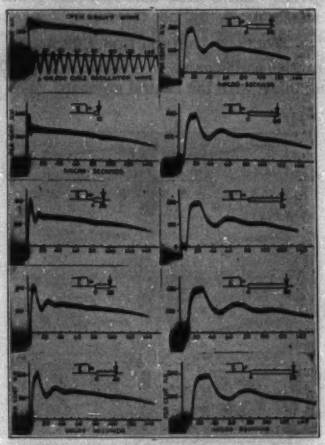

Fig. 10—Test on Fractional Lengths of 6600-Volt Winding—Neutral Open

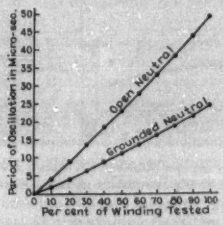


Fig. 11—Relation between Period of Oscillations and Length of Winding Tested

This follows directly from the simple method developed in Appendix A which states that the condition for which the voltage across the terminal resistance is equal to the traveling wave $E$, Fig. 7, is that $R = Z_g = Z_1$. Such a resistance, in effect, indefinitely extends the line.

The surge impedance of the 6600-volt winding was approximately 800 ohms. A resistance of this value was placed in the neutral of a single winding to ground and the same steep wave which previously gave rise to oscillations with the neutral open and grounded was applied. The oscillographic record is shown in Fig. 12.

The result is in accord with the theory. The effect is that of measuring a passing wave at various points along a line from a fixed time reference point. The wave merely passes by, not to return.

## Voltage Distribution Curves

From the oscillograms of voltage in the 6600-volt winding taken with the neutral grounded, (Fig. 5) the

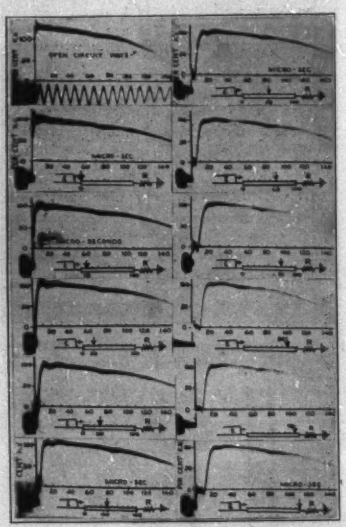

Fig. 12—Tests on 6600-Volt Winding with a Resistance Equal to the Surge Impedance in the Neutral to Ground

voltage distribution curves of Fig. 13 were determined. These curves show the voltages throughout the winding at various times. A careful study of these distribution curves will show that the initial voltage distribution is very low because of the fact that the wave requires a definite time to reach any point in the winding. As time goes on the wave enters the winding; thus the voltage distribution at 5 microseconds shows the position of the wave in the winding at that time. This also shows the distortion of the wave at the end of that time. In 12.5 microseconds the wave reaches the far end of the winding ready to reflect negatively reducing the voltage in the winding at any later time. In short, this traveling of the wave back and forth in the machine winding, reflecting with change of sign at each terminal results in the apparent oscillation of the voltage distribution curves as a standing wave, finally coming to rest at a final distribution depending upon the type of applied wave. If the applied wave is a rectangular wave, infinite in length, the final voltage distribution will be the straight line from 100 per cent voltage at the line terminal to ground potential at the neutral and about which the apparent standing wave oscillation is taking place.

This simple analysis gives a physical interpretation to well known mathematical transformations of any standing wave phenomenon to a traveling wave phenomenon and vice versa. The traveling wave explanation of the oscillation of the voltage distribution curves about the final distribution thus accounts for the change from the initial distribution to the final distribution, this difference being the criterion of a transient condition in the winding.

## Rope Analogy

The family of distribution curves shown in Fig. 13 usually suggests the oscillation of a rope or chain of finite length firmly fastened at the far end, with a sudden force applied at the home end raising it a given height (potential) above an initial horizontal position. The oscillations of such a rope are usually considered as a standing wave phenomenon, but from the above analogy it is seen that it may also be explained as a reflection phenomenon of a traveling wave. This suggests that if the reflection can be eliminated the oscillations will be reduced to a minimum.

This can be accomplished by extending the length of the rope indefinitely, so that any traveling wave which results from the suddenly applied force merely travels out on the rope indefinitely.

This may be accomplished in a winding by placing at the end of the winding an impedance to ground equal to the characteristic impedance of the winding, which for a generator is a pure resistance equal to the surge impedance of the winding. Such a resistance has the property of extending the winding to infinity so that any wave traveling in the winding will continue, and have no point of reflection to set up a disturbing oscillation in the machine. The oscillographic demonstration is shown in Fig. 12.

A similar explanation of the oscillations of an open winding can be made by assuming the far end of the finite rope to be free. This is analogous to the voltage rise at the far end of the machine winding to double the applied voltage. Those familiar with the oscillations in open and closed organ pipes will recognize a similar phenomenon.

## Generalized Theory of Neutral Protection

The elimination of the oscillations in generator windings by means of a resistance equal to the surge impe-

dance of the winding is a particular example of a general theorem which may be stated as follows:

Any type of apparatus whose internal oscillations under transient conditions can be attributed to reflections of a traveling wave from the terminals of the machine, can be protected from these oscillations by inserting at the neutral terminal to ground an impedance equal to the characteristic impedance of the machine winding.

Such an impedance when tested alone by a given transient force will perform in the same way as the winding to be protected will perform under the same transient force, when the said impedance is in the neutral of the winding to ground. This forms a laboratory verification of the proper impedance to be used in any particular case. Theoretically, if the winding to be considered can be shown to consist of a series impedance $Z_1$ per unit length and a shunt impedance to ground $Z_2$ per unit length, the characteristic impedance[12] is $\sqrt{Z_1 Z_2}$. For a transmission line $Z_1 = L p$ and $Z_2 = \frac{1}{C p}$ and the characteristic impedance becomes $\sqrt{\frac{L}{C}}$ which is dimensionally ohmic in value. This is readily shown from the fundamental energy relations on a line where

$$\frac{W}{2} = \frac{1}{2} L I^2 = \frac{1}{2} C E^2 \tag{4}$$

from which,

$$\frac{E}{I} = \sqrt{\frac{L}{C}} \tag{5}$$

the ratio between the voltage and current of a traveling wave and defined as the surge impedance of the line.

### Frequency of Oscillations

Consider a winding with a grounded neutral in which the voltage wave reflects with change of sign at each terminal. Where the length of the winding is $D$ miles it is easily seen that the wave, traveling at a velocity $v$ miles per second, will travel $2\,D$ to complete one period of its oscillation, hence

$$2\,D = v\,T \tag{6}$$

where $T$ is the period in seconds of its travel. Now the velocity of the wave is known to be

$$v = \frac{1}{\sqrt{L' C'}} \tag{7}$$

where $L^1$ and $C^1$ are the constants per mile of winding.

From these simple relations the frequency of oscillation shown on the oscillograms of Figs. 1 and 5 becomes

$$\frac{1}{T} = f = \frac{1}{2\,D\sqrt{L' C'}} \tag{8}$$

which reduces to

$$f = \frac{1}{2\,\pi\sqrt{L\,C}} \tag{9}$$

when

$$L = \frac{L'\,D}{\pi} \text{ and } C = \frac{C'\,D}{\pi} \tag{10}$$

These relations are interesting and suggest lumped circuit equivalents of a finite transmission line under transient conditions in that $L'\,D$ and $C'\,D$ are the total inductance and capacity of the winding.

In a similar manner it is obvious that the wave travels four times the length of an open winding to return to its initial starting point resulting in a frequency relation

$$f = \frac{1}{4\,\pi\sqrt{L\,C}} \tag{11}$$

which is just half of the frequency of the previous case.

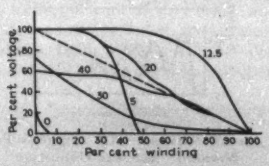


Fig. 13—Distribution Curves of Voltage in Winding of 6600-Volt Machine, Neutral Grounded

### Phase Relations

Referring to Figs. 1 and 2 it may be seen that the voltages measured throughout the winding are in time phase as far as the oscillations are concerned. This might suggest that all points in the winding reach their maximum voltage at the same time due to some mutual coupling throughout the winding; however this need not be the case. By studying the development of the calculated voltages as a result of a traveling wave phenomenon, Figs. 3 and 4, it is seen that this phase relation is fully satisfied. It will be observed, however, that the shape of the voltage oscillations are different throughout the winding. This difference is best shown in Fig. 14 where the voltages measured at 33 per cent and 66 per cent in the winding from the line terminal of the 24,000 volt machine are shown for the condition of the neutral grounded. The voltage between these two points is the difference between the two voltages to ground and is seen to be a second harmonic of the fundamental oscillation. The magnitude of this harmonic voltage is a function of the distance between the two points, the velocity of the wave in the winding and the rate of rise of voltage at the respective points. It is inherently caused by the fact that the voltage wave reaches the two points in the winding at different times, both in its initial trip through the winding and on returning through the winding due to reflections

from the terminals. This phase relation is important since it determines the maximum voltage between turns, one of the fundamental considerations in designing a competent protective unit.

By examining the oscillograms or the calculated curves for the voltages between other parts of the winding it will be found that many interesting harmonic relations exist. The voltage between the line terminal and the midpoint of the winding will be found to be of fundamental frequency. Should the voltage be determined between any two points chosen at random, curves will result which if analyzed would be found to contain many harmonics.

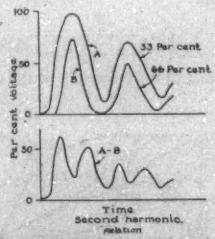


FIG. 14—VOLTAGE BETWEEN 33.3 AND 66.6 PER CENT OF WINDING—NEUTRAL GROUNDED

## TRANSMISSION LINE CONSTANTS OF GENERATOR WINDINGS

Any distributed circuit with $Z_1$ as a series element and $Z_2$ as a shunt element, has another very characteristic constant, namely the velocity of propagation[12] of a wave along the system proportional to $\sqrt{\frac{Z_2}{Z_1}}$. On a transmission line where the series element is inductance and the shunt element capacitance this constant becomes $v = \frac{1}{\sqrt{LC}}$. The surge impedances of standard transmission lines are usually between 300 and 600 ohms and the velocity of propagation of the waves is usually close to the speed of light or 186,000 miles per second.

Since a generator winding has been found to function substantially as a finite line it must also possess similar characteristic constants. These are readily obtained from the oscillograms.

Consider the tests on the 6600-volt winding shown in Figs. 5, 6, 9, 10, and 12. The surge impedance may be determined either from the difference between the open circuit voltage and the terminal voltage (provided the surge impedance of the incoming line is known, which in this case was 250 ohms), or more accurately from the proper value of resistance to prevent reflections at the neutral. Hence the resistance used in Fig. 12 to prevent reflections was 800 ohms and this may be considered to be the surge impedance of the winding.

If we assume that the wave follows the actual metallic path through the winding the velocity of propagation is just as readily obtained from the frequency of oscillations, knowing the actual length of the metallic circuit which for the case of the 6600-volt winding was 0.301 miles. Thus the average velocity of the wave through this winding was found to be 24,000 miles per second.

It would seem reasonable to assume that the velocity of the wave in the slot is much slower than in the end turns of the machine. To determine this point more accurately 10 coils were tested in series in air and the velocity of propagation of the wave found to be 125,000 miles a second. This was considered a little faster than the wave would actually travel in the end turns because the latter would have a higher inductance and capacity due to the proximity of the core of the machine. For this reason the velocity in the end turns was considered as 100,000 miles a second.

Using this velocity in the end turns it was found that the velocity of the wave in the slot portion was very close to 10,500 miles per second. This velocity was obtained within a few per cent on the three machines tested.

In order to establish one equivalent velocity in the winding it becomes necessary to determine the equivalent length of the generator winding by reducing the end turns to equivalent slot dimensions. This is determined from the fact that the wave travels approximately ten times as fast in the end turns as in the slot portion, hence, where $D$ is the core length in inches, $M\,L\,T$ is the mean length of turn in inches, and $N$ is the turns in series per phase, the effective length of the winding becomes

TABLE I
TABULATION OF TRANSMISSION LINE CONSTANTS OF GENERATOR WINDINGS
Windings Reduced to Equivalent Slot Basis

| Machine voltage | Equivalent length of winding in miles $N\,l = K\,(1.8\,D + 0.1\,M\,L\,T)\,N$ (see Eq. 12) | Time to traverse winding (microseconds) | Velocity of wave in winding (miles per second) | Surge impedance of winding (ohms) | Inductance per mile of slot (henrys) | Capacitance per mile of slot (microfarads) | Equivalent length of transmission line (miles) |
|---|---|---|---|---|---|---|---|
| $V$ | $N\,l$ | $t$ | $v$ | $Z_g$ | $L'$ | $C'$ | $L$ |
| 2,200 | 0.0343 | 3.4 | 10,100 | 685 | 0.0675 | 0.144 | 0.627 |
| 6,600 | 0.1325 | 12.5 | 10,600 | 800 | 0.0755 | 0.118 | 2.32 |
| 24,000 | 0.272 | 25 | 10,900 | 1000 | 0.0918 | 0.0918 | 4.65 |

$$N\,l = (2\,D + 0.1\,(M\,L\,T - 2\,D)\,N$$
$$N\,l = (1.8\,D + 0.1\,M\,L\,T)\,N \qquad (12)$$

The surge impedance of the various machines, the machine dimensions, velocity of propagation, capacity, and inductance per unit length as determined from tests are shown in Table I. The slot relations and arrangement of conductors are shown in Fig. 15 for the machines tested.

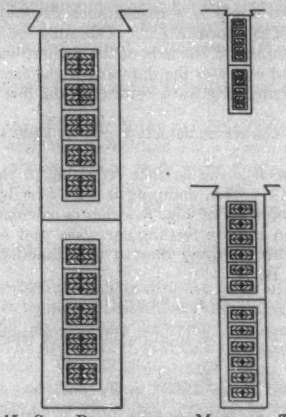

FIG. 15—SLOT PROPORTION OF MACHINES TESTED

It will be noted from the table that the velocity of propagation in each case is slightly slower as the size of the slot is reduced around the conductor. It is also interesting to note that the surge impedance is largest with the larger slot, showing that as the voltage of the machine is increased, necessitating more insulation and a larger slot, the rate of change of capacity is greater than the rate of change in inductance.

It is believed that the surge impedance and propagation constants as found for the machines under consideration are in general the same for the types of machine windings tested, the surge impedance being the more important as it will determine the maximum allowable resistance which can safely be put in an open neutral in case of a transient disturbance.

## ELIMINATION OF OSCILLATIONS

It follows from the traveling wave theory that the magnitude of the oscillations can be reduced by slowing up the front of the wave applied to a winding. This fact is appreciated when the analysis of Figs. 3 and 4 is made using a wave with a slower front. This reduction in voltage oscillations with the slower wave is inherently due to the fact that the front of the wave reflects in the winding to reduce the maximum voltages which would have occurred.

Another way of explaining this fact is by the principle of superposition. Any positive wave with a sloping front can be considered to be equivalent to a rectangular positive wave and a negative wave equal to the difference between the rectangular wave and the given wave. Allow both of these waves to reach the machine simultaneously and solve for the internal voltages for each separately. The resulting solutions may then be added in their proper time relations, obtaining the correct result. The smaller negative wave will produce predominantly negative voltages which give rise to the lowering of the resulting stresses. In this way it is readily seen that if the applied wave rises slowly enough, no oscillations would take place; moreover, that the front of the wave applied to an open winding would have to be twice as slow as that applied to the same winding with a grounded neutral to produce the same reduction in oscillations. In this way the natural frequency of a winding under any given conditions is a measure of the wave-front which will reduce these oscillations. A good criterion of such a wave is one which rises to 90 per cent of its maximum value in a time equivalent to the period of the natural frequency of the winding. Such a wave will not eliminate the oscillations, but will reduce them to a reasonable value.

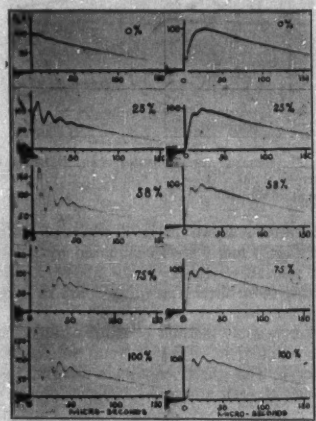


FIG. 16—OSCILLOGRAMS SHOWING THE REDUCTION IN OSCILLATIONS WITH SLOW WAVE FRONTS IN A 2200-VOLT INDUCTION MOTOR

Fig. 16 shows the reduction in internal oscillations in a 2200-volt induction motor winding with the far end of the winding open, when a 13-microsecond wave is applied, in comparison with the corresponding oscillations for a very steep wave. In studying Fig. 16 alone, one might draw the conclusion that the oscillations are necessarily associated with steep waves, but such is not the case. It is true that the oscillations would not

have occurred if the steep front had not been applied, but the oscillations are caused by the reflection phenomena at the terminals of the winding. Fig. 17 shows the oscillations in the same winding with the same steep wave applied but in the right hand case the neutral of the winding was equipped with a resistance to ground equal to 685 ohms, the surge impedance of the winding. Here it is seen that the oscillations have been practically eliminated by preventing reflections in the winding.

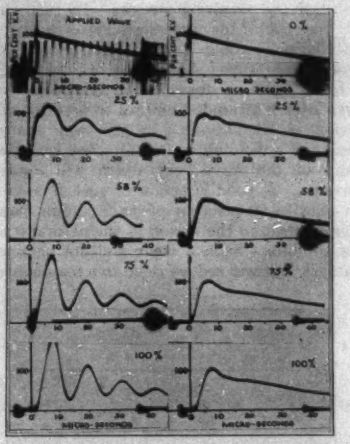


Fig. 17—Oscillograms Showing the Elimination of Oscillations in the Winding of Fig. 16 by Putting 685 Ohms in Neutral to Ground

A similar proof is shown in Fig. 12 where all the oscillations of Figs. 5 and 6 were eliminated by means of a neutral resistance. Both of the above methods of eliminating these disturbing voltages are in agreement with the traveling wave theory.

Another possible method of eliminating reflections in such windings is suggested from the transmission line theory. This scheme consists in tapering the surge impedance of each winding. If each phase of the generator winding were equipped with capacitors to ground throughout the winding in such a way that the surge impedance tapered uniformly from its normal value at the line terminal to zero ohms at the neutral and the neutral grounded, then any voltage wave entering the winding would travel through the winding at some variable speed, its magnitude dropping in proportion to the surge impedance. That is, as the wave traveled through the winding its electrostatic energy of potential would be gradually transformed into electromagnetic energy of current, and on reaching the grounded neutral discharge to ground. There would be no reflection because the impedance to ground is that of the surge impedance at that point. This method of eliminating oscillations is difficult to apply to rotating machinery. Moreover simpler methods are available for accomplishing the same result.

## Damping of Oscillations

There is a number of causes for the damping of the oscillations:

One is the fact that all the oscillations are damped at the rate of the applied wave. In all cases the tail of the applied wave is a capacitance discharge and inherently of the form $E\,\epsilon^{-\beta t}$. This may be referred to as the damping of the axis of the oscillations.

A second cause of the damping is the fact that each time the remaining wave returns to the line terminal a portion of the wave, namely $\left(\frac{2Z_1}{Z_1+Z_2}\right)$ per unit is lost to the line $Z_1$, the balance reflecting in the machine winding $Z_2$. This damping is best seen by studying the development of Fig. 8 which is calculated on the basis of an infinite rectangular wave and no machine losses. The damping due to this junction loss (see Appendix B) is:

$$\epsilon^{\left(\frac{R_0}{2L_0}\right)t} \tag{13}$$

Where $L_o = D\,L'$ = total inductance of winding

$$R_0 = Z_2 \operatorname{Log}_e \left\{ \frac{Z_2 - Z_1}{Z_2 + Z_1} \right\} \tag{14}$$

When $Z_1 = 0$, this damping is zero. When $Z_2 = Z_1$ the entire wave will return upon the line and the damping will be a maximum.

If a resistance $R$ had been placed in the neutral of the winding another damping term would enter similar to Equation (13) by replacing $Z_1$ with $R$. Here again we know that if $R = Z_2$ maximum damping will occur, that is, there will be no reflection.

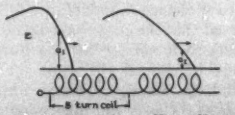


Fig. 18—Schematic Diagram of Wave Entering Generator Winding—Showing the Relation between Wave Front and Voltage between Turns

A third component of damping follows directly from the fact that the further the wave travels in the machine winding the slower the wave-front becomes. Fig. 12 shows clearly the distortion of the wave as it proceeds through the 6600-volt winding and Fig. 17 for the 2200-volt winding. This distortion may be attributed to natural losses in the winding such as skin effect, leakage, resistance, core losses, and series capacitance between turns. This natural slowing up of the wave-front as the wave proceeds through the winding together with

the fact that slower wave-fronts reduce the oscillations as shown in Fig. 16, accounts for the third component of damping.

### Three-Phase Windings

Consider a lightning disturbance to enter on all phases of an $n$ phase machine simultaneously and travel toward the common neutral which is open. Assuming that a voltage wave of $E$ volts travels in each phase of $Z_o$ ohms surge impedance and that the mutual relations between phases are small, it is desired to determine the maximum neutral voltage. Each wave on arriving at the neutral will find a surge impedance of $\left(\frac{Z_o}{n-1}\right)$ ohms, the parallel value of the remaining phases. The neutral voltage or the voltage wave which enters the remaining phases due to each wave approaching the neutral will be $\frac{2E_o}{n}$ and for $n$ phases the maximum neutral voltage will be $2E_o$ as in the case of a single winding.

It is now desired to determine the value of resistance $R$ to place in the neutral such that the maximum neutral voltage will be $E_o$, the lightning arrester voltage. It is shown in Appendix B that this resistance is equal to $Z_o/n$ ohms. This is the parallel value of all the windings to neutral. This resistance in the neutral, equal to one-third the surge impedance of a single winding for a three-phase machine, will not allow the neutral to rise above the terminal voltage. Moreover it will be found that the reflected voltages in each phase due to the wave traveling in that phase are exactly equal and opposite to the transmitted voltage waves from the other phases, and equivalent to no reflection taking place. In this respect a three-phase machine will have the properties of a single winding as discussed and shown in the oscillograms of this paper. Oscillograms taken in three-phase machines under these conditions, and not shown in the paper, bear out these statements.

### Protection of Windings

In inductive windings there are two distinct insulations to protect, namely the insulation to ground and the insulation between turns. To protect these insulations properly it is imperative to know just what factors determine the maximum stresses which will occur in the machine to ground and between various sections of the machine winding.

### Insulation to Ground (a)

The voltages to ground in practical cases are a direct function of the maximum voltage allowed by the line terminal arrester. The arrester voltage is the applied wave to the machine. However, with an open neutral machine it has been shown that due to reflections of a steep wave at the neutral double arrester voltage occurs in the winding which may cause the insulation to fail.

Consider a special case of a three-phase, 27-kv. machine connected to an overhead line where the lightning arresters allow a maximum of 80 kv. to enter each winding. If the neutral were open the maximum voltage to ground could be 160 kv. or 7.3 times normal crest voltage to ground. This can be reduced to arrester voltage by grounding the neutral, or by placing in the neutral to ground a resistance equal to or less than one-third of the surge impedance of a single winding.

The lightning arrester is essentially a device for the protection of the insulation to ground of inductive windings by limiting the maximum voltage of the wave entering the winding while the neutral resistor is an agent for the protection of the same insulation by preventing positive reflections from taking place at an open neutral. It should be observed, however, that in the protection of the insulation to ground any resistance less than this value may be used.

### Insulation Between Turns

Neglecting for the moment the induced voltages in the adjacent turns the voltage between turns for any

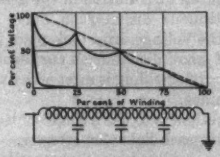


Fig. 19—Effect of Capacity Shielding on Initial Voltage Distributions in Generator Winding

given machine is a function of the steepness of the applied wave. This follows on the assumption that the wave requires a definite time to travel an integral length of the metallic circuit of the winding as indicated on the oscillograms. Consider a steep wave entering the winding of Fig. 18, the wave traveling at a velocity $v$. When the tip of the wave arrives in the second turn, directly below the point of entering the winding, the voltage between turns will be $e_1$ volts, which will be smaller with slower fronts. The effect of the induced voltage is always in a direction to lower this maximum stress. As the wave travels through the winding its front becomes slower (see Fig. 12) and hence the maximum stress occurs on the end turns. In case of an open neutral, the steepness of the wave arriving at the neutral doubles when the positive reflection occurs.

Either a steep rise or a sudden drop in voltage may produce high stresses between turns. A steep drop in voltage may be caused by any sudden change of circuit such as an insulation flashover close to the substation. Special means must be employed to reduce these steep gradients. One method which has been developed for inductive windings and found to be very effective in

reducing the stress between turns consists in shielding[9] the winding in such a way that the initial voltage distribution throughout the winding is close to the final voltage distribution. Physically, a continuous shield would be difficult to incorporate in a synchronous machine winding; however, its effect can be very closely approached by placing properly designed capacitors between various points of the winding and the line terminal. Such an arrangement of capacitors would

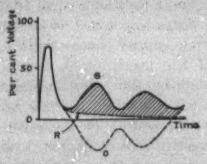


FIG. 20—TYPICAL CURVES SHOWING VOLTAGE BETWEEN TURNS OF GENERATOR WINDING UNDER VARIOUS TERMINAL CONDITIONS

Voltage between turns
*G*—Neutral grounded
*O*—Neutral open
*R*—Resistance in neutral

change the initial distribution in the generator winding from a continuous distribution curve in which the majority of the voltage drop took place in the first coil to a series of small distribution curves as shown in Fig. 19. This type of shielding is most effective for grounded neutral machines.

Another method is to use a single capacitor to ground in parallel with each lightning arrester. Such a capacitor may be considered as a protective unit for the insulation between turns of inductive windings. Moreover, in slowing up the wave-front of a steep surge the capacitor affords protection to the insulation to ground should it be necessary to operate with an open neutral. This is clearly shown in Fig. 16. In this respect the capacitor to ground at the line terminal in parallel with the arrester can be designed to eliminate practically all the oscillations in an open neutral machine and at the same time to preserve the insulation between turns. It is a very efficient protective unit.

Neutral resistances also play a small part in protecting of the insulation between turns. This follows from the fact that each time the wave reflects in the winding, it subjects the turn insulation to additional strain by increasing the time element. This is readily appreciated by studying the distribution curves of Fig. 13, realizing that the slope of these curves at any point is an indication of the voltage between turns at the point and time measured. Fig. 20 shows the voltage between turns of a representative coil near the line terminal for the three conditions of grounded neutral, open neutral, and with the proper resistance in the neutral to suppress reflections. The shaded area is the reduction in stress which is afforded by the neutral resistor.

9. For references see Bibliography.

Other factors also affect the stresses between turns for a given applied wave, the most important of which are the surge impedance of the incoming line and the resistance of the lightning arrester. These will be discussed in connection with the protective devices.

## LIGHTNING ARRESTER PROTECTION

The lightning arrester is an operator or electric valve. It receives a large incoming surge and together with the surge impedance of the incoming line allows a smaller surge to pass. In this respect the lightning arrester is a very satisfactory agent for limiting the amplitude of voltage wave which enters machine windings. It has no power to prevent oscillations within the winding.

In fact, it is entirely possible to have a wave enter the winding just below arrester breakdown, travel to an open neutral, and reflect positively to practically double arrester voltage, the reflected wave returning to the arrester causing it to go into operation for the first time; but by this time the insulation may have had ample time to fail. Here we see that it is necessary to avoid dangerous reflections at the neutral to limit the internal potentials to arrester voltage, thus crediting the arrester with its true power for protecting the insulation to ground of inductive windings.

Assuming that these precautions are taken the factors controlling the size and shape of the wave entering the winding will be considered for a given lightning surge applied to the terminal. With the advent of thyrite, the new material for lightning arresters,[1] the predetermination of arrester voltages for a given wave and cir-

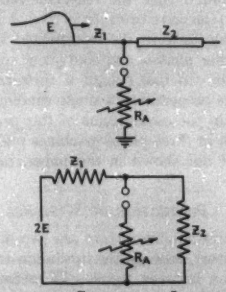


FIG. 21—EQUIVALENT CIRCUIT OF LIGHTNING ARRESTER PROTECTING A GENERATOR WINDING

cuit condition are readily obtained by a simple circuit analysis.[2]

Applying the general circuit transformation shown in Appendix A to the case of an incoming line of surge impedance $Z_1$ terminating in a generator winding of surge impedance $Z_2$, protected by a lightning arrester of resistance $R_A$ the simple lumped circuit of Fig. 21 is obtained. The wave entering the winding will always be identical to the voltage drop across the resistance $Z_2$

of the lumped circuit when the open circuit wave is applied to its terminals.

This solution of arrester voltage may be divided into three parts, (1) before arrester breakdown, (2) during arrester discharge, and (3) after arrester discharge.

(1) Before arrester breakdown, $\left(\frac{2\,Z_2}{Z_1 + Z_2}\right)$ per unit of the traveling wave enters the winding. It is important to observe that the steepness of this wave entering the winding is also increased above the slope of the traveling wave by this same percentage and that it is independent of the lightning arrester.

(2) At a predetermined voltage the arrester goes into operation causing a change in circuit. This sudden change results in a new terminal impedance $R_o$ which is the parallel value of $Z_2$ and $R_A$, the arrester resistance, the latter being a variable dependent upon the open circuit voltage. The arrester voltage then suddenly becomes $\left(\frac{2\,R_o}{Z_1 + R_o}\right)$ per unit of the traveling wave. This change results in a sudden drop in voltage which is shown in Fig. 22. This drop is independent of the rate at which the voltage rises to arrester breakdown. It will always occur when the arrester goes into operation.

(3) As the voltage drops on the tail of the wave a point will be reached where the arc of the gap goes out and the voltage will suddenly return to the initial curve, or $\left(\frac{2\,Z_2}{Z_1 + Z_2}\right)$ per unit of the applied wave. This point will depend upon the arc drop in the gap unit and will correspondingly be a point such that the new voltage will not be sufficient to rekindle the arc. This small rise in voltage may be neglected.

When the arrester goes into operation the terminal voltage will suddenly drop then slowly rise again depending on the crest value of the open circuit wave, coming to a new crest, which in case of a severe wave, may be slightly higher than arrester breakdown voltage. The maximum voltage which a given arrester may attain is hence governed by the insulator flashover value of the line.

In the foregoing relations it will be found that the surge impedance of the incoming line plays a definite part in protecting the winding, in that the larger this surge impedance, the lower the arrester voltage as seen from the relations shown above. The fact that the front of the wave will have had time to penetrate the winding, charging its capacity to a definite voltage before the arrester goes into operation and allowing this stored energy to discharge back through the arrester resistance after arrester operation, will help considerably to lower the stress on the end turns due to the drop in arrester voltage.

## Capacitor Protection

In the previous study it was observed: (1) that the arrester before breakdown does not affect the front of an incoming wave, and (2) that the steepness of the wave entering the winding has been increased to $\left(\frac{2\,Z_2}{Z_1 + Z_2}\right)$ per unit of the steepness of the incoming wave due to reflection at the change of surge impedance.

The capacitance of substation equipment plays a very small part in protecting terminal apparatus from these steep waves by providing a reservoir for the energy stored by the front of the wave and delivering this energy to the wave should any sudden change in voltage tend to take place. This inherent capacity of the terminal equipment is not sufficient to protect the insulation between turns of machine windings and it becomes necessary to provide additional capacity to reduce steep waves to safe gradients.

Introducing a capacitor in parallel with the arrester of Fig. 21 and assuming the severe case of a rectangular wave of a magnitude equal to the line insulation flash-

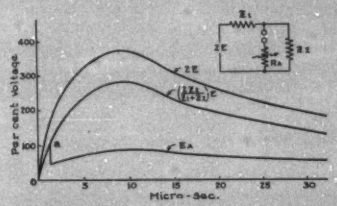


Fig. 22—Typical Form of Arrester Voltage Showing the Drop in Voltage Due to the Arrester Operation

over value for the length of wave considered, the resulting voltage may be determined.

The equation for the front of the wave entering the machine winding will be

$$E_v = \left\{ 2\,E\left(\frac{Z_2}{Z_1 + Z_2}\right)\left\langle 1 - \epsilon^{-\left(\frac{Z_1 + Z_2}{C\,Z_1\,Z_2}\right)t} \right\rangle \right\} \quad (15)$$

where $E$ is the insulator flashover value of the line. It follows from this relation that the maximum voltage between turns due to this wave, based upon the time constant of the voltage wave shown in diagram of Fig. 18, and Equation (12), will be:

$$E_T = \left(\frac{2\,E\,(1.8\,D + 0.1\,M\,L\,T)\,K\,10^9 \text{ volts}}{v\,Z_1\,C}\right) \quad (16)$$

Where $t = \frac{l}{v}$

Assuming a velocity of 10,500 miles per second in the slot as found by tests, this relation reduces to:

$$E_T = E\left\{\frac{3\,(1.8\,D + 0.1\,M\,L\,T)}{Z_1\,C} \text{ volts}\right\} \quad (17)$$

where

$E_T$ = maximum voltage between turns in volts
$E$ = insulating flashover in kv.
$Z_1$ = surge impedance of incoming line in ohms
$C$ = capacitance to ground in microfarads
$D$ = core length in inches

$$K = \left(\frac{1}{12 \times 5280}\right)$$

$M\,L\,T$ = mean length of turn in inches

At a definite voltage the arrester goes into the circuit, but due to the stored energy in the capacitor the voltage will not drop suddenly but will discharge to the original arrester voltage through the parallel resistance paths afforded by the arrester and adjacent lines. This discharge circuit is shown in Fig. 23 and becomes important in considering the limiting condition of a sphere-gap in place of the arrester. Independent of how slowly the voltage may have risen to gap breakdown with the assistance of additional capacitors to ground, when the gap breaks down all of the stored energy in the capacitor is immediately short circuited to ground, resulting in a sudden drop in voltage. This is excellent protection for the insulation to ground but may increase the stress on the insulation between turns.

In this respect the resistance of the arrester provides

Fig. 23—Discharge Circuit After Arrester Breakdown

a discharge circuit with a reasonable time constant, allowing the gradient after arrester breakdown to be within the limits for the protection of the insulation between turns.

Should a flashover occur on the line close to the capacitor the time constant of the resulting discharge circuit would be so small that the stored energy in the capacitor would be of little value in reducing the sudden drop in voltage. The chance of such a flashover near the station is confined to the probability of a direct stroke occurring in this region since any traveling wave will reflect as a negative wave from the arrester.

It has been shown that by slowing up the front of the wave the oscillations can be considerably reduced, thereby effecting protection for the insulation to ground of open neutral machines. By making a close study of Fig. 16 it is found that to obtain the reduction shown in the figure it is necessary to provide a capacitor which would allow a steep wave to rise to arrester breakdown in a time close to the period of the natural frequency of the open circuit winding. The period is given by the equation

$$T = \left\{\frac{4\,N\,l}{v}\right\} \tag{18}$$

where $N\,l$ is the effective length of the winding given in the Table I and $v$ = 10,500 miles per second.

Making this time substitution in Equation (15) and solving for the required capacitance there results the expression

$$C = -\left\{\frac{(Z_1 + Z_2)}{Z_1\,Z_2}\left\langle\frac{4\,N\,l}{\text{Log.}\left\{\dfrac{(Z_2(2-m) - m\,Z_1)}{2\,Z_2}\right\}v}\right\rangle\right\} \tag{19}$$

where

$Z_1$ = surge impedance of incoming line
$Z_2$ = surge impedance of winding
$m$ = arrester breakdown in per unit of line insulator flashover
$v$ = velocity of the wave in the winding.

Consider the capacitor required to reduce the oscillations in the 24,000-volt winding when connected to 300-ohm line whose insulator flashover is 450 kv. and the arrester breakdown set at 90 kv. Here $m$ = 0.2. Solving for $C$ it is found that 3.12 microfarads are required to reduce the oscillations. This is considerable capacity and far in excess of that required for the protection of the turn insulation of the same winding, the amount required for this being approximately 0.3 microfarad.

When it is necessary to use line reactors to limit the short-circuit currents they can be employed effectively in connection with the surge protection of the same machine. This is accomplished by properly shunting the reactor with a resistor[8] and using a smaller capacitor to ground than would have otherwise been necessary to produce the same reduction in wave-front. The resistor shunting the reactor is necessary to damp the oscillations between the reactor and capacitor so that the crest valve of the first peak of the oscillations will be well below the strength of the insulation to ground of the machine winding. When the reactor is placed between the capacitor and the lightning arrester it will offer an additional safeguard to the terminal equipment in the event of a flashover near the station. This is evident since such an impedance between the capacitor and the flashover will furnish a circuit with a reasonable time constant allowing any stored energy in the capacitor to become effective in reducing the gradient of the sudden drop in voltage.

Another advantage of the capacitor is that it will permit the location of the lightning arrester further from the terminal apparatus which it is to protect from traveling surges. This is true because it will not allow reflections to build up between the arrester and the apparatus. This will be appreciated when it is realized that the slow wave-front of Fig. 16 was sufficient to prevent oscillations in the generator winding which is equivalent to an open line of 3300 ft.

Other factors must be considered also in the use of capacitors which in certain cases may become quite

important, namely, the effect upon carrier current systems and the circulation of harmonic currents generated by the machine.

### Neutral Protection

On a transmission line basis the neutral of a machine winding is several miles from the line terminals. It has also been shown that steep waves traveling on all three phases of Y-connected machine may cause the neutral to rise to twice arrester voltage if the neutral were open. From this standpoint the concept of neutral lightning protection is introduced as a necessary addition to the protection of ungrounded machines exposed to lightning or switching surges.

The ideal neutral protection from the traveling wave standpoint would be a pure resistance to ground equal to the surge impedance of the several phases in parallel. Often such a resistance cannot be used because of short-circuit protection or telephone interference problems. Consider a practical case of three arrester-protected generators in parallel feeding an overhead line, one of the generators being grounded through a very small resistance to furnish current for the short-circuit protection of the group, the other two generator neutrals being left open. The two open neutral machines may be subjected to internal potentials to ground double the maximum arrester voltage while the grounded machine is adequately protected. Should resistors of 200 ohms be put in the neutrals of the two exposed machines the resulting circulating currents may be undesirable. This difficulty is overcome when it is realized that this form of neutral protection is only desired in case of surges, thus permitting the use of any device which will automatically lower the neutral voltage in case of a disturbance entering the winding. A material excellently adapted to this purpose is thyrite.[1] Consider a unit of thyrite properly designed and placed in the neutral to ground of the two open neutral machines. Under normal operation the neutral potential of the machine is low and the corresponding resistance of the thyrite is extremely high, permitting only a few milliamperes of circulating current, effectively an open neutral. Now when the neutral voltage tends to rise due to a disturbing transient reflection the resistance of the thyrite immediately drops. Every time the neutral voltage is doubled the resistance to ground becomes one-sixth of its former value. In this way the neutral protector can be designed to give the proper resistance to ground in the presence of half the lightning arrester potential, thereby affording the desired surge protection and still operating effectively as an open neutral during normal operation.

Consider the case of a large synchronous condenser connected directly to an overhead line, while near by on the same system are several groups of transformers feeding a metropolitan area, the transformer neutrals providing the short-circuit protection of the substation. In case the synchronous condenser has certain harmonics in its wave form it may be desirable to leave the neutral open to avoid interference with the neighboring telephone circuits, at the same time subjecting the insulation to double arrester voltage in case of a steep surge. Should a resistance equal to the surge impedance of the several windings in parallel be placed in the neutral for adequate surge protection, it may be found that the interference currents are still appreciable. These difficulties may be overcome by placing thyrite in the neutral to ground. It will function as in the preceding case in the event of a surge, while during normal operation its high resistance property will allow only a fraction of a milliampere of harmonic currents to flow in the presence of 1000 volts of harmonic voltages at the neutral. In this respect thyrite offers advantages in reducing telephone interference currents.

Many neutral protection devices are possible and might have specific application in certain cases, such as a neutral reactor in parallel with thyrite. Gaps in the neutral preferably are avoided except in cases where there is a reservoir of energy and a discharge circuit with a reasonable time constant to take the shock of the sudden gap operation. The principle here is the same as outlined in connection with the line terminal protection.

It should be restated that whereas a grounded neutral winding will allow a negative reflection to take place, the stress on the insulation to ground will not be in excess of the lightning arrester voltage and for this reason machines operating with solidly grounded neutrals or with a resistance below the parallel value of the surge impedance of the respective phases, should not require any additional neutral protection.

### Summary and Discussion

An oscillographic study of the transient oscillations in machine windings has been presented which reveals the following facts:

(1) That machine windings subjected to transient surges function as finite transmission lines of several miles in length obeying the natural laws of reflection and propagation of surges on an open line.

(2) That due to reflections at open neutrals the maximum voltage to ground in a machine winding due to a unidirectional surge is double the maximum arrester voltage.

(3) That the surge impedance of machine winding tested is in the neighborhood of 600 to 1000 ohms while the velocity of propagation of the waves is in the neighborhood of 10,000 miles per second in the slot portions.

The traveling wave analysis of the voltage oscillations has very simply accounted for the following secondary phenomena:

(1) Relations between natural frequency and voltage magnitude in open, ground, and fractional windings.

(2) Phase displacements and harmonic relations between various points in the winding.

(3) Oscillation of voltage distribution curves as standing waves about the final voltage distribution.

(4) Damping of the oscillations.

Three possible methods of reducing the disturbing oscillations in rotating machines were discussed. They are:

(1) Reduction by slowing the front of the applied wave with a capacitor in parallel with the lightning arrester.

(2) Preventing reflections at the neutral by grounding the neutral through the characteristic impedance of the machine windings.

(3) Tapering the surge impedance of each phase from its normal value at the line terminal to a very small value at the grounded neutral.

In the light of the facts made known in this investigation the following conclusions regarding protective equipment were reached.

(1) That the lightning arrester is the most effective protective unit now available for the protection of machine windings. However, it only limits the magnitude of the wave which enters the machine winding and cannot control the oscillations within the winding. It does not affect the front of the wave below arrester breakdown.

(2) Neutral impedance when used can be made of thyrite and effectively be an open neutral during normal operation and yet afford the necessary additional protection in case of a dangerous surge.

(3) Capacitors in parallel with the lightning arrester afford adequate protection for the insulation between turns of machine windings. They also provide protection for the insulation to ground of machine windings by reducing internal oscillations in cases where the neutral is open. In this respect they may even be designed to eliminate the oscillations in short open neutral windings.

(4) The principles of shielding which have proved successful in protecting transformers[3] may also be applied to generator windings.

(5) For the adequate protection of large units connected directly to the line and with neutral open, some protector in addition to lightning arresters is necessary in order to insure that the internal voltages to ground will not exceed the arrester voltage and to adequately protect the insulation between turns.

ACKNOWLEDGMENT

The author wishes to acknowledge the helpful suggestions of Mr. P. L. Alger under whose direction this investigation has been made possible.

Much credit is also due to Mr. C. M. Foust and his assistants Messrs. N. Rohats, H. R. Walker, and others whose help has made possible the oscillographic tests shown in this paper.

## Appendix A

The purpose of this appendix is:

(1) To prove that the laboratory test circuit used for obtaining the results shown in this paper is an accurate representation of actual field conditions.

(2) To show that these laboratory circuits are based upon the equivalent lumped circuits of the distributed transmission line field circuits under transient conditions, the latter being rigorously derived and forming a convenient and accurate method of applying simple circuit theory to the calculation of the performance of protective equipment, avoiding completely the introduction of the old traveling wave equations.

The increasing use of high-voltage laboratories for conducting investigations to study the performance of electrical equipment under transient disturbances and for testing the insulation strength of transmission line equipment points to the desirability of the standardization of testing methods. This need will be further appreciated when it is realized that where traveling wave conditions are to be satisfied in the laboratory it not only becomes necessary to obtain voltages which appear to be similar to those found in practise but it is also necessary to satisfy the corresponding current relations. In satisfying both current and voltage relations the complete energy relations of the traveling wave are satisfied and the laboratory results may be used with safety as criterions of field conditions.

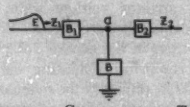


FIG. 24—GENERALIZED CIRCUIT OF A TRAVELING WAVE APPROACHING A JUNCTION IMPEDANCE

The ratio of the voltage to current of a traveling wave is defined as the surge impedance of the line and by definition is ohmic in value. This ohmic property of a transmission line to traveling surges is extremely important and should receive a definite place in the equivalent test circuit.

The rigorous derivation of a general equivalent circuit of a transmission line meeting any type of terminal or junction impedance for surge conditions appears in the literature[3] and only the results of this analysis will be given here.

Consider the general circuit of Fig. 24 consisting of two transmission lines with junction impedances $B_1$, $B_2$, and $B$ and the wave approaching from the left on the line of surge impedance $Z_1$.

The impedance $B_1$ and $B_2$ may be reactors, series capacitors, etc. while $B$ is the impedance of the terminal equipment to ground.

Using the classical wave equations of traveling waves on transmission lines with which actual line performance has been calculated many times,[3,4,5] it is readily

shown that the expression for the current wave entering the line $Z_2$ of Fig. 24 for the wave $e$ approaching on the line $Z_1$, is,

$$i_{z2} = \left\{ \frac{2\,e\,B}{B(Z_1+Z_2+B_1+B_2)+(Z_1+B_1)(Z_2+B_2)} \right\} \quad (20)$$

Now consider the transmission line circuit of Fig. 24 closed into the lumped circuit of Fig. 25 by allowing the surge impedances to have the property of

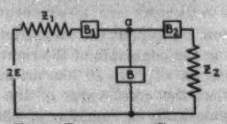


Fig. 25—Exact Equivalent Circuit of Fig. 25

lumped resistance equal to the ohmic surge impedance of the respective lines.[13] Solving for the current in $Z_2$ of this circuit for the application of $2\,e$ or the open circuit voltage on the line, there results the identical equation that was obtained above by the well known, but rarely used, wave equations. In the same way, every voltage and current in the lumped circuit satisfies the classical wave solution to the extent that all transmitted and reflected waves may be computed[3] by the application of Ohm's and Kirchoff's laws to the simple lumped circuit of Fig. 25.

This circuit has been used successfully to calculate the terminal voltages of transformers when used in connection with choke coils and reactors, both with and without lightning arresters, when subjected to traveling waves over the transmission line of the Turners Falls Electric Company during the summer of 1929. The calculations were in excellent agreement with the oscillograph records.[3] This agreement would naturally be expected if the equivalent circuit were correct. The fact that this equivalent circuit is lumped, immediately suggests that it is also readily adapted as a laboratory circuit for conducting other investigations where traveling waves are impressed upon terminal apparatus. Used as a laboratory circuit it naturally follows that the calculations of such laboratory tests would involve the same procedure and results as would be obtained if the investigation had proceeded in the field. This agreement has made it possible to reproduce fields tests in the laboratory repeatedly with the above circuit.

In adapting Fig. 25 as a laboratory test circuit a slight modification is necessary in order to take care of the capacitance of the lightning generator which is always in the circuit. This modification in turn will be handled in a perfectly rigorous manner, which should result in the design of a testing circuit which will satisfy all the time-energy relations of a traveling wave solution.

Examining Fig. 25 it is seen that looking from the terminal impedance back into the equivalent transmission line, a pure resistance equal to the surge impedance of the incoming line, is found. This pure resistance property of the equivalent circuit of Fig. 25 must be satisfied in the equivalent laboratory test circuit. This is uniquely accomplished by employing a well known parallel circuit consisting of the capacitance $C$ of the lightning generator in series with a resistance $R_1$, this in parallel with a series circuit consisting of an inductance $L$ and resistance $R_2$. This is shown as the left hand circuit of Fig. 26. This parallel circuit has the property of a pure resistance for all frequencies when $R_1 = R_2 = \sqrt{\frac{L}{C}}$ = resistance of the parallel circuit. This property under these conditions avoids any error being introduced because of the necessity of the capacitance of the lightning generator remaining in the circuit after the initial discharge. (21)

The resulting laboratory test circuit is shown in Fig. 26 and will now be considered in detail to show that under transient conditions it functions as an incoming transmission line.

It should be obvious that in designing the left hand circuit of Fig. 26 for an equivalent surge impedance of $Z_1$ ohms, the following relations are imperative:

$$R_1 = R_2 = R \quad (22)$$

and

$$R_3 + R = Z_1 \quad (23)$$

Moreover, with a given capacitance $C$ in the lightning generator the necessary inductance is predetermined to satisfy the conditions of Equation (21), that is,

$$L = C\,R^2 \quad (24)$$

The discharge of a capacitance, charged to a voltage $E_c$, can be rigorously determined by solving the cir-

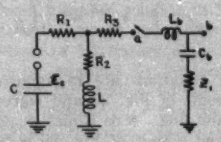


Fig. 26—Laboratory Test Circuit which is the Exact Transient Equivalent of a Transmission Line

cuit as if a battery of $E_c$ volts had been introduced in series with the uncharged condenser.[11] Solving for the open circuit voltage at $a$ of Fig. 27 and letting this voltage be represented by $2\,e$ as in the text of the paper, there results,

$$2\,e = E_c \left\{ \left( \frac{L\,p + R}{L\,p + \frac{1}{C\,p} + 2\,R} \right) \right\} 1 \quad (25)$$

which reduces to

$$2\,e = E_c \left\{ \left( \frac{p^2 + b\,p}{(p+b)^2 + \omega^2} \right) \right\} 1 = E_c\, \epsilon^{-bt} \operatorname{Cos} \omega t \quad (26)$$

Where

$$b = \frac{R}{L} \text{ or } \frac{1}{R\,C} \text{ and } \omega = \sqrt{\frac{1}{L\,C} - (b)^2}$$

However, for the peculiar conditions imposed upon the parallel circuit, $\omega$ becomes 0 and the open circuit voltage reduces to

$$2\,e = E_c \left\{ \left( \frac{p}{p+b} \right) 1 \right\} \quad (27)$$

which is recognized[11] as

$$2\,e = E_c\, \epsilon^{-\frac{R}{L}t} \text{ or } E_c\, \epsilon^{-\frac{t}{RC}} \quad (28)$$

Similarly, solving for the current for the case where the terminal $a$ is grounded, simulating a grounded line, there results,

$$2\,i = \left\{ \left( \frac{E_c}{R + R_1} \right) \right\} \epsilon^{-\frac{t}{RC}} = \frac{E_c}{Z_1}\, \epsilon^{-\frac{t}{RC}} = \frac{2\,E}{Z_1} \quad (29)$$

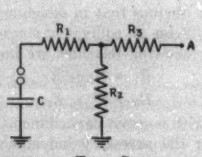


Fig. 27—Laboratory Test Circuit which is a Very Close Approximation of Fig. 27 when the Capacitance $C$ is Relatively Large

Consider the general case of junction impedance $Z_{(p)}$ solving for the terminal voltage there results,

$$E_a = E_c \left\{ \left( \frac{Z_{(p)}}{Z_1 + Z_{(p)}} \right) \right\} \epsilon^{-\frac{t}{RC}} = 2 \left\{ \left( \frac{Z_{(p)}}{Z_1 + Z_{(p)}} \right) \right\} E \quad (30)$$

The above equations are in agreement with the equivalent circuit of Fig. 25 and correspondingly on the transmission line. (See Equation (2).)

The left hand circuit of Fig. 26 is limited in that it will deliver only a wave of rectangular front. This is easily overcome without affecting the surge impedance property of the lightning generator by the addition of the right hand circuit of Fig. 26. This small circuit is designed so that $Z_1$ satisfies Equation (23) and $\sqrt{L_b/C_b} = Z_1$. When these relations are met the impedance from the new open circuit terminal $b$ to ground is still a pure resistance equal to $Z_1$, at all frequencies. This small circuit actually subtracts a wave of the form $E_c\, \epsilon^{-\alpha t}$ from the open circuit wave of the original circuit. The expression for the new open circuit wave is:

$$2\,e = E_c \left( \frac{\alpha}{B} \right) \left| \epsilon^{-bt} - \epsilon^{-\alpha t} \right|$$

where,

$$\alpha = \frac{1}{Z_1\, C_b} = \frac{Z_1}{L_b}$$

$$b = \left( \frac{1}{R\,C} \right) = \left( \frac{R}{L} \right) \text{ (See Eq. (22))}$$

$$B = (\alpha - b)$$

Such a circuit will permit the wave-front to be modified by altering the constants of the right hand circuit only. The circuit of Fig. 26 has an additional advantage in that the crest value of the open circuit wave is automatically a function of the wave-front in a similar relation to the waves found in practise.

Under all the terminal conditions which can be imposed upon this circuit it will be found to function just as if a transmission line for which the generator is designed were terminating in the laboratory. The validity of the circuit has been demonstrated both mathematically and by actually reproducing field tests in the laboratory, both of which have been readily calculated by the use of the equivalent circuit of Fig. 25.

The use of this circuit will permit the testing of inductive apparatus in the laboratory, reducing to a minimum the possibility of oscillations taking place between the inductance of the apparatus to be tested and the capacitance of the lightning generator. This is clearly seen by a study of Equation (30) and the corresponding circuit for conditions other than imposed by Equation (21).

In the laboratory testing of protective equipment, such as lightning arresters, *to determine the actual reduction in voltage which the arrester will permit*, should the surge impedance property be omitted from the generator circuit the results will be inaccurate. This will be appreciated when it is realized that the fundamental principle upon which the lightning arrester operates is merely the potentiometer principle, the reduction in voltage at the end of an open line being, $\left( \frac{R_a}{Z_1 + R_a} \right)$ per unit of the open circuit voltage where $R_a$ is the arrester resistance (a variable) and $Z_1$ the surge impedance of the incoming line. Any parallel terminal impedance or extended line will always aid the arrester operation because it merely tends to reduce the equivalent arrester resistance.

Any particular terminal or junction condition can be rigorously set up in the laboratory for tests under impulse conditions by applying the simple principles outlined above. In fact the principles of representing all surge impedance by pure resistance to ground, the line delivering the wave by the proper surge impedance in the peculiar form of the circuit shown in Fig. 26,

each particular case satisfying the equivalent circuit of Fig. 25, makes a very flexible arrangement which can be utilized effectively in carrying on these investigations with laboratory equipment.

For the purpose of tests shown in the text of the paper the test circuit of Fig. 26 was modified slightly with no appreciable loss in accuracy. Owing to the *relatively* large electrostatic capacity of the lightning generator and because the transient impedance of the apparatus to be tested was essentially ohmic, that is, the surge impedance of the respective windings, the inductance of the parallel circuit was omitted. Under these conditions it will be found, by carrying through similar calculations shown above, that the capacitance of the generator will only affect the reflected wave from the neutral of the winding to a slight degree.

The test circuit used is shown in Fig. 27. Here the resistors were designed so that,

$$R_3 + \left( \frac{R_2 R_1}{R_1 + R_2} \right) = Z_1 \qquad (31)$$

where $Z_1 = 250$ ohms, the assumed surge impedance of the incoming line.

The laboratory verification of the circuit is also readily made by studying the excellent agreement of the oscillograms with the corresponding calculations of what would be expected with an actual line of 250 ohms meeting a generator winding of 800 ohms. See also Equation (3).

Since it has been found that natural lightning can produce very steep waves at the terminals of apparatus,[6] the effect of these waves can readily be computed[2] with the aid of the equivalent circuit of Fig. 25, provided the impedance of the terminal apparatus to such surges is known.

During the summer of 1929 it was shown experimentally[7] that externally transformers functioned as capacitors to traveling surges.[10] The failure to detect any impedance in parallel with this capacitance is readily accounted for in that any large ohmic impedance in parallel with the lightning arrester used would only help to reduce the arrester resistance a fraction of one per cent and could not be detected on the oscillograms, and as far as the *external* properties of a transformer are concerned it may be neglected.

The investigation presented in the text of this paper shows that generator windings function as finite transmission lines to such surges but also have a very small capacitance to ground at the line terminal, this capacitance being the small capacitance of the end turns around the winding in parallel with the capacitance of the first few turns to ground. This external capacitance to ground of the generator winding has also been found to produce oscillations with adjacent reactors when the resistance (surge impedance) of adjacent lines would permit. The external equivalent circuit of a generator winding is therefore a small capacitance in parallel with a resistor equal to the surge impedance of the winding.

This information permits one general lumped circuit to be given which will suffice for practically all cases of junction or terminal equipment subject to traveling surges. This circuit is rigorous and includes the impedances of terminal apparatus as determined from tests. It is shown in Fig. 28.

The various parameters are:

$Z_1$ is a resistance equal to the surge impedance of the line on which the traveling wave $E$ is approaching the substation.

$Z_2$ is the parallel value of the surge impedances of all outgoing transmission lines on the same circuit.

$R_A$ is the resistance of the arrester protecting the substation.

$B_1$ is any series element such as reactors or series capacitors.

$C$ is the external capacitance of the substation equipment to ground.

$Z_g$ is the surge impedance of all machine windings in parallel connected to that phase.

$2E$ is the open circuit wave or twice the incoming wave. Its maximum value can be twice the insulator flashover value of the incoming line.

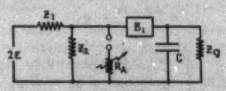


Fig. 28—Generalized Circuit for Calculating the Effect of any Incoming Wave upon any Terminal Equipment

The voltage drop across $Z_g$ is the wave which enters machine windings and which in the case of open neutrals will reflect to double arrester voltage.

This surge impedance $Z_g$ will represent an infinite line when the proper impedances are put in the neutral to ground of each machine winding, otherwise reflections from the neutral would have to be considered.

For the purpose of laboratory tests the circuit of Fig. 28 would be modified by replacing the surge impedance $Z_1$ and the applied voltage with the test circuit of Fig. 26 designed for the surge impedance $Z_1$ as outlined above, Equation (23). This constitutes a rigorous analysis of a method of testing any terminal arrangement under transient surges. Where surges enter on more than one line and their combined effects are desired on terminal equipment, simple tests should be made for both and the results properly superimposed.

In Appendix B some interesting equivalent circuits representing generator windings under special terminal conditions will be considered.

## Conclusions

(1) Equivalent lumped circuits of traveling wave problems are available which will satisfy all the energy relations of the classical wave equations.

(2) These equivalent circuits are readily adapted as laboratory test circuits and may be used as such to reproduce or extend field investigations pertaining to the problems of protecting terminal equipment from traveling surges.

(3) These circuits are also excellently adapted to the laboratory determination of the equivalent transient impedances of terminal equipment and to study the internal disturbances caused by such surges.

## Appendix B

(1) *Damping of Oscillations.* One component of the damping is shown in Fig. 8 to be attributed to the loss of part of the wave to the incoming line. Each time a reflected wave returns to the line terminal $\left(\frac{2 Z_1}{Z_1 + Z_2}\right)$ per unit of the remaining wave is lost. The part which returns in the winding is therefore $\left\{\frac{Z_2 - Z_1}{Z_2 + Z_1}\right\}$ per unit of the remaining wave.

Consider now the bottom diagram of Fig. 8. Realizing that the damping is exponential, the following relations may be written.

$$\epsilon^{-\alpha t_1} = y_1 \tag{32}$$

$$\epsilon^{-\alpha(t_1 + T)} = y_2 \tag{33}$$

But

$$y_2 = \left\{\frac{Z_2 - Z_1}{Z_2 + Z_1}\right\} y_1 = B\, y_1 \tag{34}$$

Substituting (34) in the above equations there results,

$$\epsilon^{-\alpha T} = B \tag{35}$$

from which,

$$-\alpha = \frac{\text{Log.}\, B}{T} \tag{36}$$

Now

$$T = \frac{2 D}{v} = 2 D \sqrt{L' C'} = \frac{2 D L'}{Z_2} = \frac{2 L_o}{Z_2} \tag{37}$$

Hence

$$-\alpha = \left\{\frac{Z_2 \text{Log.}\left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)}{2 L_0}\right\} = \left(\frac{R_o}{2 L_o}\right) \tag{38}$$

The resulting damping is therefore

$$\epsilon^{\left(\frac{R_o}{2 L_o}\right) t} \tag{39}$$

where $R_o = Z_2 \text{Log.} \left\{\frac{Z_2 - Z_1}{Z_2 + Z_1}\right\}$

and $L_o$ is $D L'$ or the total inductance of the finite winding.

In the case of an open neutral winding $T = \frac{4 D}{v}$ and the resulting damping takes place at the rate

$$\epsilon^{\left(\frac{R_o}{4 L_o}\right) t} \tag{40}$$

with the open circuit wave as the reference axis.

(2) *Equivalent Circuit of Generator Winding Under Transient Conditions.* The natural frequency of the open circuited generator winding has been shown (Equation **11**) to be

$$f = \frac{1}{4 \pi \sqrt{L C}} \tag{41}$$

Furthermore the oscillograms shown in Fig. 17, have, by inspection, the general form

$$e = E\, \epsilon^{-kt} (1 - \text{Cos}\, w\, t.). \tag{42}$$

These facts suggest that the equivalent circuit of an open circuited generator winding under transient conditions is an inductance in series with a capacitor to ground, the line terminal of the inductance representing the line terminal of the machine winding and the point between the capacitor and inductance representing the open circuited neutral. Such a circuit is only valid, of course, for the approximation of the voltages to ground in the machine winding and for this purpose it may be used to show the effect of various waves and terminal impedances. To include the effect of damping, resistors may be put in series with the inductance.

When a unidirectional voltage $E$ is applied to the terminal of the inductance, the voltage at the neutral will be $e = E\,(1 - \text{Cos}\, w\, t.)$. The voltage at the midpoint of the inductance will be $e = E\left\{1 - \frac{1}{2}\ \text{Cos}\ w\, t.\right\}$ which is a close approximation to the voltage at the midpoint of the winding.

The effect of any neutral impedance can be approximated by placing such an impedance in series with the capacitor to ground in the equivalent circuit. Consider a resistance $R$ equal to the surge impedance of the winding placed in the neutral. The resulting neutral voltage will be

$$e = E\left(1 - \epsilon^{-\left(\frac{R}{L_o}\right) t}\right) \tag{43}$$

showing that the neutral voltage will not rise above the applied voltage. The resulting circuit in this case will be found as the right hand circuit of Fig. 26, showing that this small circuit which was used to control the front to the lighting generator wave is actually the transient lumped circuit equivalent of a finite transmission line terminating in its surge impedance.

(3) *Maximum Open Neutral Voltage in the Case of an n Phase Machine.* The maximum transient voltage at the open neutral of an $n$ phase machine will occur when waves of equal magnitude travel in all three phases arriving at the neutral simultaneously.

Consider now that the three phases were isolated, each being protected by a resistor to ground equal to the surge impedance $Z_o$ of the single phase. Now

when a voltage wave $E_s$ travels in each phase simultaneously the corresponding points of the various phases will be at the same potential at each instant, allowing the neutrals of the respective phases to be electrically connected without affecting the voltages. The resulting resistance to ground will, therefore, be $Z_s/n$. This analysis neglects the induced voltages in the various phases which will tend to make the surge impedance of the three phases in parallel less than one-third of the surge impedance of a single phase.

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## Discussion

### EFFECTS OF LIGHTNING VOLTAGES ON ROTATING MACHINES AND METHODS OF PROTECTING AGAINST THEM

(Fielder and Beck)

### VOLTAGE OSCILLATIONS IN ARMATURE WINDINGS UNDER LIGHTNING IMPULSES

(Boehne)

**K. B. McEachron:** The papers by Messrs. Fielder and Beck and by Mr. E. W. Boehne indicate the same general trend in forms of protection of rotating machines, which are subject to lightning voltages.

Fortunately it is now possible to make accurate calculations relating to arrester performance, either alone or in combination with capacitors as suggested by Mr. Boehne for protection of rotating machinery. This method of calculation is shown in Fig. 1 in which any assumed form of applied wave with respect to voltage and current is plotted as shown in the curve marked $2E_1$. The assumed form of the traveling wave is plotted with double voltage values at the left of the figure and is marked, "Voltage without arrester." This is the voltage which would be measured at the end of the line without the arrester.

Underneath the open circuit volt-time curve is the volt-time curve of the arrester during discharge, which is obtained in the following manner.

The straight line $E_a$ at the right is the arrester characteristic, while $Z_1 I_a$ represent the product of assumed surge impedance ($Z$) of the line and any arrester current ($I_a$) which may flow. These two curves are added together for each value of current giving the curve marked $E_a + Z_1 I_a$. To determine the arrester voltage and arrester current for any given value of applied voltage as at $A$, first find the arrester current $I_a$ from

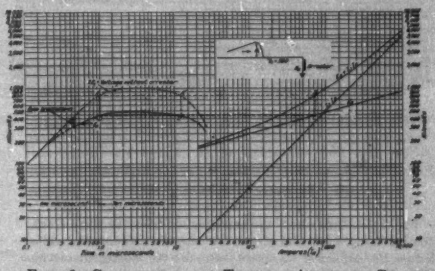

Fig. 1—Calculation of Thyrite Arrester Performance for Grounded-Neutral Circuit (115-Kv. Thyrite Arrester at the End of the Line)

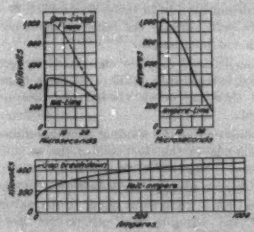

Fig. 2—Thyrite Arrester Performance Curves

the curve $E_a + Z_1 I_a$ for that applied voltage as at $B$ and then find the arrester voltage from the curve $E_a$ as at $C$. The values for $E_a$ for each value of $2E_1$ are plotted against time as the arrester characteristic. From a curve, such as shown in Fig. 1, all of the arrester characteristics may be obtained for any assumed wave, line condition or arrester connection. Such a set of curves appear in Fig. 2 for the case calculated in Fig. 1.

A similar method is shown in Fig. 3 for the combination of a Thyrite arrester and a capacitor. For the calculation, a 23-kv. arrester in parallel with a capacitor having an electrostatic capacity of 0.1 microfarad are connected at the end of a line having a surge impedance of 500 ohms. A perpendicular wave front is assumed as representing the worst conditions from the standpoint of wave front. The crest potential of the traveling wave entering the station will depend on the insulation of the

incoming circuit. In Fig. 3 this crest voltage was taken as 250 kv. Using the equation

$$E_c = 2\,E_1 \frac{Z_2}{Z_1 + Z_2}\,[1 - \epsilon^{-\alpha t}]$$

Where $Z_1$ is the surge impedance of any outgoing lines and $\alpha = \dfrac{Z_1 + Z_2}{Z_1\,Z_2\,C}$ the voltage rise across the capacity with respect to time is obtained. When the arrester is connected in parallel the curve $E_{ac}$ is obtained, which is the protective characteristic of the combination of arrester and capacitor. Such a calculation can be readily made for any assumed set of conditions and the protection determined.

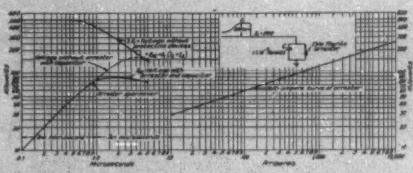

FIG. 3—CURVES FOR THE CALCULATION OF PERFORMANCE OF THE ARRESTER-CAPACITOR COMBINATION

Fig. 3 illustrates how the capacity modifies the wave front of the incoming wave and shows the arrester reducing the voltage across the capacitor to a safe value for the connected machine. Thus both turn to turn insulation and the major insulation to ground are properly protected.

**L. V. Bewley:** Mr. Boehne's investigation has shown that:

a. The internal oscillations in the windings of rotating machines are primarily due to successive reflections of traveling waves, and are substantially the same as those occurring on a transmission line of finite length.

b. These oscillations may be eliminated by grounding the winding through a resistance equal to its surge impedance, as is evident from traveling wave theory and the oscillographic results obtained.

c. The gradient along the winding, and therefore the turn-to-turn stress, depends on the steepness of the wave front, and is doubled at a total voltage reflection point.

d. The severity of oscillations is decreased by slowing up the wave front, and for a wave front equal to the natural period of oscillation of the winding the oscillations are completely eliminated.

e. An abrupt tail, such as caused by an insulator flashover, is as bad as an abrupt front.

f. The surge impedance of the transmission line has considerable influence on the character of the oscillations in the machine windings, not only with respect to the initial incident wave, but also due to the "junction damping" associated with the successive reflections.

While it is evident from the mass of experimental data which Mr. Boehne has obtained and analyzed that the internal oscillations in the windings of rotating machines are largely traveling wave phenomena, yet a casual examination of the oscillograms which he has presented show that series capacitance and mutual inductance are also present. This is evidenced by the considerable distortion of wave shape experienced by the waves entering the winding, and the building up of voltages at certain points in excess of values which would be expected from the theory of pure traveling waves. For instance, in Fig. 1 of Mr. Boehne's paper, referring to a grounded neutral machine, the potential at a point 10.7 per cent from the line end reaches a potential of 117 per cent, or 17 per cent higher than is possible with pure traveling waves. In this same figure the applied wave has a front of about 5 microseconds but after traveling half way through the winding it has been increased to 15 microseconds. All of the other oscillograms in the paper exhibit these same irregularities, to a greater or less extent.

In view of these differences it is of interest to consider the effects of series and shunt capacitances, self and mutual inductances, and losses on the character of the oscillations in ideal machine circuits. Four typical cases will be considered, on the assumption of a suddenly applied d-c. voltage $E$. The response to an applied wave of any shape is obtainable from the solution corresponding to the infinite rectangular wave, through an application of Duhamel's theorem or other means of superposition.

The four typical cases are:

1. $(L, C_g)$. Circuit consisting of uniformly distributed series inductance $L$, and shunt capacitance $C_g$. This is the ideal transmission line, without losses.

2. $(L, C_g, C_s)$. Circuit consisting of uniformly distributed series inductance $L$, shunt capacitance $C_g$ and series capacitance $C_s$. This is sometimes erroneously used as an approximation to the high frequency circuit of the transformer.

3. $(M, C_g)$. Circuit consisting of uniformly distributed mutual inductance $M$ (linearly graded), and shunt capacitance $C_g$.

4. $(M, C_g, C_s)$. Circuit consisting of uniformly distributed mutual inductance $M$ (linearly graded), shunt capacitance $C_g$, and series capacitance $C_s$. This is the circuit of an ideal transformer, and suffices for the analytic description of transformer high frequency oscillations.

The potential $e$ at any point $x$ of the circuit measured from the grounded end, and time $t$, for any of the above circuits is given by equations of the same form:

$$e = E\left(\frac{x}{l} + \sum_1^\infty B_s \frac{2\cos s\pi}{s\pi} \sin\frac{s\pi x}{l} \cos\omega_s t\right) \tag{1a}$$

$$= E\left(\frac{x}{l} + \sum_1^\infty B_s \frac{\cos s\pi}{s\pi}\left[\sin\left(\frac{s\pi x}{l} + \omega_s t\right) + \sin\left(\frac{s\pi x}{l} - \omega_s t\right)\right]\right) \tag{1b}$$

$$= E\sum_1^\infty \frac{2}{\pi s}\left[B_s \cos(s\pi - \omega_s t) - \cos s\pi\right] \sin\frac{s\pi x}{l} \tag{1c}$$

The initial distribution, found by substituting $t = 0$, is

$$e_{t=0} = E\sum_1^\infty (B_s - 1)\frac{2\cos s\pi}{s\pi} \cdot \sin\frac{s\pi x}{l} \tag{2}$$

The final distribution, after the oscillations have died away, is

$$e_{t=\infty} = E\frac{x}{l} = -E\sum_1^\infty \frac{2\cos s\pi}{s\pi} \cdot \sin\frac{s\pi x}{l} \tag{3}$$

where the infinite series expression is the Fourier expansion of $(x/l)$ between the limits $x = 0$ and $x = l$. Of course Equations (1) do not reduce to (3) on substituting $t = \infty$, because Equations (1) were derived on the assumption of zero losses. Actually, however, there will always be losses present, so that eventually the oscillations will die away.

Each space harmonic of order $s$ in Equation (1b) has a velocity of propagation

$$v_s = \frac{l\,\omega_s}{s\pi} \tag{4}$$

The amplitude $B_s$, angular velocity $\omega_s$, linear velocity $v_s$, initial and final distributions and the type of propagation, for

each of the four cases under consideration are given in the following table, where $\alpha = \sqrt{C_g/C_s}$.

| Case | 1 $(L, C_g)$ | 2 $(L, C_g, C_s)$ | 3 $(M, C_g)$ | 4 $(M, C_g, C_s)$ |
|---|---|---|---|---|
| $B_s$ | 1 | $\frac{\alpha^2}{s^2\pi^2+\alpha^2}$ | 1 | $\frac{\alpha^2}{s^2\pi^2+\alpha^2}$ |
| $\omega_s$ | $\frac{s\pi}{\sqrt{L\,C_g}}$ | $\frac{s\pi}{\sqrt{L(C_s s^2\pi^2+C_g)}}$ | $\frac{s^2\pi^2}{\sqrt{M\,C_g}}$ | $\frac{s^2\pi^2}{\sqrt{M(C_s s^2\pi^2+C_g)}}$ |
| $v_s$ | $\frac{l}{\sqrt{L\,C_g}}$ | $\frac{l}{\sqrt{L\,(C_s s^2\pi^2+C_g}}$ | $\frac{s\pi l}{\sqrt{M\,C_g}}$ | $\frac{s\pi l}{\sqrt{M(C_s s^2\pi^2+C_g)}}$ |
| $e_{l=o}$ | 0 | $\frac{\sinh \alpha x/l}{\sinh \alpha}$ | 0 | $\frac{\sinh \alpha x/l}{\sinh \alpha}$ |
| $e_{l=\infty}$ | $x/l$ | $x/l$ | $x/l$ | $x/l$ |
| Type of propagation | As a rigid distribution | High harmonics behind | High harmonics ahead | High harmonics ahead |

It may be remarked that the hyperbolic *sinh* expressions for the initial distributions are obtained by recognizing them as the appropriate functions corresponding to the Fourier series of Equation (2). They can also be found by solving the $C_s$ and $C_g$ circuit, since at the first instant no current flows through the inductances, and therefore the initial distribution is completely determined by the capacitance circuit. Still another way of obtaining these expressions for the initial distribution is to substitute $p = d/dt = \infty$ in the operational equations from which the solutions given here were derived.

In cases 2 and 4 the amplitudes of the space harmonics are completely determined by the capacitances $C_g$ and $C_s$. In fact, these amplitudes are the coefficients of the Fourier analysis of the initial distribution with respect to the final. If

$$\alpha = \sqrt{C_g/C_s} \rightarrow 0 \tag{5}$$

then $B_s \rightarrow 0$ and the oscillations disappear. The basic principle of all methods of electrostatic shielding by means of auxiliary capacitance is to bring about the condition of Equation (5); either by reinforcing the series capacitance $C_s$ or by nullifying the shunt capacitance $C_g$. Thus if $\alpha = o$ the initial and final distributions are the same, and there are no oscillations.

From Equation (1c) and the values given in the table under case 1, there is

$$e = \sum_1^\infty \frac{2}{s\pi}\left[\cos s\pi\left(1-\frac{1}{\sqrt{L\,C_g}}\right) - \cos s\pi\right]\sin\frac{s\pi x}{l}$$

$$= \sum_1^\infty \frac{2}{s\pi}\left[\cos\frac{s\pi y}{l} - \cos s\pi\right]\sin\frac{s\pi x}{l} \tag{6}$$

$$\text{where} \qquad Y = \left(l - \frac{l}{\sqrt{L\,C_g}}\,t\right) = (l - v\,t) \tag{7}$$

But (6) is the Fourier series of a rectangular wave which has penetrated the winding to a point distance $y$ from the neutral. When this wave reaches the neutral it reverses and returns to the line end of the winding. The cycle is then repeated. This is the only case in which pure wave motion is present. Thus there are three ways of looking at the phenomena of oscillations in an $(L, C_g)$ circuit, corresponding respectively to Equations (1a), (1b), and (1c) as follows:

| Eq. | Point of view |
|---|---|
| 1a | (Fixed distribution) + (harmonic standing waves) |
| 1b | (Fixed distribution) + (pairs of harmonic traveling waves) |
| 1c | (Simple traveling wave) |

The only effect of the inductance is in determining the angular velocities $\omega_s$ of the space harmonics, and the corresponding linear velocities $v_s$. If the inductance is purely self-inductance, the harmonics vibrate as their order, but if mutual inductance (linearly graded) is in the circuit the harmonics vibrate as the square of their order.

The presence of either mutual inductance or series capacitance will cause the harmonics to vibrate at such rates as to present the possibility of an eventual piling up of the harmonics in time phase, so as to cause abnormal voltages at points in the winding, in excess of the terminal voltage. The mutual inductance is generally more dangerous in this respect than the series capacitance, since the piling up can occur on the first oscillation of the fundamental, and before the effect of losses or of a decreasing applied wave are seriously felt.

Losses in the circuit, due to series or shunt resistance, have two different effects. First, they introduce a decrement factor for each harmonic causing it to be damped out; and second, they slow down, or even actually prohibit, the rates of harmonic vibration. As a rule, the losses do not exert an appreciable influence on the first complete oscillation of the fundamental and therefore cannot be depended upon as any protection to the machine.

**C. W. Guth:** A series of tests were made on turbine generator armature coil insulation to determine the ratio of the dielectric breakdown strength of the insulation when tested with an impulse voltage to the dielectric breakdown strength of the insulation when tested at 60 cycles.

Several bars were insulated with micarta folium insulation for use in these tests. The bars were made from a number of copper straps, each of which was mica taped, and represented a section of the slot portion of an armature coil for a 94,200 kv-a., 13,800-volt turbine generator. The bars were approximately 100 in. long and were wrapped with the standard thickness of micarta folium which is used for 13,800 volt generators. A number of condensers was built up at each end of the bars by using treated cloth tape with tin foil applied at definite locations. The purpose of the condensers was to shield the bar and prevent flashover to the ends of the bar during test.

The bars were tested as follows:

1. A surge voltage of 40 kv. was applied and 10 shots were made in succession. All the surge voltage tests were made with a 2 microsecond wave.

2. A voltage of 20 kv. at 60 cycles was applied momentarily to check for failure. This voltage is approximately equal to 1.5 times the operating voltage of the machine.

3. A surge voltage of 60 kv. was applied and 10 shots made in succession.

4. The 60 cycle test at 20 kv. was then repeated.

5. The impulse tests were then repeated, increasing the voltage in steps of 20 kv. up to 160 kv., followed by steps of 10 kv. above this voltage. Ten shots of the impulse voltage were applied at each voltage. The impulse tests at each voltage were followed by the 60-cycle, 20-kv. test, to check for failure.

Two of the bars were broken down under impulse voltages of 160 kv. and 170 kv. respectively. The other two coils which were tested withstood a test of 190 kv., which was the limit of the testing set. These coils were then tested with 60 cycle voltage and failure occurred at 92 kv. and 70 kv.

The bars were re-insulated with micarta folium, and a 60-cycle voltage test was then applied, the voltage being raised until failure occurred. Breakdown occurred at 100, 120, 120 and 140-kv. respectively.

The results of the tests indicate a ratio of impulse breakdown to 60 cycle breakdown of approximately 1½ to 1. However, the impulse tests should be considered in the nature of an endurance test as the insulation was subjected to a large number of tests at the lower voltages before final breakdown occurred. The ratio

of the impulse breakdown value to the operating voltage is approximately 13 to 1.

The extent to which the insulation was weakened is illustrated by the 60-cycle breakdown values obtained on the bars which had previously been subjected to impulse tests compared to those which had not been previously tested, *i. e.*, 80 kv. average breakdown against 120 kv. However, it should be noted that the insulation still shows good dielectric strength, even after a large number of impulse tests was applied.

**K. K. Palueff:** In February 1919, Messrs. Blume and Boyajian presented to the Institute what I previously described as a classic theory of principles governing the voltage oscillations within transformer windings.

Mr. Boehne presents in his paper, what can be called a classic theory of transient voltage oscillations within generator windings. He has done it in a very clear and convincing manner.

It is hoped that in the near future he will completely cover the subject by presenting results of his studies on voltage distribution found in separate coils of the winding and also on the effect of the presence of the rotor.

In studying the effect of the rotor, I believe it would be of interest to make tests with the rotor in different angular positions. Furthermore, these studies should cover cases where only one out of three phases is subjected to a surge, as in such a case the effect of the rotor should be essentially different from that found with all three phases simultaneously subjected to a surge.

It appears to me that the presence of the rotor should also have an effect on the surge impedance of the machine, and if so, the surge impedance would become a function of angular position of the rotor. It also should be expected that the natural period of oscillation is affected by the rotor.

If all of the above suppositions prove to be correct, the reduction of transient voltage stresses by neutral resistance, equal to surge impedance of the machine, would become more complicated and on the whole, probably less effective.

Furthermore, even under conditions of the test discussed in this paper, the neutral resistance is not as effective as it may appear at first. This happens because in case of simultaneous surge on all three phases the proper value for the neutral resistance is one-third of the value required in case of only one phase subjected to a surge. The latter value cannot be secured as two idle phases in effect are connected in parallel with the neutral resistance. Their combined value is one-half of the surge impedance of one phase, while the total value required for resistance (or surge impedance) at neutral end of the phase that is struck is equal to the surge impedance. Therefore, appreciable oscillations will be present either in one case or the other. It cannot be depended upon that in service all three phases will be always simultaneously subjected to a surge.

It is also essential to consider not only single traveling waves, but also damped oscillations produced by various causes in transmission systems. While their magnitudes are much lower than those of lightning, the effect of successive cycles is cumulative, and therefore equally dangerous stresses may be produced in the winding with much lower applied voltages.

### Protection of Generators Connected Directly to Overhead Transmission Lines

The protection of a generator is a far more difficult problem than that of a transformer.

Far greater responsibility is placed on devices protecting a generator than on those protecting a transformer. This is because the impulse ratio of dry insulation used in generators is about one-third of that of the transformer insulation, the cost of the generator per kv-a. is about six times that of the transformer while repairing of the generator takes materially more time and is more expensive. In addition the low voltage transmission lines are generally so much overinsulated in comparison with the insulation strength of generators that there is little hope of co-ordination of the two.

It follows that devices suitable for protection of generators must be considerably more than a usual arrester or arrester and condenser, as they are called upon to reduce the incoming wave not to 50 per cent but to 10 per cent or less, and also to protect against oscillatory transients.

Taking all of the above into consideration, it appears that the protective device must form an impervious barrier between the

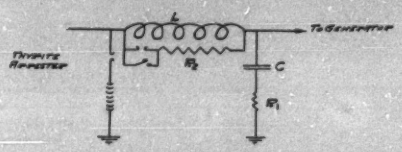


Fig. 4—Protector Against Transient Voltages

line and the generator for voltage transients originated on the line. Such a device which was developed quite some time ago is shown on Figs. 4, 5, 6. Its action is based on the principle described in the author's paper of January 1929. In accordance with this principle, the high frequency voltage will distribute uniformly throughout an inductive winding when an incident wave has both front and tail at least as long as the natural period of the winding. I am glad to find that Mr. Boehne as well as Messrs. Fielder and Beck approve of this principle.

The constants of the devices are so proportioned that the incident wave is modified so that the shape of its front and tail satisfy the above requirement while its crest is reduced to a

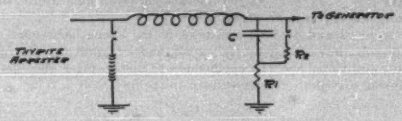


Fig. 5—Protector Against Transient Voltages

predetermined safe value. It will do this even without assistance of the arrester. The arrester is used because by chopping the wave it allows a use of a smaller inductance and capacitance. Therefore, in some cases, the use of an arrester was found economically justifiable. Similar economic advantages may be obtained by proper co-ordination of the strength of adjacent line insulation and of the size of the inductance and the capacitance.

The resistances are inserted for elimination of the possibility of resonance of the inductance and capacitance with other parts of the system or with the harmonics of operating frequency. It appears that this protective scheme is often cheaper with a

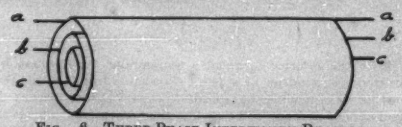


Fig. 6—Three-Phase Interwoven Reactor

relatively high inductance. To permit the use of such an inductance (some 15 per cent of the generator capacity) without appreciably increasing the impedance for the load current, the three reactors of the three phases are interwound so that the impedance to the balanced load current can be made as small as desired. The reactor is oil immersed and its insulation strength is co-ordinated with the adjacent line insulation. The device

thus serves as protection not only against transient voltages, but also against excessive currents in case of a single phase short circuit.

### Traveling vs. Standing Wave Oscillations of Inductive Windings

The oscillograms of free voltage oscillations of transformer and generator windings are at first glance so similar that it may be easily supposed that they illustrate identical phenomena.

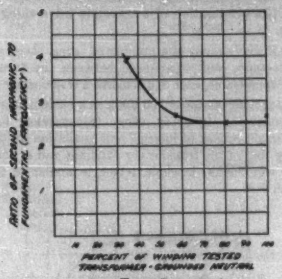


Fig. 7

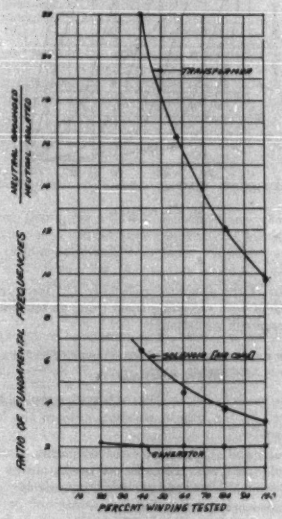


Fig. 8

However, more careful scrutiny indicates that the two phenomena are essentially different. Transformer oscillations consist of oscillations of a number of standing waves, the transformer winding serving as the base or line of equilibrium. Generator oscillation, as Mr. Boehne demonstrated in his paper, consists essentially of a traveling wave surging back and forth in the winding.

The difference between the two oscillations can be stated as follows: When one terminal of a transformer winding is struck by a wave with steep front, the internal oscillation produced thereby starts *simultaneously throughout* the winding. In the case of a generator, these oscillations develop *progressively along* the winding, beginning at the terminal that is struck by the wave.

This difference is not only of academic interest but is also of practical importance. It is responsible for the appreciable difference in magnitude and distribution of high frequency voltage stresses found in the two kinds of windings. The time is too limited to allow detailed discussion of it here, but the

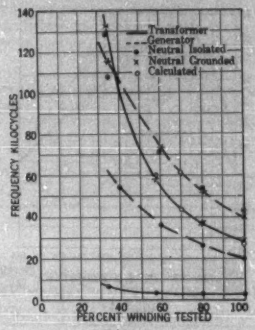


Fig. 9

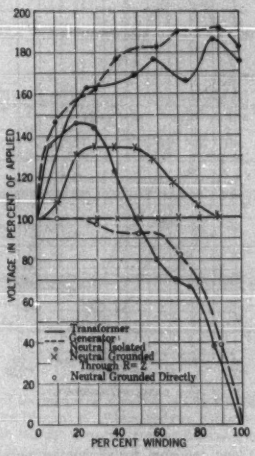


Fig. 10

difference in the effect of neutral resistance on the oscillations can be taken as an example. In case of a generator, a neutral resistance equal to its surge impedance eliminates oscillations, as Mr. Boehne has illustrated, but it does not eliminate them in a transformer grounded through a resistance equal to its, so called, surge impedance.

The oscillation in a transformer develops *simultaneously*, principally due to the presence of high mutual inductance between all parts of the windings. The flow of any current along conductors of the turns near the line end immediately creates a magnetic flux which induces voltages of various magnitudes and phase angles throughout the winding. Therefore, the speed of propagation of the disturbance from one end to the other is equal to the speed of propagation of magnetic flux along the transformer core. The core leg covered with winding is generally

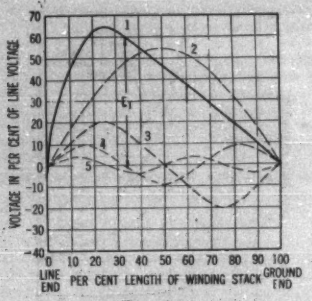


FIG. 11A

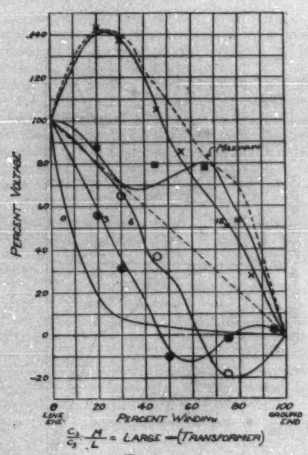


FIG. 11B

only a few feet long, therefore, for all practical purposes, it can be said that the oscillation starts simultaneously throughout the winding. The immediate transmission of disturbance from one end to the other is also facilitated by the presence of the series capacitance between all adjacent coils of the winding from end to end.

It is quite obvious that in a generator the mutual inductance between coils is very much smaller than in a transformer, particularly between the end and the middle coils, with the rotor either removed or bearing a short *circuited winding*.

The series capacitance, (that is, the capacitance from coil to coil) is absent between parts imbedded in iron and is small between the remaining parts.

Under such conditions, the only way a high frequency disturbance can be transmitted to the parts of the winding "electrically removed" from the line end coil is by progressive movement from coil to coil through connections between the coils, very much like propagation of a traveling wave along a transmission line.

However if coils consist of a number of turns, then, since the mutual inductance and capacitance between the turns of the same coil is appreciable, each coil acts like a transformer winding.

A generator then can be looked upon as a chain of transformer windings connected by very short transmission lines. Its oscillation would consist of internal coil oscillation in its nature, approaching that of the transformer windings and of the oscillation of the windings as a whole, which is similar to that of a transmission line.

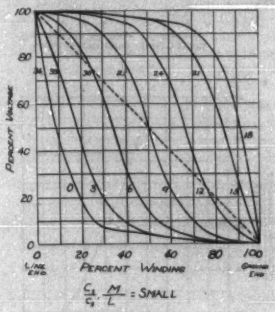


FIG. 11C

Since most of the generator coils have but few turns, only traveling waves with exceeding steep front or tail are able to produce internal coil oscillations.

## COMPARISON OF CHARACTERISTICS OF STANDING AND TRAVELING WAVE OSCILLATIONS

The oscillation following the laws of traveling wave differ from that governed by the laws of standing wave in the following respects. Let:

$f_{1i}$, $f_{2i}$, $f_{3i}$ etc. and $f_{1g}$, $f_{2g}$, $f_{3g}$ etc. be frequency of the first, second, third, etc. harmonics of oscillation of winding with natural isolated and grounded respectively.

$Z$ surge impedance of the winding.

$f_{1ip}$, $f_{1gp}$ is frequency of the first harmonic of portion $p$ of the entire winding with neutral isolated and grounded respectively.

$E_o$ crest of rectangular traveling wave applied to the winding.

$L$ self-inductance of winding element.

$M$ Mutual inductance between adjacent elements.

$C_s$ capacitance between adjacent elements.

$C_g$ capacitance between element and ground.

The figures referred to below are based on test results. Data

on generators are taken from Mr. Boehne's paper. Data on transformers are taken from the author's investigations.

Then:

| | In case of | |
|---|---|---|
| | Traveling wave | Standing wave |
| a. | | |
| $f_{14} : f_{24} : f_{34}$ | 1 : 2 : 3 | more than 1 : 2 : 3<br>1 : 4 : 8 for example |
| $f_{19} : f_{29} : f_{39}$ (Fig. 7) | 1 : 2 : 3 | more than 1 : 2 : 3 |
| b. | | |
| $f_1 : f_{18}$ (Fig. 8) | 1 : 2 | more than 1 : 2 (particularly with iron core)<br>1 : 22 for example |
| c. | | |
| $f_{14} : f_{14p}$ (Fig. 9) | $p$ | Within a wide range practically unity |
| d. | | |
| $f_{19} : f_{19p}$ (Fig. 9) | $p$ | less than $p$<br>$p^{1.5}$ for example |
| e. | | |
| Maximum voltage to ground throughout winding with neutral grounded directly (Fig. 10) | $E_0$ | more than $E_0$<br>1.43 $E_0$ for example |
| f. | | |
| Maximum voltage to ground throughout winding with neutral grounded through $R = Z$ (Fig. 10) | $E_0$ | more than $E_0$<br>1.35 $E_0$ for example |

The above difference is due to the fact that in case of a traveling wave the phenomenon is dominated by $L$ and $C_g$ as $\frac{M}{L}$ and $\frac{C_s}{C_g}$ are negligible, while where $M$ or $C_s$, or $M$ and $C_s$ are appreciable with $\frac{M}{L}$ and $\frac{C_s}{C_g}$ large the standing wave phenomenon dominates. These considerations allowed the present author to construct the "spectrum" of high frequency equivalent circuits published in his paper of last May and reproduced as Fig. 12 here. Mr. Boehne thus found that generators, under the test conditions used, act like circuit No. 2.

It is interesting to note that the ratio of frequencies of harmonics ($f_1 : f_2 : f_3$, etc.) is of fundamental importance.

The frequency of harmonics, in the case of a standing wave, increases faster than the first power of their order, because the presence of $C_s$ and $M$ facilitates direct transmission of energy to distant parts of the winding.

This is illustrated by Fig. 11A where No. 1 of $A$ is "initial voltage distortion" curve and No. 2, 3, etc. its harmonics (space harmonics) as found in *a certain transformer* tested by the author. If each of the above harmonics is made to oscillate with its frequency found in the transformer, then the simultaneous voltage distribution throughout the winding at 0, 3, 6, etc. microseconds after the impact will be as shown by corresponding curve on $B$ of Fig. 11B. Should ratios of frequency of the same harmonics (without change of their amplitudes) be made to correspond to their order ($f_1 : f_2 : f_3 = 1 : 2 : 3$), as the traveling wave phenomenon demands, the simultaneous voltage distribution would be as shown on $C$ of the same figure.

It is obvious that the latter illustrates a traveling wave oscillation.

As was predicted, $B$ and $C$ differ in the following:

The maximum voltage in $B$ is substantially more than the applied, while in $C$ it does not exceed it.

The disturbance starts simultaneously throughout the winding in $B$ and gradually progresses from line to neutral in $C$.

The first and second half of cycles are identical in $C$ (3 + 33, 6 = 30, etc.) while in $B$ the simultaneous distribution never occurs. This feature is not demonstrated on $B$ where only the first half cycle is shown, as it would make the diagram unintelligible.

Thus it appears that the method used for the analysis of a transformer winding oscillation, being more general, is applicable to the analysis of a generator winding oscillation, while the reverse is not true.

**F. D. Fielder and Edward Beck:** The general agreement in the two papers dealing with surge voltages in rotating machines is gratifying. Mr. Boehne has laid more stress on one phase of the problem and we on another, namely the voltage distribution during the front of the incoming transient which we considered the most likely cause of trouble. Thus, the two papers together with the discussions present a rather comprehensive picture of the conditions as they are today.

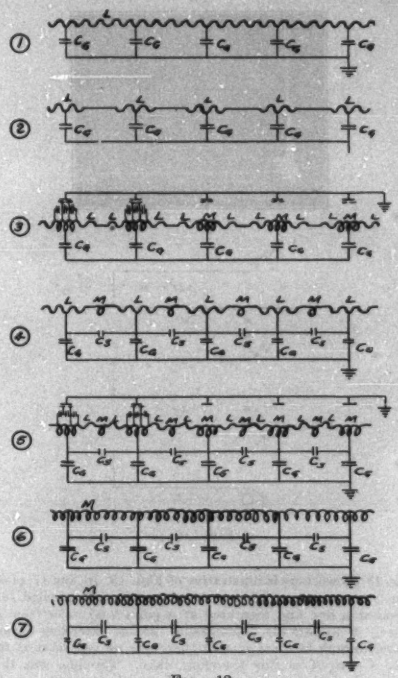

Fig. 12

Several methods of protection have been described, some of which we consider more efficient than others. In general, if the machine is directly connected to overhead lines the most efficacious way of influencing the distribution appears to be the use of distributed capacities or arresters. Of those methods which can be used without modifying the construction of the machine itself, we consider the use of a combination of inductance, capacity and arresters as illustrated in Fig. 14 of the paper the most efficient.

Other methods may sometimes be advisable considering the economics of the question. However, as pointed out in our paper arresters alone at the machine terminals may not prevent bad distribution; and the use of capacity only with an arrester, unless the capacity is large, may not exert sufficient influence on the wave front before the arrester commences to discharge to prevent poor distribution because, as pointed out in the appendix to our paper the rate of rise of voltage at the condenser terminals depends not only on its capacity and the effective surge impedance of the line but on the magnitude and steepness of the incoming surge. In the case of very high overvoltages the rate of rise of voltage up to arrester discharge may be high.

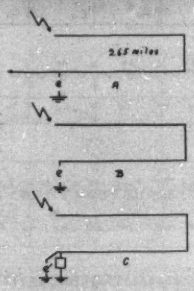


Fig. 13

Fig. 13 shown here is illustrative of Figs. 15, 16, and 17, of our paper. A surge from an impulse generator was applied to a transmission line and measured at a point 2.65 miles from its origin by a cathode ray oscillograph, the line extending beyond the oscillograph location so that there was no reflection at this point. Curve *A* is this traveling wave. The line was then terminated at the oscillograph location and the same impulse applied from the generator. The reflection of *A* produced a voltage *B* at this point. Next an autovalve arrester was connected from line to ground at the oscillograph location. On the application of the same impulse the voltage *C* appeared, this being the voltage across the arrester during discharge or in other words a volt-time characteristic. The flat top practically independent of discharge current, and smooth transition from the non-conducting to the conducting state are characteristics of this valve type arrester, further illustrated by the two volt-ampere characteristics of a section of such an arrester shown in Fig. 14.

Fig. 13 further shows that although the original wave reached its crest in a relatively long time, about 10 micro-seconds, the voltage rose to arrester discharge in about 1 micro-second which would give a distribution in a machine such as the one used in the tests described in our paper, between Figs. 4 and 6. The benefit of the addition of a wave sloping device is thus apparent.

**E. W. Boehne:** In the lightning protection of directly connected equipment the *fundamental consideration is the magnitude and duration of voltage stresses* of the various insulations in the machine. It follows, therefore, that the true measure of any protective scheme is its ability to reduce these insulation stresses. Now from a careful study of the phenomena presented in the paper it is apparent that the maximum stress which occurs between turns for any wave occurs at or near the line terminal and throughout the dissipation of this surge the stresses between turns at any point will never exceed this initial turn stress. This fact is independent of the condition of the neutral and is primarily the result of the change in wave form as the transient proceeds through the winding the first time.

This brings us to the consideration of the neutral resistor as an effective protective measure for open neutral machines as questioned by Mr. Palueff in the early part of his discussion. From the above paragraph it is evident that the only insulation which this neutral resistor is called upon to safeguard is the major insulation to ground. Any device which may be placed in the open neutral which will not allow the maximum voltage at the neutral under the most severe conditions to exceed the lightning arrester potential, has performed its function one hundred per cent efficiently. The most severe lightning condition in this respect is to have surges enter on all three phases simultaneously. The ideal resistor at the neutral under such conditions has been shown to be equal to surge impedance of all phases in parallel at the neutral. Now it is true that should surges enter on one phase or two phases only there will be a *negative* reflection at the neutral and a voltage oscillation will be set up in the machine. Here our fears are immediately relieved with the realization *that voltage oscillations in themselves are as harmless as thunder and need only be considered with respect to the stresses they may produce.* In the case of *negative reflections* at the neutral the potentials in the winding are obviously reduced, the maximum voltage to ground never being in excess of the lightning arrester voltage, the objective of neutral resistor.

Fig. 14

In this respect the neutral resistor can have any resistance less than the above mentioned value and still be as effective in reducing the maximum voltages to ground.

The reader is referred to the last paragraph of the paper prior to the Summary and Discussion.

Fig. 12 of Mr. Palueff's discussion shows a very good summary of the transient investigations made upon generators and transformer windings, however, a great deal of flexibility accompanies such a classification. Mr. Palueff points out that the transformer theory of standing wave oscillations reduces to a simple traveling wave when the constants of the circuit are such that the various harmonics vibrate at a rate proportional to their order, that is, when the third harmonic vibrates 3 times as fast as the funda-

mental, the fifth 5 times as fast, etc. Such a case is more easily and clearly analyzed if the phenomena be considered as a traveling wave in the winding. On the other hand, in such circuits where the harmonics are found to vibrate at a slightly different rate than their natural order as mentioned above, does not mean that all the traveling wave properties of the phenomena are lost. Oscillograms taken on transformer winding have been found to exhibit traveling wave properties. Such a case is shown in Fig. 9 of Mr. Hodnette's paper, *Effect of Surges on Transformer Windings*," A. I. E. E. JOURNAL, Nov. 1929 and reproduced again as Fig. 2 in the Electrical Machinery Technical Report, Summer Convention, 1930. These oscillograms show clearly that the *fundamental oscillation* is caused by a traveling wave reflecting back and forth in the transformer winding as was found in the case of generator windings (compare with Fig. 1 of this paper).

# Vertical Shaft 25,000-Kv-A., Synchronous Condensers

## 25-Cycle, 500-rev. per min., Outdoor Type Units for Toronto Leaside Transformer Station

BY H. A. RICKER,* Non-Member J. R. DUNBAR,* Member, A. I. E. E. and R. E. DAY* Non-Member

*Synopsis.—This paper is a description of the 25,000-kv-a., 13,200-volt, 25-cycle, 500-rev. per min., vertical-shaft, outdoor type, self-starting synchronous condensers installed in the Toronto-Leaside Transformer Station, of the Hydro-Electric Power Commission of Ontario. Some of the special problems encountered because of the vertical-shaft, outdoor type arrangement are discussed. In the appendix, the automatic starting and stopping sequence is given, with a comparison between the results obtained by using open circuit transition and the results to be expected by using closed circuit transition.*

*The following table of contents explains the plan of presentation followed:*

1. *Introduction.*
2. *Mechanical Design.*
3. *Type of Condenser.*
4. *General Arrangement.*
5. *Weights and Dimensions.*
6. *Shipment and Installation.*
7. *Detail Description—Stator.*
8. *Detail Description—Rotor.*
9. *Detail Description—Brackets, Bearings, and Housing.*
   *Upper Bracket and Bearings.*
   *Thrust Bracket.*
   *Thrust Bearing.*
   *Exciter Bearing.*
   *Speed Relay.*
   *Housing.*
10. *Maintenance.*
11. *Ventilation.*
12. *Bearing Protection.*
13. *Fire Protection.*
14. *Electrical Protection.*
15. *Ground Detector.*
16. *Calculated Electrical Characteristics.*
17. *Starting and Stopping Procedure.*
18. *Operation.*
    *Appendix.*

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### I. Introduction

In November 1929 the first of the 25,000-kv-a. vertical shaft, outdoor type, synchronous condensers for the Toronto-Leaside Transformer Station of the Hydro Electric Power Commission of Ontario was placed in service. At the present time there are two condensers in service, and two more, which are now being manufactured, should be in service by the end of this year. The condensers are nominally rated at 25,000-kv-a., 13,200 volts, three-phase, 25-cycle, 500-rev. per min., 6-pole, zero per cent power factor leading, with maximum ratings of 30,000 kv-a. at 13,200 volts and 25,000 kv-a. at 14,500 volts. The specified capacity, under excited, is 12,500 kv-a. at 13,200 volts. The guaranteed temperature rise at normal rating is 60 deg. cent. by detectors in the armature winding and 75 deg. cent. by resistance in the field. These ratings were determined after extensive studies made by the Hydro-Electric Power Commission engineers, particulars of which are described in a companion paper.

These condensers are located at the receiving end of the Hydro-Electric Power Commission's 220-kv. transmission line from Paugan Falls to Leaside. It was decided that quick response excitation was necessary to insure proper operation of the condensers in this location. Accordingly, a laminated-frame, direct-connected exciter with a separate constant-voltage pilot exciter was used for each condenser. By this excitation arrangement, it was possible to obtain a calculated speed of response of the main exciter of the order of 800 volts per second.

Each unit includes the synchronous condenser, the laminated-frame main exciter, and the pilot exciter on one shaft. Before the units were ordered, an auxiliary synchronous motor was considered which would have been mounted on the same shaft as the condenser, and would have been of sufficient capacity to drive the condenser and to supply the losses of half a transmission line. It was decided, however, that the auxiliary motor was not necessary as the condenser could be brought up to speed from the Niagara System, and then the transmission line tested during the period in which the condenser was slowing down. It has since been found that the Hydro-Electric Power Commission (Gatineau) line may be connected to the Niagara System at full voltage, so line testing can be carried on without using a condenser. As mentioned elsewhere, a starting motor was not necessary.

### II. Mechanical Design

Perhaps the first impression an engineer, accustomed to the arrangement of vertical shaft units, gets from the assembly of this condenser is that it is quite reversed to the usual. In fact it was a rather long study that produced the arrangement. One at a time, study after

*All of the Canadian Westinghouse Company, Limited, Hamilton, Canada.

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30-85

study, first the thrust bearing, then the large exciter with collector, next the pilot exciter and finally the speed relay went to the bottom. For this unit, it is doubtful if any other arrangement would have been more convenient.

## III. Type of Condenser

*Outdoor, Vertical-Shaft, Air-Cooled, Self-Starting*

For some years things electric have been gradually moving to the out-of-doors. There seemed to be no insurmountable difficulty in putting these condensers also there. It only required that the units be covered with a suitable encasement and that they be arranged so that a miminum amount of exposure would be necessary in case of repairs.

One question in connection with the design has been repeatedly asked: "Why were they designed with vertical shafts?" Obviously a vertical unit could be more economically enclosed for outside location than could a horizontal unit. The removal of a rotor from the stator, or the arrangement of a unit so that the stator may be shifted clear of the rotor, usually presents a tedious problem with a large, high-speed, horizontal unit. Accordingly, a vertical unit should be preferred providing the head room could be kept within reason.

Open air machines with air filters were chosen. Fully enclosed machines were considered. With fully enclosed machines, water cooling of the ventilating gas would be required. Hydrogen could not be justified economically as the ventilating gas, since the peripheral speed of the condenser is not high enough to show a material reduction in losses with its use. Air would have to be used whether fully enclosed or open. Inasmuch as there would be no place in which to make use of the heat transferred from the air to the water, the water would have to be spray-pond cooled, which feature was undesirable. In addition, the cost of water coolers for the air was found to be more than double that of air filters.

The atmosphere in the vicinity of the station apparently would never be heavily laden with dust and smoke; accordingly the cost of maintaining air filters would not be high. Heated air could conveniently be circulated and used for the heating of the basement and tunnels.

In the event that it was found desirable to resort to water cooling at some time in the future, certain inexpensive alterations could be made to accommodate.

Self starting was desired. With the arrangement of forced lubrication to the thrust bearing as described in a subsequent paragraph, a special starting motor was not required. The starting kv-a. was specified as not to exceed 50 per cent of full-load kv-a.

## IV. General Arrangement

The general arrangement of the unit on the foundation is well shown in Fig. 1, this figure being supplied by the Hydro-Electric Power Commission of Ontario.

On what we may term the ground elevation, the main stator stands on its support. On top of the stator, and supported on a stator frame extension, is mounted a comparatively light eight-armed girder type bracket for guide bearing support.

The thrust bearing is located at the ground elevation and is supported on a girder type bracket which, in turn, rests on the foundation. Beneath this thrust bearing bracket is located the main exciter, the stator of which is supported on another girder type bracket, while the pilot exciter and a speed relay are underslung from the main exciter bracket.

The whole main stator from ground elevation is encased in a housing suitably arranged for ventilation and for protection from the weather.

The unit, apart from the electrically active materials, is fabricated practically throughout of steel plate, bars, and sections. Only a few parts such as the upper guide bearing, some Kingsbury bearing parts, collector parts, and exciter spider are of cast construction.

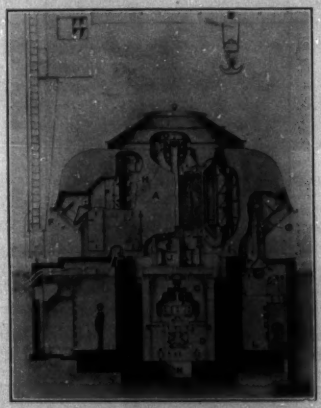

Fig. 1—General Arrangement of Unit on Foundations

A 25,000-Kv-a. condenser 500 revolutions per minute
B 80-Ton gantry crane
C 150-Kw. 125-volt main exciter
D 30-Kw. 250-volt pilot exciter
F Main incoming air damper
G Main outgoing air damper
H Recirculating air damper
J Damper for basement heating
K Spherical thrust bearing
L Upper guide bearing
N High-pressure oil pump for starting
O Truck for handling exciters
P Threaded hole for rotor lifting eye
Q Air filters
Q Current transformers

The basement under the unit provides a convenient location, quite large enough for the necessary switching, for the oil pumps and storage, and for other incidental purposes.

## V. Weights and Dimensions

The weight of the complete unit is approximately 210 ton. The stator frame of the main unit complete with iron and coils, weighs 84½ ton, the rotor of the main unit, completely assembled on the shaft, weighs 75 tons. The maximum weight required to be lifted by the crane at any one time is 85 ton. The weight of a

single pole with field coil is over 9½ ton, which weight is greater than a pole and coil of a Queenston 55,000-kv-a. generator. The field coil weighs nearly two ton itself. An armature coil, too, is longer, wider, and heavier than a similar coil from a 55,000-kv-a. generator.

The over-all height of the unit from the bottom of the speed relay to the top of the housing is 34 ft. The maximum width of the unit over the housing, exclusive of the ventilating extensions, is 19½ ft.

Fig. 2—Up-ending and Lifting of Rotor from Railroad Car

## VI. Shipment and Installation

The arrangement of these units made necessary the installation of the thrust deck with bearing first. The

Fig. 3—Turning and Lifting Stator During Installation

rotor had then to be installed and lowered into the pit, after which the stator was put in place.

Before shipment, the rotor was completely wound. The stator winding was completed except for some of the end connections. Each, the rotor and the stator, made a heavy car load and each was turned horizontally for shipment. For the stator special clearances had to be secured from the railways as the coil ends overhung the width of the car. Fig. 2 shows fairly well the unloading and up-ending of the rotor. It may be noted that the regular lifting eye could not be used. A cable was threaded through the hollow shaft and a bushing with an easy radius for the cable inserted in the shaft end. Fig. 3 shows the stator lifted with a beam after the turning had been completed.

## VII. Detail Description—Stator

A detail cross-section of the unit is shown in Fig. 4.

The design of the active material of the stator and rotor presented few new problems.

In order to keep the peripheral speed at a reasonable value, the condenser had to be built with a core width of 80 in. On account of the low temperature guarantee and considering the great depth of the armature punchings of a six-pole machine, the core had to be divided into unusually small sections. These sections are separated from each other by I-beam spacers. In

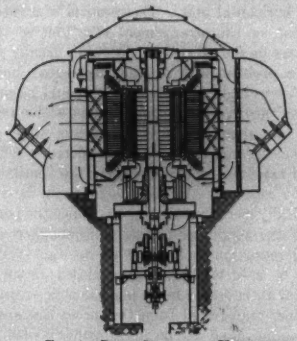

Fig. 4—Cross-Section of Unit

addition to these regular air ducts provided for ventilating purposes, a one-inch duct has been provided in the center for the purpose of facilitating the removal of armature coils.

The armature coils are insulated with micarta folium, which will stand an operating temperature of 150 deg. cent. without injury. Each coil is made up of four turns subdivided into eight strands each, with some of the strands mica-taped in order to insulate them from the adjacent strands and so to reduce eddy-current losses. To reduce still further additional losses, the winding has also been transposed once between coils.

The stator frame is constructed of steel plate and bars, amply braced. A large ventilating hole is provided in the outer frame plate for the outlet of hot air. Two smaller openings are provided for the mounting of the customer's re-circulating dampers. Two heavy plates, one on each side of the frame, are welded in for the mounting of trunions for use in lifting and turning the stator. The silicon steel laminations are assembled on round rods rather than in slotted dovetails. The coils are formed in the usual way, with sufficient clearance

between coils on the diamond ends to pass insulated bolts for bracing to the triangular shaped brackets, in turn bolted to the stator end plates.

This style of coil bracing is without a doubt one of the best, if not the very best, for coils of wide throw. It has some disadvantages, such as requiring a little more copper on the coil ends, and it is expensive. However, to offset the objections, it is, when properly applied, a most rigid form of bracing and little trouble is ever experienced with it.

## VIII. Detail Description—Rotor

The field coils are made up of three different sizes of straps of which the widest has a width of 4.5 in. The insulation between turns consists of two layers of asbestos with one layer of mica sandwiched between. This was desirable on account of the high pressure between turns, due to the centrifugal force. The coils are insulated from the poles with mica, which insulation will stand a temperature of 150 deg. cent. continuously.

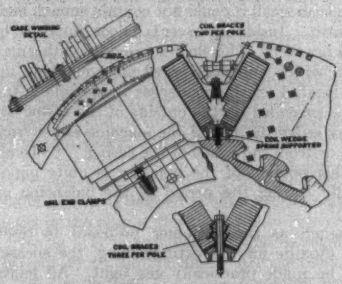


Fig. 5—Some Details of Rotor Design

The rotor spider is of plate steel construction dovetailed for the poles. Each pole is provided with two dovetails. Each dovetail is keyed on each side with a single taper key. The dovetail slots in the rotor are skewed sufficiently to allow for the key taper. With this method of keying, the designer need not provide a radially split-pole body to be assured of good dovetail contact on all four sides as is often done when two keys are used on one side only of each dovetail.

Some details of design may be seen by referring to Fig. 5.

Located between adjacent coils, and next to the spider is a metal wedge to present a flat rest for and to support the coil insulation. Under this wedge, and inserted in drilled holes in the spider, is a series of coil springs that press against the metal wedge in order to insure tight insulation even after some shrinkage in service.

One of the points that required the most careful consideration was the design of suitable braces between coils to counteract the tangential forces of the coil sides. The space was limited and the ventilation between poles could not be blocked. These braces had to be held in place by the pole tips. This required several inches of nickel steel laminations in the pole.

The starting squirrel-cage winding required special attention to satisfy the current carrying requirements and the centrifugal force. The bars were brazed to angles of copper and these angles, in turn, bolted to a laminated ring consisting of hard drawn copper bars bent cold and brazed. Each ring is of three thicknesses of copper, the brazes of different sections of the ring being located at 120 deg. so that two-thirds of the ring cross section consists of good hard copper, the tensile properties of which are good.

The ventilating fan located on the top of the rotor is formed of comparatively thin plate while the fan located at the bottom is of very heavy construction. This fan forms also the brake ring used in stopping the unit. It also forms the support on which the rotor rests when the thrust bearing is opened for inspection, or is removed. Inasmuch as this ring has to form a blower, it had to be designed for that purpose; it had to have sufficient capacity for heat to give a limited amount of expansion when braking; and it had to be strong enough to support the rotor weight at the four brake points and to resist the torque due to friction.

## IX. Detail Descriptions—Brackets, Bearings, and Housing

*Upper Bracket.* The upper bearing bracket, or guide bearing support, is arranged with a demountable center, rectangular in shape, only large enough that the crane block may pass through the hole. This demountable center may be removed through the outer encasement through a round hole of approximately the same size. This arrangement permits the attachment of the crane to the shaft without the exposure of the whole top surface of the unit as would be the case if the entire top bracket had to be removed.

Lubrication and cooling of this top guide bearing is accomplished by forced oil feed from a circulating pump. Only a small portion of the oil is allowed to drain down through the rotor. The arrangement is a little unusual inasmuch as the feed is at the bottom of the bearing and the main overflow is at its top.

On the top of this guide bearing is located a small annular oil pot that fills automatically with overflow oil from the bearing. This container forms a reservoir for automatic feed back to the bearing during the shutdown period and as an emergency protection in case the lubricating system should fail.

*Thrust Bracket.* The thrust bearing bracket is naturally of very stiff construction. It consists primarily of heavy H-beam girders with plates welded top and bottom. Mounting is provided on the top plate for the air brake pedestals.

The oil reservoir is, in this case, mounted on the thrust-bearing base plate for convenience of insulating.

It is made square, with demountable cover and side plates.

*Thrust Bearing.* An enlarged detail cross-section of the thrust bearing is illustrated in Fig. 6.

This bearing is of the Kingsbury tilting-shoe type. The shoes and runner differ from the ordinary in that their actual bearing faces are spherical, so that the bearing forms not only the thrust bearing but also the lower guide bearing of the main unit. This bearing seems to be particularly applicable to these units. The fact that it occupies a minimum of space and is extremely easy to dismantle in a limited and difficult position are perhaps the principal points in its favor. It is self-alining, self-contained, and easily lubricated.

The heat generated in the oil film of this bearing has to be dissipated by external means. In the preliminary study air coolers for the oil, located in the passage of the incoming air, were considered. The cost was found to be excessive, so water cooling was resorted to.

Owing to the fact that the thrust bearing space is limited, there was not room for the ordinary arrangement of cooling coils in the oil pot. Thus, an external system of oil circulation to the bearing is employed. The oil drained from the bearing is cooled with water from the customer's spray pond, circulated in suitable coolers.

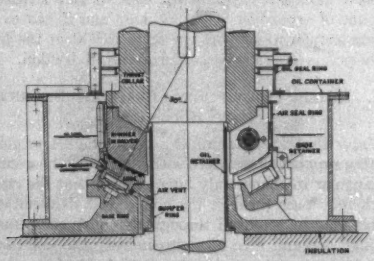


FIG. 6—CROSS-SECTION OF KINGSBURY SPHERICAL BEARING

In order to have easy starting, a high-pressure pump is arranged to force oil through a lead to the center of each Kingsbury shoe surface. This is the first application of its kind made to a Kingsbury bearing. As in similar applications with horizontal journal bearings the starting torque required is reduced considerably.

*Exciter Bearing.* The exciter guide bearing is self-lubricated by centrifugal force and is self-cooled, radiating fins being welded to the housing. It is located at a point too low to permit the draining of oil from it, back into the main lubricating system.

*Speed Relay.* The speed relay located on the bottom end of the exciter shaft operates centrifugally. It has three functions to perform, one of which is to cause the machine to be cut out of service in case of a dangerous overspeed. It also permits the application of field current to the condenser during the starting cycle and causes the application of the air brakes during the stopping cycle. These latter two functions are referred to again.

*Housing.* The contract for the condenser included the metal encasement necessary to the protection of the unit from the weather and for ventilation. The Hydro-Electric Power Commission designed and supplied the housing extensions with dampers which are located on the air intake and outlet sides.

The outer housing is made large enough for one to walk around the condenser frame within the cold air duct. Entrance is provided through a full-sized door in the vertical wall.

The main portion of the cover of the encasement is conical in shape and is provided with a foot rail around its circumference. The extreme top cover is spherical. Both portions of the cover are lagged with felt to prevent possible condensation. This lagging hardly seems necessary, for the air within does not circulate, and the volume is so small it could not contain enough moisture to do harm. Inside the cover is a floor supported by the bearing bracket. This floor is provided with a manhole through which one may crawl after climbing up the ladder located on the condenser frame side. Another ladder is provided on the outside of the casing so that one may enter the top of the machine either from the outside or from the inside of the casing. To be able to enter this portion of the machine is quite important especially during the period of the balancing of the rotor.

Inasmuch as the customer proposed to resort to carbon dioxide for fire extinguishing, the encasement had to be made practically gas tight. All joints not actually welded are provided with felt and canvas gaskets.

To complete the enclosure a plate covering, with manhole, is provided on the underneath side of the thrust bearing deck.

## X. MAINTENANCE

In order to remove the two exciters from under the main unit the Hydro-Electric Power Commission have provided a light truck on a track below the exciter level. This truck may be moved along the track under the exciter supporting bracket. Jacks are provided on the truck to lift the two exciters. The truck is illustrated in Fig. 1. After the electrical leads and mechanical attachments are disconnected, the truck with exciter support bracket and exciters may be moved along the track out of the way. The exciter shafts and bracket are arranged in such a manner that the weight of the armatures is carried by the bracket when the shaft flange is disconnected.

The condenser rotor and thrust deck may now be lowered into the pit thus cleared, a ring key being first inserted around the shaft under the thrust deck in order that the thrust deck may be lifted and lowered with the

rotor. Upon removal of the upper guide bearing and its supporting housing the crane hook may be attached to a suitable eye bolt screwed into the shaft. The rotor and thrust deck are then lifted slightly so that bridge plates under the arms of the thrust deck may be slid back out of the way and the main rotor lowered into the pit under the stator, the thrust deck arms following down slots provided in the foundation.

With the rotor in this position cleaning and all ordinary repairs may be done to the rotor and stator windings.

## XI. Ventilation

Normally the air for cooling the units (see Fig. 4) enters at one side through the housing extension. Here it is filtered before it enters the cold air housing. From this duct the air is distributed to the top and to the bottom of the machine, where the previously described fans force it between the poles, along the air-gap and through the ventilating ducts in the laminations. From the back of the laminations the air is carried around inside the frame, which forms the hot air duct, where it normally exhausts into the atmosphere through the opposite housing extension.

To describe fully the heating and recirculation system designed and installed by the Hydro-Electric Power Commission would take considerable space and the details of that description can well be left to the designers who are more familiar with it. For the purpose of this article, it will be sufficient to state that a fully automatic scheme is devised so that hot air may be recirculated in the rear of the air filters to prevent them from freezing over in bad weather, and to regulate the flow of cold air to the machine. Arrangement is also made that the temperature of the basement under the units will be regulated by a flow of air through dampers inserted in the basement ceiling. Any degree of heating may be acquired. The arrangement is shown in some detail in Fig. 1.

## XII. Bearing Protection

Every designer of electrical generators and motors will state that shaft currents are the greatest enemy that bearings have. It is good practise, especially on important installations, to guard in the design, against the possibility of these currents flowing, whether or not they are anticipated. Accordingly all bearings on these units are insulated. In fact the complete rotor is insulated from the stator so that a simple test may be applied at any time to determine if the insulation is intact. Tests made after installation indicate that this precaution was not necessary on this installation as the potential taken from end to end of shaft was found to be very small, certainly not sufficient to break down an oil film.

Each bearing is provided with a thermometer for bearing temperature indication, also with a hand reset thermostat whose contacts will close and start in operation the stopping cycle in case the bearing temperature exceeds the temperature for which the thermostat is set.

Each machine has two oil circulating pumps so arranged that if one pump should fail in operation, the other will automatically start. In addition, if the oil pressure fails, a relay will operate causing a shutdown.

## XIII. Fire Protection

At both top and bottom of the armature is installed a sprinkler pipe for water. The sprinkler pipe is of copper to prevent the possibility of corrosion. To make these pipes of copper does not add materially to the cost but it would appear to be an unnecessary precaution.

The Hydro-Electric Power Commission have installed a complete carbon dioxide flooding equipment which, no doubt, would be used in preference to the objectionable water system. The water system would be brought into play only as a last resort.

## XIV. Electrical Protection

Electrically the machine is protected by the commonly described split-phase balanced relay system. This system, since the stator is in three parallels, required the installation of 18 current transformers on the legs of the different phase parallels. These 18 transformers are mounted on the top frame extension and are equally spaced around the circumference. The mounting of these transformers is illustrated in Fig. 4.

A relay arrangement will actuate and cut the machine out of service if either the field or armature is overloaded for a dangerous period. Another arrangement will cut the machine out of service if the voltage drops below a predetermined value on the armature, or if the condenser should lose its field.

Thermocouples are located in the armature slots so that the temperature of operation may be recorded.

Realizing that a partially shorted field, due to unbalanced magnetic pull, might cause serious damage to the unit, not only was special insulation used on the field coils, but a ground detector for the field was also installed. This detector may or may not, at the customer's wish, be arranged to cut the unit out of service.

## XV. Ground Detector

The ground detector circuit is as shown on Fig. 7. A voltage of 110 a-c. is applied through the coil of a relay to the mid-point of two resistors connected across the field circuit. One side of this a-c. circuit is grounded so that a ground anywhere on the field circuit will complete the circuit and cause operation of the relay. The relay has a ½ ampere setting and the equipment has been found to be very sensitive. In case the apparatus indicates a ground, the same may be removed before a second one occurs to produce the objectionable short circuit.

Owing to the bearings being insulated, it was necessary to ground the rotor shaft through a brush in order

that the ground detector circuit might be effectively completed in case of a ground on the rotor winding.

This ground detector scheme does not increase the voltage between any part of the field circuit and ground, and it protects the exciter armature as well as the condenser field. It has the same sensitivity regardless of the voltage across the main exciter armature and field circuit.

## XVI. Calculated Electrical Characteristics

Fig. 9 shows the calculated no-load and full-load zero per cent power-factor saturation curves, also the short-

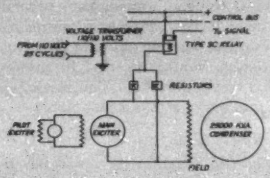


Fig. 7—Field Ground Detector Connections

circuit current and the V-curve at 13,200 volts. The transient reactance of the condenser is calculated to be approximately 32 per cent and the short-circuit ratio is approximately 0.7.

The excitation required at 30,000 kv-a. 13,200 volts,

Fig. 8—General View of Location after Installation of No. 1 Condenser

zero per cent power factor leading, is approximately 100 kw. and the guaranteed total loss at 25,000 kv-a., 13,200 volts, zero per cent power factor leading is 510 kw.

Up to the time of preparation of this paper, tests had not been made, but casual readings taken during operation check the calculated values reasonably well.

## XVII. Starting and Stopping Procedure

The starting and stopping of these machines is entirely automatic. When the starting button is pressed, relays take control, and if everything is normal, the complete sequence of operations progresses until the condenser is synchronized under regulator control and is carrying its share of the load. When the stopping button is pressed, or a protective relay operates, the condenser is automatically disconnected and brought to rest by a combination of dynamic braking and air brakes. This is amplified slightly in the Appendix.

By the use of the customary three-breaker method of reduced voltage starting, with open circuit transition from starting to running voltage, it was found possible to keep the inrush during the starting period down to a

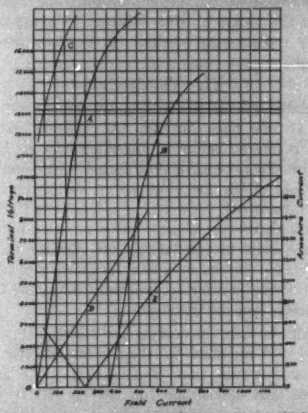


Fig. 9—Calculated Saturation Curves of the 25,000-Kv-a. Condensers

A. No-load saturation
B. 1095 Amperes, 0% P. F. leading saturation
C. 548 Amperes, % P. F. lagging saturation
D. Short-circuit saturation
E. V-curve, 13,200 volts

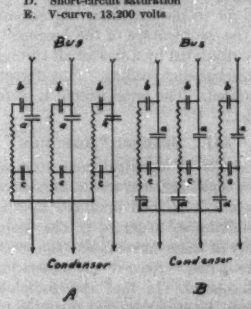


Fig. 10—Open- and Closed-Circuit Methods of Starting

A. Open-circuit transition
B. Closed-circuit transition

reasonable value, so that there was no undue disturbance to the bus voltage. Closed circuit transition was considered but it was discarded as being of no material assistance, and it would introduce an extra breaker, since the Commission did not wish the auto-transformer to be energized all the time. Fig. 10 shows diagrammatically the connections for the open-circuit method

that was used, and for the closed-circuit transition method that was considered. The sequences of breaker operation are as follows:

*For the open-circuit method:*

To start: (1) Close breakers *c* and *b*

To change to running position: (2) Open breakers *b* and *c*
(3) Close breaker *a*

*For the closed-circuit method:*

To start: (1) Close breakers *c*, *d*, and *b*

To change to running position: (2) Open breaker *d*
(3) Close breaker *a*
(4) Open breakers *b* and *c*.

The current that would flow at the instant of starting is the same for either method, if the same transformer

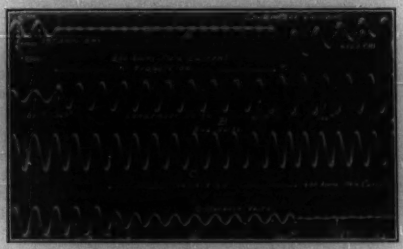

Fig. 11—Oscillograms of Transition Period; Field Current 650 Amperes

A. Line current
B. Condenser terminal voltage
C. Bus voltage
D. Difference between condenser terminal voltage and bus voltage

tap is used. Also with the equipment supplied for this installation, the current rush at the moment of transition is practically the same, if the time of transition is the same. If closed circuit transition is used, and the voltage of the condenser is adjusted to be equal to line voltage, with the condenser operating in synchronism through the auto-transformer, the inrush is increased. This is discussed in detail in the Appendix.

## XVIII. Operation

The only tests that had been made, previous to the writing of this paper, were starting tests, to determine the best auto-transformer tap and the best value of field current to use. Fig. 11 is a print of oscillograms showing:

A. Line current
B. Condenser terminal voltage
C. Bus voltage
D. The difference between the condenser terminal voltage and the bus voltage.

The field current for these oscillograms was 650 amperes, which, as reference to the calculated saturation curves Fig. 9 will show, is approximately the full load field current for normal voltage. The auto-transformer was connected for a turn ratio of 26.2 per cent. The starting tests seem to indicate that this gave the least disturbance on transition, with a low value of starting kv-a.

It is noteworthy that with this particular installation the condenser invariably reached synchronous speed on the low voltage applied by the auto-transformer and before field current was impressed.

As has already been mentioned, casual readings taken from time to time during operation seem to be close to the calculated figures. It is shown in the Appendix that the oscillograms reproduced in Fig. 11 check calculated figures very closely.

## Appendix

The operation of this station being completely automatic it may be of interest to give a very brief outline of the starting and stopping steps as they take place. Starting and stopping and protection are controlled by a number of relays.

*Normal Starting.* When the starting button is pushed a master relay closes, provided all conditions are normal. This relay remains closed only providing operation after operation takes place in regular and proper sequence. For instance, it will not close if the phase rotation is reversed or if the line voltage is too low, if the air brakes have been left on by hand control, or if any other operation has not been properly performed.

The master relay closing causes, first of all, the high-pressure pump connected to the Kingsbury bearing shoes, as well as one of the oil circulating pumps, to start. When the oil circulation has been built up to the proper value and after a lapse of time, in which a film of oil is being forced to the Kingsbury shoes, a contact making gage causes, provided other conditions are normal, the starting and magnetizing breakers to be closed and reduced voltage to be applied to the condenser, at which time the field will begin to rotate. When the speed of rotation has reached a required value, field is built up on the condenser and when the field current reaches a predetermined value the transition occurs, that is, the starting breakers open and the running breaker closes, at which time the condenser is automatically put under the control of the voltage regulator, and it takes its share of the load. At this time the high-pressure pump stops.

*Normal Stopping.* Pushing the stop button, or the operation of a protective relay, causes the opening of the same master relay used in starting. When this relay opens, the condenser is disconnected, the oil circulating pump stops immediately, and the condenser field breaker opens. Upon the opening of the condenser field circuit, the breaker controlling the dynamic brakes, closes the main exciter armature circuit through a re-

sistor and as the main exciter field is maintained a load is imposed on the exciter, quickly reducing the speed of the whole unit.

When the speed has been reduced by this means to one-half of full rev. per min., a contact on the speed relay closes and the air brakes are applied. The application of the air brakes removes the dynamic braking.

*Test Values.* The values of current and of voltage, as read from the oscillograms shown in Fig. 11, are as follows:

| | | |
|---|---|---|
| *Condenser terminal voltage* (per cent of bus voltage) | | |
| Before transition | | 28% |
| After starting breaker is opened | | 56% |
| Before the running breaker was closed | | 81% |
| *Difference between condenser terminal voltage and bus voltage* (per cent of bus voltage) | | |
| Before transition | | 72% |
| After starting breaker is opened | | 50% |
| Before the running breaker was closed | | 26% |
| *Line current* (per cent values are in per cent of condenser rated current) | | |
| Before transition | 397 amperes, r. m. s | 36% |
| After transition | | |
| Maximum unsymmetrical | 2750 amperes peak | 178% |
| A-c. component | | |
| Initial value | 940 amperes r. m. s. | 86% |
| At first peak | 850 amperes r. m. s. | 77% |
| D-c. component | | |
| Initial value | 1840 amperes peak | 116% |
| At first peak | 1600 amperes peak | 101% |

*Open Circuit Transition.* The current which flows momentarily when the condenser is connected to the bus at the conclusion of the transition period is proportional to the difference between the condenser terminal voltage and the bus voltage, if the d-c. component and components due to subtransient reactances are neglected. This difference is vectorial and depends on the magnitude and direction of the vector representing condenser terminal voltage. Fig. 12A shows the vector diagram of voltage corresponding to the oscillogram shown in Fig. 11. This indicates that the condenser terminal voltage lags behind the bus voltage by approximately 12 deg. The value of this angle of lag depends on the losses and on the fly wheel effect of the rotor. It would therefore be expected that with a higher value of field current this angle of lag would be greater since the losses are higher. This is borne out by Fig. 12B which shows the corresponding vector diagram obtained from other oscillograms for 750 amperes field current, showing an angle of lag of approximately 12½ deg.

The voltage which appears at the condenser terminals immediately after the starting breakers are opened is equal to the internal voltage in the condenser before the breakers were opened. With 650 amperes field current and with the condenser connected to the 26.2 per cent tap the line current was 397 amperes. This gives approximately 1500 amperes in the condenser. From the calculated saturation curves, Fig. 9, and from the calculated characteristics of the condenser, the current that should flow for 650 amperes field current with 28 per cent terminal voltage would be approximately 1700 amperes. This is a reasonably good check considering that the curves used are calculated, and the test result is taken from an oscillogram. Using the 1500-ampere value of current and the calculated machine characteristics, the internal voltage would be approximately 58 per cent of rated voltage. This checks well with the oscillogram value of 56 per cent. During the transition period the field voltage is higher than the $I\,R$ drop corresponding to the field current flowing, due to the inductive kick which reduces the field current when the starting breaker is opened, and therefore the field current tends to increase and the terminal voltage tends to "creep." From the oscillo-

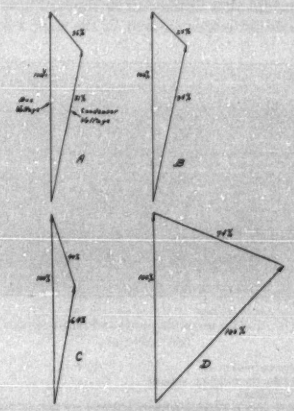


Fig. 12—Voltage Vector Diagrams at Instant of Closing Running Breaker

A. Open-circuit transition—650 amperes field current
B. Open-circuit transition—750 amperes field current
C. Open-circuit transition—300 amperes field current
D. Closed-circuit transition

grams taken, when the running breaker was closed the terminal voltage had increased to 144 per cent of the value immediately after the starting breaker was opened. This increase is reasonable considering the design of the excitation system.

It is possible to calculate the vector difference between the condenser terminal voltage and the bus voltage for other values of field current and of starting voltage by following the above procedure. The magnitude of the condenser terminal voltage is equal to the internal voltage before the starting breaker was opened, which can be readily calculated, plus the "creep." The "creep" may be interpolated from figures for other values of field current, or may be calculated from the condenser and exciter characteristics. The angle of

lag may be interpolated from test figures, or it may be calculated from the losses, the flywheel effect of the rotor, and the time of transition.

Fig. 12c shows the vector diagram corresponding to 300 amperes field current with the condenser terminal voltage vector interpolated from the oscillogram results. From this it will be seen that the difference in voltage is 40 per cent, which is much higher than for 650 or 750 amperes field current.

*Current Values.* The initial value of the a-c. component of current which flows immediately after the running breaker is closed is equal to this difference in voltage divided by the transient reactance of the machine. Using the figure of 26 per cent for the difference in voltage and the calculated transient reactance of 32 per cent, the initial value of the a-c. component is found to be 81.3 per cent. This is a very close check with the oscillogram value of 86 per cent. In fact, these oscillograms justify this method of computing the a-c. component of current after the running breaker is closed. Of course an allowance must be made for the d-c. component in determining the maximum unsymmetrical value of current which may flow. In this case the maximum unsymmetrical value is practically double the initial value of the a-c. component.

By means of this method the a-c. component of the current on transition for 300 amperes field current would be approximately 125 per cent. This is very much higher than the value corresponding to 650 amperes field current, and it is thus seen that the high value of field current gives better transition conditions. The oscillograms and the analysis show very little difference between 650 and 750 amperes but the tests seem to indicate less disturbance for 650 amperes.

It must be mentioned, however, that the second condenser was operating on the bus, under regulator control, during these tests. This is the normal operating condition for this installation. With this condition, the automatic regulator on the second condenser would hold the bus voltage constant, even though the leading current drawn by the incoming condenser tends to raise it. If there were no other condenser on the line, it is probable that a lower value of field current would give better results, since the higher value of excitation would tend to raise the bus voltage while on the starting tap, so that the difference between bus voltage and machine voltage would not be much diminished by using very high values of field current.

*Closed-Circuit Transition.* With the closed circuit method of transition, the series winding of the auto-transformer is left in circuit between the bus and the condenser, so that current will flow depending on the excitation characteristics of the transformer and on the voltage across the transformer. Fig. 13 shows the excitation characteristics of the auto-transformers used with the Leaside condensers when connected on the middle tap (28.4 per cent). When the transformers are connected for the 28.4 per cent tap there are 90 per cent of the turns in the series winding as when they are connected for 26.2 per cent tap. Therefore the values of current and voltage as read from Fig. 13 must be corrected by this factor to give the values for the 26.2 per cent tap.

As an initial approximation let us assume that the voltage across the transformer is equal to the difference in voltage between the condenser terminal voltage and the bus voltage in the open circuit method. For 650 amperes field current this voltage is 26 per cent and the corresponding exciting current for the auto-transformer is 0.05 per cent of the condenser full-load current. This current is so small that it can have practically no effect on the starting characteristics of the condenser and therefore the current inrush for the closed circuit

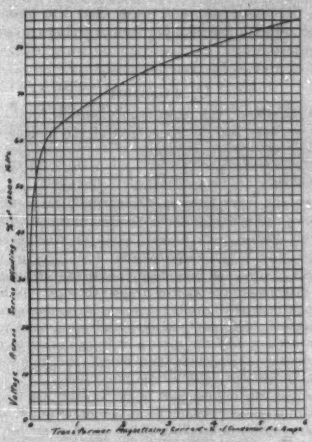

Fig. 13—Exciting Current of Starting Auto-Transformers for 27.4 per cent Tap

method with high speed timing of the breakers would not change the starting characteristics materially.

If a pause is made between the time of opening the neutral breaker and of closing the shunt breaker, sufficient time may elapse to allow the machine to build up to normal voltage and to reach a condition of constant phase angle displacement behind the bus voltage. On the assumption that the machine voltage is thus adjusted to equal the bus voltage, the phase angle between the condenser terminal voltage and the bus voltage will be determined by the voltage across the series winding of the transformers. If we assume that one per cent of machine rated current is required to supply its losses at no-load and to keep it in synchronism we find that the voltage across the series winding of the

auto transformers must be 74 per cent in order to pass this current, neglecting power factor. The vector diagram for this condition is shown in Fig. 12D. Again the a-c. component of current after transition is equal to the difference between the condenser terminal voltage and the bus voltage divided by the transient reactance, that is 231 per cent. This is considerably higher than the current obtained by the open-circuit method of starting.

### Conclusion

The above theoretical considerations show that for the Leaside condensers the optimum condition for starting is with a field current of the order of full-load field current using the open circuit method of transition. Tests confirm that the field current should be approximately equal to the value corresponding to rated full load on the condenser, and show that the best results are obtained with the 26.2 per cent starting tap on auto-transformer.

## Discussion

**F. H. Chandler:** This paper is an important addition to the very few we have had on the subject of the designs of large synchronous condensers, especially as these machines have a number of new features and are unique in being the first and only outdoor condensers of the vertical type in operation.

There are one or two features of this installation mentioned in the paper which I believe may be enlarged upon with interest to the plant engineer.

### Ventilation

The past practise of providing ventilating air control on electrical machines of the open or straight through type has been by means of manual controlled dampers or no dampers at all. The application of $CO_2$ gas to automatically controlled machines for fire protection, and the departure from indoor to outdoor rotating machines demand electrical damper controls which are as essential to the machine as its relay protection.

The main ventilating dampers of the Leaside condensers are automatic in operation, stream line in design for quietness of air flow and are capable of handling 50,000 cu. ft. of air per minute which is the machine requirement. They close automatically in sequence when shutting down the machine and open to the full open position when the machine is started. These dampers are operated by d-c. valve type motors rated at 12 lb. ft. at 230 volts. A shock absorber of spring construction is used in this mechanism to make certain that these dampers close tightly, these springs having a deflection of 1 in. in compression at 1500 lb. Provision is also made for partial opening or closing of the dampers to suit weather conditions by push-button control. Means are also provided to supply heat to the windings from the basement during shutdown periods in the winter months to prevent condensation on the windings.

Bearing in mind the wide variation in temperature during summer and winter months with resultant contraction and expansion of copper in the coils, the Commission has endeavored by means of thermostatically controlled dampers to minimize this variation. A minimum temperature of 85 deg. fahr. has been arbitrarily set as the outgoing air temperature of the machine which is satisfactory for basement heating. The principle of the control is such that the required quantity of discharge air at 85 deg. fahr. is automatically mixed with incoming air at temperatures ranging from 30 deg. fahr. below zero and up, to maintain the discharge air at 85 deg. fahr. This temperature will, of course, exceed 85 deg. fahr. during extreme summer heat. The recirculation dampers have a maximum by-pass rating of 25,000 cu. ft. per minute.

Butterfly dampers are used for re-circulation with gearing arrangement such that without the timing relay the damper will operate from full open to close in 10 minutes. To allow the ventilating air time to adjust itself to the new condition and to prevent hunting of this damper, the Commission has developed a special centrifugal contactor operating on the float principle in oil which allows 30 sec. operation of the damper and five min. time interval before the next operation. If the thermostats have opened in the meantime the dampers remain in that position until load change or outside temperature change again starts the operation. With this arrangement 90 min. is taken for full one-way operation of the damper.

When an internal machine failure occurs causing operation of the differential relays, the automatic features are such that the main dampers close, the re-circulating damper opens, and $CO_2$ gas is discharged inside the case on the incoming air side of the machine. The damper used for heating the basement is automatically tripped by the gas when discharged, confining the gas in the machine case.

Totally enclosed machines were considered, but the cost of cooling ponds, pumps, etc., for the air coolers on a transformer station site was considerably in excess of the arrangement provided. Reasons against the use of hydrogen cooling have been mentioned in the authors' paper. At the time of the purchase of these machines, the Commission was not convinced that a satisfactory sealed casing with vertical bearing glands had been developed and that the machines would be immune from the hazard of explosion. Water cooling would also be required for this ventilating medium.

### Machine Foundations

Vertical machine foundations where massive power house substructure is not available necessitated in the case of the Leaside condensers an exhaustive study to arrive at the proportions used. All articles in leading periodicals were referred to with the result that little authentic data could be produced.

Analysis of the sub soil taken from test holes drilled at the extreme corners of the foundations showed an average of 80 per cent clay, 2.9 per cent shale and 16 per cent sand which can be considered for rotating machinery as being capable of safe loading up to 2000 lb.

The only formula for computing the foundation mass which appeared to have merit, and which was not a proportion based on past experience, was received from one of the large turbine manufacturers. This formula is as follows,—Weight of foundation equals weight of machine times the cube root of the speed in hundreds. In the case of the Leaside condensers, this works out that the weight of the foundation is 1.71 times the weight of the machine. Our final design calculation shows this ratio to be 1.76 to 1. Soil pressure has been calculated at 1510 lb. per sq. ft.

A very accurate balance of the machine has been obtained, its high speed, heavy pole pieces and small rotor diameter demanding a running balance in the field. It has been noted that a 2 lb. weight one side of the rotor 20 in. from shaft center will throw the machine considerably out of balance.

Seven months' operation under the most adverse weather conditions have proven that the designs adopted have been exceedingly practical.

**G. D. Floyd:** The synchronous condensers described in the above paper were purchased primarily for power factor correction at the Toronto-Leaside Station. The proper regulation of the 220-kv. line from Paugan Falls to Leaside requires that the load at the receiving end have a power factor of approximately unity and as the load power factor might be 90 per cent lagging or less, synchronous condensers of approximately 100,000 kv-a. capacity were required to meet this condition.

The benefits to be derived from quick response excitation were

appreciated and excitation of this type was specified although no definite values as to the amount of response were laid down, this question being left to the discretion of the manufacturer.

A number of tests was made recently to determine the quickness of response of these condensers under various conditions.

Fig. 1 shows the response of two condensers to a simultaneous

Fig. 1

Fig. 2

Fig. 3

drop in voltage, artificially produced, the condensers initially operating at practically zero load. These condensers are provided with a field limiting relay which prevents the field current from rising beyond a predetermined value. During the tests, No. 1 condenser was operating with this field current limiting relay blocked and No. 2 condenser was operating normally.

It is usual to express the quickness of response of synchronous condensers by the rate of rise of the exciter voltage. This record indicates that a better method of so rating a condenser would be to express the response by the rate of rise of the condenser field current or better, by the rate of rise of condenser kv-a. It will be noted that although the exciter voltage rises within a few cycles to its ceiling value, the field current of the condenser is much slower in response.

Fig. 2 is similar to Fig. 1 except that approximately 40 per cent of rated kv-a. leading was being carried by each machine initially.

Fig. 3 shows the response of the two condensers to a drop in system voltage when the field current limit relays of both units had been blocked. This test was made to determine whether the condensers could be operated together and would respond approximately equally to a drop in system voltage.

Data worked up from these tests indicates that the response of the two condensers is approximately the same, being at the rate of approximately 20,000 kv-a. per second if the abnormal condition is limited to about 2 seconds. The rate of response appears to be about the same whether the condensers are operating initially at lagging power factor or at leading power factor.

No. 220-kv. faults have occurred since these condensers went into service, but they have performed very satisfactorily through several 110-kv. faults.

It would appear that the chief advantage of their quick response characteristics would be during faults on the 110-kv. system west of Toronto, in which case they should assist materially in maintaining the voltage at the point of interconnection of the 110-kv. and 220-kv. systems. With the high speed of clearance of 220-kv. faults contemplated at the present time, it would appear from the data obtained that the condensers would hardly have time to respond before the fault would be cleared. There would be no necessity however, for them to do so.

**L. W. Riggs:** The authors have written a very interesting paper and have shown great resourcefulness and ability in their design.

Outdoor synchronous condensers seem to be a logical development, and, as operating experience is gained, the demand for such machines will no doubt increase.

The General Electric Company has built several outdoor synchronous condensers, some of which are hydrogen cooled, others of which are air cooled. All of them are of the horizontal shaft type.

In general, vertical machines cost more than horizontal machines. They are also usually more difficult to ventilate due to supporting structures for bearings impeding the flow of air.

There are many possibilities of varying the design of the exterior parts to suit any weather or ventilating conditions that may be encountered. One of the best designs is to re-circulate the air through surface water coolers when cheap water is available. Other layouts may incorporate air conditioning apparatus either in the machine housing or in a separate structure. If the air is reasonably clean, however, it is no more necessary to condition the air for an outdoor machine than for the large number of indoor machines that are now taking their air supply from outdoors.

The General Electric Company has been using springs under field coils for a number of years and has found them to be effective in automatically taking up any expansion of copper or shrinkage of insulation that may occur in the field coils.

The problem of predicting the best value of field current to use during the change from starting to running position is quite complicated due to the many interdependent variables. A little experimenting by the operator, however, will quickly determine a satisfactory value.

# The East River Generating Station
## of the New York Edison Company

BY C. B. GRADY,[1] W. H. LAWRENCE,[2] and R. H. TAPSCOTT[3]
Non-member Member, A. I. E. E. Fellow, A. I. E. E.

***Synopsis.***—*This paper deals with the design and operating characteristics of the East River Generating Station of the New York Edison Company. This station, having an ultimate capacity of 1,240,000 kw., occupying as it does a site approximately a quarter of a mile long by 200 ft. wide, presents a number of design and operating features which are a departure from normal practise. Among the items of particular interest are:*

*1. The location of all of the circulating water pumps in a pit at the river end of the station, each set of pumps supplying its condenser through cast iron circulating water pipes six feet in diameter.*

*2. The adoption of steam turbine drive for the essential auxiliaries.*

*3. The adoption of pulverized fuel firing in what had hitherto been an exclusively stoker territory.*

*4. The burning of pulverized coal in a completely water cooled furnace containing practically no refractories.*

*5. The use of the largest boiler yet built.*

*6. The first use of a double winding generator which is also the largest generator in operation.*

*The paper presents some of the major considerations influencing the decisions reached on these items of design and the extent to which the expectations of the designers have been realized.*

* * * * *

THE New York Edison Company and affiliated companies operate two 25-cycle stations aggregating 402,000 kw., four combined 25- and 60-cycle stations aggregating 1,110,000 kw., and two 60-cycle stations aggregating 405,000 kw., a total generating capacity of 1,917,000 kw. with a 1929 peak load of 1,225,200 kw.

All stations are interconnected by means of tie feeders which approximate, in each instance, the capacity of the largest unit. Five frequency changers with a total capacity of 190,000 kw. tie the 25- and 60-cycle systems.

The arrangement of connections for the entire New York Edison System showing the relation thereto of the East River Station is given in Fig. 1. The 25-cycle system is operated radially, the high-tension feeders not normally being paralleled on the a-c. side of the rotary converters at the substations. The substations are usually supplied from more than one generating station to assure continuity and to facilitate load transfer.

The 60-cycle system is operated in parallel at the load (synchronized at the load), each section in a generating station being considered electrically as a separate station with ties only at the substation low-voltage busses or at the network.

At the time East River Station was designed, Manhattan Island was served almost exclusively from the 25-cycle system with conversion to direct current. The policy of the company at the present time, however, is to curtail the d-c. load in favor of the 60-cycle network. This paper deals with the development of the East River station as originally planned under a proposed growth of the 25-cycle system. Under the present policy of the company, no additional 25-cycle units will be installed, and the future development of the station will be devoted exclusively to 60 cycles. It is estimated that in 10 years the 60-cycle load of the New York Edison System will be at least four times the 25-cycle load.

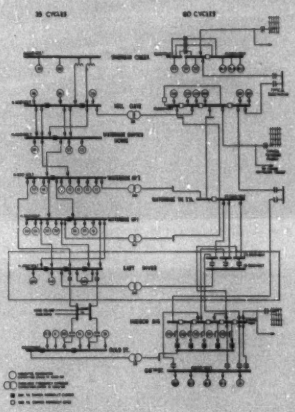


FIG. 1—SYSTEM CONNECTIONS

### SITE

There were very few areas on Manhattan Island where sufficient space together with other essential requirements satisfied the specifications for the station contemplated. The site chosen has the following advantages: it is near the center of the Manhattan load; it provides a continuous area for future expansion both

1. Mechanical Engineer, The New York Edison Company, New York, N. Y.

2. Chief Operating Engineer, The New York Edison Company, New York, N. Y.

3. Electrical Engineer, The New York Edison Company, New York, N. Y.

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as to buildings and high-tension feeder outlets; favorable waterfront conditions provide ample water depth, some thirty feet, for docking ocean going colliers and for large disposal of ashes.

The arrangement of the buildings and structures is shown in Fig. 2. The generating plant, which lies between 14th and 15th Streets, Avenue C and the East River, will be 1092 ft. long and 206 ft. wide. The coal preparation plant and the coal towers are between 13th and 14th Streets, Avenue D and the East River. A cross-sectional elevation of the original installation is shown in Fig. 3.

## Coal Handling and Preparation

The coal is at present brought to the station in 1000-ton barges and unloaded by two electric traveling coal towers each having a capacity of 350 tons per hour. The coal is crushed in the towers and discharged to belt conveyors for delivery to the 5000-ton bunker in the coal preparation house.

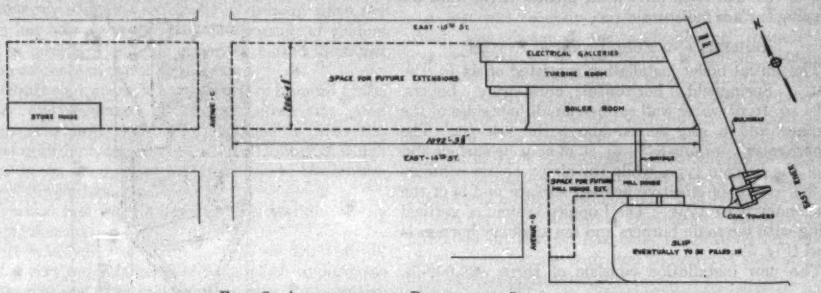


Fig. 2—Arrangement of Buildings on Site

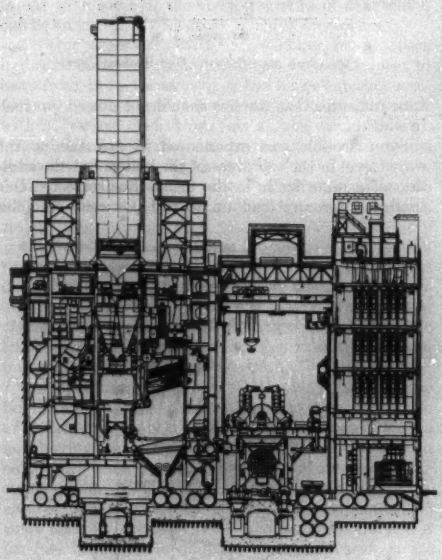

Fig. 3—Cross Section—Station

The pulverizing equipment consists of two 15-ton and four 25-ton Raymond air-swept mills, the drying being accomplished therein by the admission of preheated air. The coal is fed into these mills by gravity through individual chutes from the raw coal bunker, the quantity being regulated by star feeders of which there are two per mill. Each mill has six rollers, 20 in. in diameter, each weighing 700 lb.

The air required by each 15-ton mill is supplied by a 28,000 cu. ft. per min. constant speed, motor-driven fan which operates in a closed system comprising the mill, the cyclone separator, and the fan. Adequate drying of the coal is obtained by means of preheated air drawn by a 14,000 cu. ft. per min. fan through a low-pressure heater at 15 lb. gage and a high-pressure heater at 400 lb. gage. The temperature of the air and coal leaving the mill does not exceed 105 deg. fahr. To compensate for this hot air introduced, an equal amount is exhausted from the system by another 14,000-cu.-ft.-per-min. fan. This exhausted air is passed through an additional cyclone separator for removal of the coal, which is led back into the system, while the air is vented through a U-shaped water spray air washer, (Fig. 4). With this method of coal drying, precautions must always be taken to start the heater fan before turning on the steam to the heaters to prevent fires due to dust collection on the tubes.

The arrangement of the 25-ton mills is similar, their larger fans being equipped with variable-speed instead of constant-speed motors.

The coal collected in the cyclone separator of the closed system flows by gravity into a transport pump which conveys it to the boiler coal bins. One 100-ton

coal bin is provided for each of the original boilers and two for each of the new boilers.

The average fineness of the coal is approximately 96 per cent through a 60-mesh, 90 per cent through a 100-mesh, and 70 per cent through a 200-mesh sieve. The moisture content of the coal affects the capacity of the mills to a certain extent but the grain characteristics of the coal itself have a far greater effect than the varying surface moisture.

### Boilers and Fuel Burning System

The initial boiler installation consisted of six 14,809-sq-ft., Springfield, horizontal cross-drum boilers, 4134 sq. ft. of water wall surface on all four sides of the furnace and a slag screen above the ash pit. The superheater contains 3430 sq. ft. of heating surface and is of the hairpin type, while the air preheater contains 28,900 sq. ft. of effective heating surface and is of the stationary plate type. The Lopulco system of vertical firing with ten main burners and ten auxiliary burners is used (Fig. 5).

The new installation consists of three 800,000-lb.

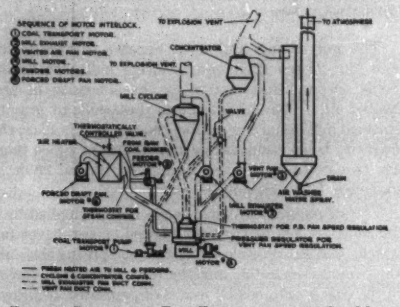


Fig. 4—Pulverizing Fuel Equipment for 25-Ton Mill

per-hr. boilers of the Ladd type fired from both ends. Each boiler contains 60,706 sq. ft. of heating surface and 7345 sq. ft. of water wall surface on all four sides of the furnace, with a slag screen above the ash pit (Fig. 6). The superheater contains 13,900 sq. ft. of heating surface and is of the hairpin type. The air preheater contains 82,721 sq. ft. of effective heating surface and is of the plate type. The furnace has a volume of 38,200 cu. ft. with a heat liberation of 29,300 B. t. u. per cu. ft. of furnace volume when operating at 800,000 lb. steam per hour. The steam conditions are 425 lb. gage pressure with 725 deg. fahr. total temperature, and feed water temperature of 360 deg. fahr. at 800,000 lb. per hour evaporation. The air temperature leaving the air preheater at this rating is 450 deg. fahr. The Lopulco system of vertical firing is used, with a total of 20 main and 20 auxiliary burners, or 10 of each on each end.

Subsequent to the initial starting period operating difficulties have been of a minor nature, little clinker trouble having been experienced either on the boiler tubes or the lower water wall headers. Any accumulation of ash or slag on the lower headers or sides of the ash pit is removed by means of a hand lance, while the boiler is in operation. Experience with the fin type

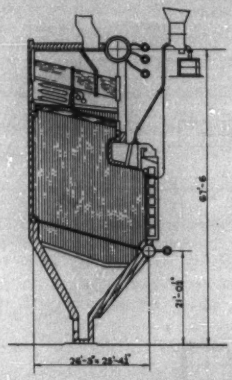


Fig. 5—Cross-Section Old Boiler Units

tube indicates that the fins should not exceed one inch in width.

Some trouble was experienced in maintaining the water level in the top drum of the boilers but the addition of a plate baffle in the drums has corrected this condition for any load up to 600 per cent of boiler

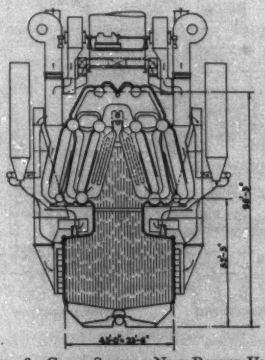


Fig. 6—Cross-Section New Boiler Units

rating. The normal operating rate of these boilers is approximately 350 to 400 per cent. Table I gives the principal data from a test of No. 4 boiler.

Superheaters are installed in all boilers. The results obtained have been on the whole satisfactory, both as to the superheat output conditions and maintenance. The main trouble experienced has been leaking of ball and socket joints, since remedied by the use of copper gaskets.

The plate type air preheaters have given very good service. No sticking of clinkers has been experienced, nor have any elements required replacement since the station has been in operation. The passage of cinders with the gases has kept the plates clean, and there has been no evidence of corrosion or erosion.

The draft equipment, which consists of induced draft, primary and secondary air fans has given very good service. The only trouble experienced is with the induced draft fans, the blades and scroll linings of which have to be replaced every two years due to the erosive action of the cinders.

Pulverized fuel was adopted for this station for the following reasons:

1. It was believed that this type of firing would permit a very much larger field from which to purchase suitable coal and that high efficiencies could be maintained with some of the cheaper grades of coal which can be burned only with great difficulty on stokers.

2. Our experience with large stoker fired boilers indicated that with such equipment, we must expect to have from 10 to 15 per cent of the boiler capacity continuously out of service for repairs. It was felt that with pulverized fuel firing, this outage would be very largely eliminated, resulting in the installation of less boiler capacity to meet a given load.

3. The experience of others in burning pulverized fuel indicated a much flatter efficiency curve than with stoker firing.

4. On account of the close proximity of the station to the congested sections of New York City, it was deemed essential that every effort be made to eliminate any possible nuisance due to the emission of smoke and cinders from the stack. It was felt that objectionable stack discharges would be more easily controlled from pulverized fuel than from stoker firing.

Our operating experience to date indicates that the field from which we can buy our coal supply includes any place in the world that can produce coal. We are now buying coal of equal heat value for this station at a cost of 24 cents per ton less than we are paying for stoker plants. This differential more than offsets the cost of coal preparation which averages about 18.5 cents per ton including labor, maintenance and power (at fuel cost) and in addition to this advantage, the repairs to the boiler and furnace due to the use of the completely water-cooled walls, is almost nothing compared to the repair costs on stoker fired plants.

The degree in which our expectations have been realized in the elimination of boiler outage for repairs, is illustrated by the fact that for a period of eight months last year, none of the boilers in this station was out for repairs other than between midnight and 6 a. m. on week days and on Sunday during periods of light load.

It will be seen from Table I, that the small boilers have a very flat efficiency curve, there being only 2 per cent difference in efficiency between an output of 108,000 lb. of steam per hour and an output of 240,000 lb. of steam per hour.

A test was recently run on one of the new boilers which was designed for a maximum capacity of 800,000 lb. of steam per hr. on which an output of 1,000,000 lb. of steam per hr. was maintained continuously for twelve hours with entirely stable furnace and water level conditions and with no signs of distress in any part of the equipment. A heat balance of this run is given in Table II indicating an efficiency of 86.5 per cent at an output of 25 per cent above the maximum guaranteed capacity, thus amply justifying our expectations for high sustained efficiencies. An output of 1,250,000 lb. per hr. has been maintained on one of these boilers for one hour and 15 minutes accompanied by a slight drop in efficiency.

With the exception of the first few months of operation, while initial adjustments of the equipment was being made, we have had no complaints due to either smoke or cinders from this station. The efficiency of the electrostatic and cyclone dust catching apparatus is such that we have been unable to locate any deposits of flue dust in the surrounding neighborhood.

Up to the time when this station was designed, practically all pulverized fuel furnaces had been very largely refractory lined and it was thought by designers that in spite of the high maintenance cost on such furnaces, a refractory lining was necessary to maintain stable fire conditions, particularly with low volatile coal. The furnaces in this station departed radically from previous designs in that they were completely water-cooled, in spite of the fact that our normal coal supply is of a low volatile character.

Considerable difficulty was experienced in the early stages of the station operation in maintaining stable firing conditions with the vertical burner system originally installed. After experimenting in various ways Mr. A. J. Wheeler, Jr., superintendent of the station, conceived and developed the idea that by applying a flame to the stream of coal immediately after its entrance to the furnace, combustion could be accelerated to a point where the heat radiated from the flame to the water-cooled walls did not reduce the flame temperature to a point where combustion was retarded.

Applying this principle, small auxiliary burners have been installed at right angles to each vertical burner, so disposed as to impinge on the stream of fuel leaving the vertical burner at a point slightly below its entrance into the furnace.

This method of burning coal has reduced the un-

TABLE I

| | | April 23, 1929 | May 7, 1929 | May 14, 1929 |
|---|---|---|---|---|
| Actual evaporation per hour | lb. | 108,630 | 169,100 | 239,720 |
| Heat absorbed by steam | per cent | 86.1 | 87.1 | 84.1 |
| Heat absorbed by air preheater and returned to other boilers | per cent | 2.0 | 0.5 | 1.0 |
| Heat loss due to moisture in coal | per cent | 0.2 | 0.3 | 0.2 |
| Heat loss due to moisture in burning hydrogen | per cent | 3.2 | 3.2 | 3.1 |
| Heat loss due to dry chimney gases | per cent | 6.9 | 7.3 | 6.1 |
| Heat loss due to combustible in refuse | per cent | 0.8 | 0.8 | 2.5 |
| Heat loss due to radiation and unaccounted for | per cent | 1.7 | 0.8 | 3.0 |
| Total | per cent | 100.0 | 100.0 | 100.0 |

| | | April 23, 1929 | May 7, 1929 | May 14, 1929 |
|---|---|---|---|---|
| Actual evaporation per hour | lb. | 108,630 | 169,100 | 239,720 |
| Boiler horsepower | | 3,545 | 5,715 | 7,885 |
| Per cent rating (including water walls) | | 187 | 302 | 416 |
| Per cent rating (excluding water walls) | | 240 | 386 | 532 |
| Steam pressure, boiler-gage | lb. per sq. in. | 404 | 414 | 425 |
| Steam pressure, superheater outlet | lb. per sq. in. | 398 | 399 | 400 |
| Steam temperature | deg. fahr. | 685 | 711 | 710 |
| Air to air preheater | deg. fahr. | 106 | 108 | 111 |
| Average temperature of gases leaving air preheater | deg. fahr. | 328 | 382 | 368 |
| Temperature feed water | deg. fahr. | 293 | 294 | 298 |
| Fuel, as fired per hour (weighed) | lb. | 10,030 | 15,650 | 22,200 |
| Fuel dry, per hour | lb. | 9,740 | 15,060 | 21,080 |
| Combustion space per lb. dry coal | cu. ft. | 1.63 | 1.05 | 0.73 |
| Actual evaporation per lb. dry fuel | lb. | 11.15 | 11.23 | 10.99 |
| Actual evaporation per lb. fuel as fired | lb. | 10.82 | 10.80 | 10.80 |
| Factor of evaporation | | 1.126 | 1.137 | 1.135 |
| Equivalent evaporation per lb. dry fuel | lb. | 12.48 | 12.76 | 12.47 |
| Thousands B. t. u. absorbed per hour | | 118,730 | 186,520 | 263,810 |
| Thousands B. t. u. absorbed per sq. ft. boiler heating surface including water walls | | 6.27 | 10.40 | 14.37 |
| Refuse, per cent of fuel, dry | | 9.1 | 8.7 | 10.4 |
| Per cent combustible in ash to ash pit | | 1.0 | 0.8 | 2.1 |
| Per cent combustible in fly ash | | 9.7 | 10.0 | 25.8 |
| Per cent combustible in refuse | | 8.8 | 9.1 | 23.3 |

| | | Semi-bituminous storage | Semi-bituminous storage | Semi-bituminous fresh mined |
|---|---|---|---|---|
| Proximate analysis dry: | | | | |
| Volatile matter | per cent | 18.8 | 19.2 | 19.5 |
| Ash | per cent | 8.3 | 7.9 | 8.0 |
| Fixed carbon | per cent | 72.9 | 72.9 | 72.5 |
| Moisture—as fired | per cent | 2.9 | 3.8 | 1.9 |
| Heating value per lb. dry | B. t. u. | 14,140 | 14,220 | 14,410 |
| Ultimate analysis: | | | | |
| Carbon | per cent | 80.65 | 80.60 | 80.70 |
| Hydrogen | per cent | 4.25 | 4.28 | 4.29 |
| Oxygen | per cent | 4.70 | 5.22 | 4.38 |
| Nitrogen | per cent | 1.25 | 1.22 | 1.25 |
| Sulphur | per cent | 6.89 | 0.78 | 1.36 |
| Ash | per cent | 8.28 | 7.90 | 8.02 |
| Fineness: | | | | |
| Through 60 mesh screen | per cent | 92 | 95 | 80 |
| 100 mesh screen | per cent | 85 | 89 | 69 |
| 200 mesh screen | per cent | 72 | 73 | 54 |

TABLE II

HEAT BALANCE OF NO. 7 BOILER—OUTPUT 1,000,000 LB. PER HR.

| | B. t. u. | Per cent |
|---|---|---|
| Loss due to moisture in coal | 11 | 0.1 |
| Hydrogen | 453 | 3.0 |
| Dry chimney gases | 1,137 | 7.7 |
| Combustible in refuse | 73 | 0.5 |
| Moisture in air | 30 | 0.2 |
| Radiation and unaccounted for | 294 | 2.0 |
| Total losses | 1,998 | 13.5 |
| Efficiency and heat to boiler | 12,772 | 86.5 |
| Total | 14,770 | 100.0 |

burned carbon losses, increased the furnace capacity, eliminated all slag trouble, and made possible stable firing conditions at all rates of operation.

## Ash Handling

The ashes from all the boilers are drawn into trenches running along both sides of the boiler room. They are sluiced along these trenches to a central ash pit into which the ashes collected from the cyclone separators and precipitators are also discharged. Centrifugal pumps remove these to a large concrete ash hopper on the dock from which they are loaded into scows by gantry cranes. Approximately 80 to 90 per cent of the ashes pass up through the boiler, the remaining 10 to 20 per cent being drawn from the ash pit.

Two types of cinder catchers are in use, cyclone separators and precipitators. A Davidson cyclone separator was installed on each of the first six boilers with satisfactory results. The only maintenance required has been the relining of the helix after two years of service. Two Cottrell precipitators have been installed on each of the three new boilers. They are

giving excellent service, test runs showing efficiencies of 90 to 95 per cent.

### Generating Equipment

The generating building will have accomodations for nine steam turbo generators of large capacity, three of which are already in operation. The first, of 60,000-kw., designated Unit No. 2 went into service November 19, 1926; the second, a 60,000-kw., Unit No. 1, on

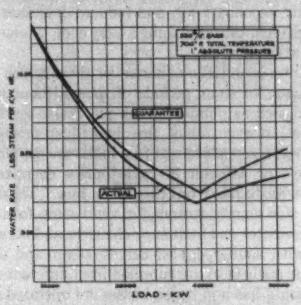


Fig. 7—Steam Rate Curve Turbines No. 1 and 2

February 21, 1927; the third, a 160,000-kw. Unit, No. 4, on October 10, 1929. This unit which has a tandem compound turbine, using straight steam flow on the high pressure and double flow on the low pressure, has been operating very satisfactorily. To date no water rate tests have been made on this unit. (See Figs. 7, 8, and 9.)

The generated potential is 11,400 volts, three phase,

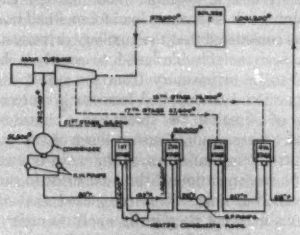

Fig. 8—Heat Balance—Unit No. 4

25 cycles. All 25-cycle energy is transmitted at this voltage except for two 33-kv. feeders which tie through Lorimer Street substation with the Brooklyn Edison Company's Gold Street Generating Station and serve both as a supply to the Long Island Railroad and as a means of interchanging power between the generating stations. Three 15,000-kv-a. transformers step up the energy from the 60-cycle end of the frequency changer to 27,600 volts.

While it is expected that all future additions to this station will be for 60-cycle operation, the future operating voltage has not as yet been determined.

### Excitation Supply

Excitation for the main units is furnished exclusively by direct-connected exciters, each exciter being con-

Fig. 8—160,000-Kw. Generator

nected solidly to the main field through the main field rheostat. The exciter field circuit is equipped with remote control air circuit breakers which are automatic in operation when actuated by the over-all differential relay of the main unit.

The exciter field breakers of the 160,000-kw., two-winding generator No. 4 are tripped automatically also by the winding differential relay. The main and exciter field rheostats and the exciter field breakers are controlled from the generator control panel in the high-tension switchboard room.

### Frequency Changer

A 40,000-kw. frequency changer, designated Unit No. 3, is of the synchronous induction type. The 60-cycle induction generator excited by means of an 18,500-kw. transformer from the 25-cycle system provides a transformer tie as well as a power tie, (Fig. 10).

The frequency changer was installed for a twofold

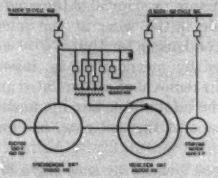

Fig. 10—Frequency Changer Connections

purpose, first, to make possible the pooling of the spare capacity on the 60-cycle and 25-cycle systems, and second, to maintain the two systems in synchronism.

At the time the frequency changer was installed, the rotary converters supplying the d-c. network were all

25-cycle machines, but it was thought that in view of the pronounced trend toward 60 cycles as a standard frequency it might become desirable in future installations to use 60-cycle converters. In order to obtain satisfactory operation of the two types of rotary converters it was realized that it would be essential to keep the two systems in synchronism and that, furthermore, to prevent possible damage to the commutation equipment, the tie between the two systems should be as strong as possible. It was with this thought in mind that the synchronous induction type of frequency changer was chosen. Although the anticipated use of the 60-cycle rotary converters has not developed due to the expansion of the a-c. network system in Manhattan, it is felt that the use of the synchronous induction type of frequency changer has been of advantage in increasing the stability of operation between the two systems. By taking advantage of this it is possible to keep on the system only such frequency changer capacity as may be required for load interchange without operating additional machines for the sole purpose of maintaining synchronism. In view of the magnitude of the two systems it is felt that the performance from this point of view has been very gratifying.

### Condensers

The condensers for the three units are all of the single-pass, surface type, those for Units No. 1 and 2 having 47,500 sq. ft. of surface and that for Unit No. 4, 90,000 sq. ft. of surface. Each condenser has two circulating water pumps which are all located in a pump room at the east end of the turbine room basement, adjacent to the water front. The water is pumped through cast iron pipes, 72 in. in diameter, embedded in the concrete mat, to the perspective condensers, the length of these pipes varying with the distance from the pumps. The last unit to be installed in the station will be approximately 1000 ft. away from the pumps. The overboard water from the condensers is discharged through individual 72-in. pipes to the river.

Units No. 1 and 2 each have two hot-well pumps while Unit No. 4 has three hot-well pumps. Steam jet vacuum pumps are used on all of the condensers.

Considerable initial wear at the inlet ends of the tubes in the condensers for Units No. 1 and No. 2 have been corrected by means of 12-in. inserts. This, together with the removal of accumulated air or gases from the tope of the inlet water box by means of a connection to the tope of the tail pipe, has greatly lessened tube failures.

The tubes are cleaned by shooting a mixture of sand and pulverized fuel ash in equal proportions, and water through the tubes by means of compressed air. The cleaning is done by sections whenever the turbines are shut down, usually on the 12:00 midnight to 8:00 a. m. watch or on Sundays.

Four stages of feed water heating is the practise at the East River Station, three by steam bled from the main units and one by the exhaust steam from the steam auxiliaries. Units No. 1 and 2 are bled from the 11th, 14th, and 18th stages and Unit No. 4 from the 13th, 17th, and 21st stages. The cycle of feed water heating is given in the accompanying typical heat balance for Unit No. 4.

### Auxiliaries

Steam driven auxiliaries are used for the circulating water, boiler feed, and condensate pumping. The primary air, secondary air, and induced draft fans are also steam driven, thus providing a very even acceleration or deceleration of speed.

The non-essential auxiliaries, or those which may be shut down for short periods of time without affecting service, such as pumps for ash pit, house service, hot-well test, storage tanks, fire lines, dust precipitators, coal towers and powdered fuel mills, are supplied from 2300-volt or 440-volt 25-cycle busses energized from house transformers on the main bus. These house busses also supply motors for ventilating fans for the main generator and frequency changers and other auxiliaries with similar duplex drives (steam and electric).

The transformers are supplied from different sections of the main bus and house busses are operated radially although provision has been made for parallel operation either as a solid bus or sectionalized by reactors.

A 125/250-volt d-c. house bus supplied from geared cross connected turbo generator units is provided for the operation of boiler fuel feed. The fuel feed motors of each boiler are supplied from a motor generator set connected to the d-c. house bus and provided with a Ward Leonard automatic control. The 250-volt bus also furnishes all building lighting and some small miscellaneous power. As a standby to the turbo-generator units there is a 2240-ampere-hour battery capable of maintaining full emergency load for one-half hour.

It was considered that the auxiliary drive system for a station such as this, designed to supply a large d-c. system, to be satisfactory from the standpoint of reliability, should be supplied from such sources that in the case of a break in any steam line, a shut-down of all the main generator units, a shut-down of any one auxiliary unit or the shut-down of the main bus would not interrupt the operation of the auxiliaries to more than one generating unit. It is recognized that these assumptions may not necessarily apply to other projects or to present day conditions in the territory served.

The careful study of all the systems in use at the time indicated that the following systems met the above requirements:

A. Steam turbines.

B. D-c. electric supply from the main bus with storage battery reserve.

C. A-c. electric supply from shaft alternators with main bus and house alternator reserve.

Designs and cost estimates were made for each of these three systems. These cost estimates indicated

that the a-c. electric supply systems would cost 35 per cent more than steam turbines and the d-c. system 120 per cent more than steam turbines. (Electric supply estimates include a charge of $40.00 per kw. for electric generating capacity used for auxiliaries.) Heat balance calculations indicated that the additional fuel consumption of the steam drive system would if capitalized, reduce the above differential in the case of a-c. drive two per cent and with direct current three per cent.

Steam drive for these auxiliaries has been entirely

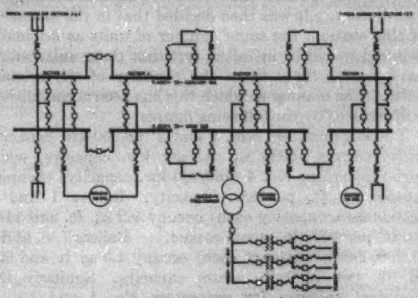

Fig. 11—Station Bus Arrangement

satisfactory from the point of view of reliability. The steam consumption, however, is somewhat higher than the original calculations.

### Electrical Equipment of 160,000-Kw. Unit

The main and emergency busses for the first two 60,000-kw. units were sectionalized,—one section for each generator with its complement of feeders, the sections being connected through 10 per cent reactors based on the full load of a generator.

In the latest addition, the one 160,000-kw. unit is of the single shaft type and due to the high current of a unit of this size it was impossible to procure single generator switches of sufficient carrying capacity. It was therefore necessary to consider two switches in parallel. The use of a double winding generator, however, provided a very simple means of assuring satisfactory load division between the output circuits and at the same time reduced the current capacity and interrupting duty on the switches, (See Fig. 11.) In this unit the windings in alternate slots are connected to separate circuits and the circuits alternated under adjacent pole faces, thus distributing the circuits and producing balanced magnetic forces. This method of winding results in an added number of end connections and leads, but is otherwise identical with a standard single winding unit.

It may be interesting to digress for a moment at this point to consider the application of such a unit to the general layout of a system. The increase in capacity of units, stations, and systems in recent years with the consequent requirement of greater interrupting capacity of circuit breakers and other costly problems resulting from excessive currents and high magnetic forces has brought to the art entirely new conceptions of station bus layouts, all tending toward the splitting up of stations into small sections which may in themselves be considered as separate generating stations.

The first of these new designs was incorporated in the Hudson Avenue Station of the Brooklyn Edison Company in which the individual generator sections are synchronized only through a high-reactance synchronizing bus. Following this point, synchronizing was carried to the substations, whereas in the case of the United Electric Light & Power Company the generator sections were synchronized at the load in the network area or at the secondaries of the substation transformers in other areas, the reactance between bus sections being even higher in this scheme than in the case of the synchronizing bus.

The double winding generator through its transformer action creates a very high reactance between windings (equivalent to generator bus sections) but due to the linkage of a common field the stability is not decreased by this increase in reactance. In large sized generators it seems feasible to increase the number of windings

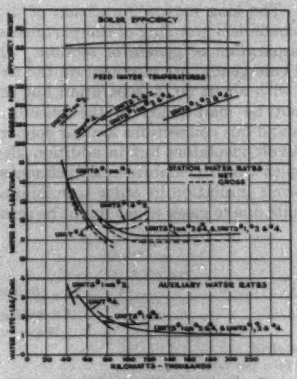


Fig. 12—Station Performance Data

which may be brought out of a unit and by use of multiple windings in conjunction with the scheme of synchronizing at the load to still further reduce the magnitude and extent of short-circuit disturbances and at the same time to improve system stability.

For the one 160,000-kw. unit at East River it was, however, possible to use only the high reactance sectionalizing due to double windings as the 25-cycle system is not operated as a parallel system at the substations. While there were no immediate economies over the previous layout of one generator to a section

with 10 per cent sectionalizing reactance, the adoption of the double winding design looked forward to future economy due to the elimination of bus tie switches and reactors. The decrease in maximum instantaneous short-circuit duty from approximately 2,500,000 kv-a. to 1,500,000 kv-a. was one of the outstanding advantages of the new design.

### Feeder Arrangement

In order to still further reduce the number of switches required, outgoing feeders were grouped together. The H arrangement was used in this station with two selector and two feeder switches per group. The standard feeder is 350,000 cir. mils and supplies one 4200-kw. converter in a substation. In the first two sections of East River, double feeders were used, the bifurcation being made at some remote point in the street and in the last section triple feeders were similarly employed, the new groups now serving six normal feeders or a connected load of 25,000-kw. direct current (approximately 32,000-kw. high-tension alternating current.)

### Electrical Galleries

The electrical galleries are of the vertical isolated phase type; there are few special features incorporated which are not common to all modern isolated phase galleries. The long narrow formation of the building permits economical grouping of compartments and easy physical separation of generator sections; the busses, main and emergency, are mounted on the two sides of the room with about 30 ft. separation but this separation cannot be maintained in the selector switches. All busses and bus connections are bar copper mounted on 25,000-volt insulators but in addition all copper is wrapped with varnish cambric to a thickness equivalent to 15,000-volt insulation in order to minimize possible short circuits due to gases which might be present as the result of minor disturbances. All feeder cables are single conductor lead, both in the station and in the adjacent streets and no cable joints are made within the station.

### General Design Features of 1929 Extension

When it was decided to go ahead with the first extension of this station, it was found that turbine builders were prepared to supply single turbo generators, having a capacity of 160,000 kw. each, at a considerably lower cost per kw. than for the 60,000-kw. units in the original installation. It was then decided that in the extension of this station, the same number of units as originally planned would be installed, but that these units would have nearly three times the capacity of the original units. The manner in which this has been accomplished is illustrated by the following figures:

Turbo generators Nos. 1 and 2 (60,000-kw. capacity each) occupy 0.083 sq. ft. per kw. capacity, while turbo generator No. 4 (160,000-kw. capacity) occupies 0.0452 sq. ft. per kw. capacity. Boilers 1 and 6 (250,000-lb. capacity each) occupy 9.2 sq. ft. and 1140 cu. ft. per 1000-lb. steam capacity. Boilers 7, 8, and 9 (1,000,000-lb. capacity each) occupy 4.5 sq. ft. and 625 cu. ft. per 1000 lb. steam capacity. Similarly the electrical galleries for generators No. 1 and No. 2 require 0.48 sq. ft. of floor area and 7.39 cu. ft. per kw. capacity, whereas similar equipment for generator No. 4 occupies 0.215 floor area and 3.92 cu. ft.

### Station Operating Data

Fig. 12 shows in graphic form boiler efficiency, feedwater temperatures, total station and auxiliary water rates of this station when carrying loads from 35,000 to 210,000 kw. These curves are based on the station performance for the months of February and March 1930. The station heat rate is 15,000 B. t. u. per net kw-hr.

| | UNITS NO. 1 AND 2 | UNIT NO. 4 |
|---|---|---|
| *Boilers—Superheaters and preheaters* | | |
| Type of boilers | Springfield, horizontal, cross-drums. Water cooled walls | Combustion Engg. Corp. Water cooled walls |
| Number installed | 6 | 3 |
| Heating surface per boiler, sq. ft. | 14,809 | 60,706 |
| Heating surface of water walls per boiler, sq. ft. | 4,134 | 7,345 |
| Furnace volume, cu. ft. above water screen | 15,888 | 38,200 |
| Furnace volume, cu. ft. below water screen | 4,969 | |
| Boiler pressure, lb. gage | 410 | 425 |
| Superheat, deg. fahr. | 257 | 271 |
| Total steam temperature, deg. fahr. | 700 | 725 |
| Superheater, location | Superheater Co. Between upper and lower bank of boiler tubes in first pass | Superheater Company. In first pass |
| Superheating surface per boiler, sq. ft. | 3,430 | 13,900 |
| Air preheater, type | Combustion Engg. Corp. Stationary steel plate | Combustion Engg. Corp. Stationary steel plate |
| Heating surface of air preheater per boiler, sq. ft. | 28,900 | 82,721 |

| | UNITS NO. 1 AND 2 | UNIT NO. 4—Continued |
|---|---|---|
| | *Stack and Draft Equipment* | |
| Type of stack | Steel, unlined | |
| Number | 2 | |
| Diameter, inside ft | 22 | |
| Height above basement floor, ft | 376.5 | |
| Support | On building steel | |
| | *Induced Draft Fans* | |
| Induced draft fans | B. F. Sturtevant Co. 150,000 cu. ft. per min. at 8.5 in. static pressure | B. F. Sturtevant Co. 260,000 cu. ft. per min. at 17 in. static pressure |
| Number per boiler | 1 | 2 |
| Drive | Sturtevant turbine and gear. 400 hp. turbine | Sturtevant turbine and gear. 1150 hp. turbine |
| | *Forced Draft Fans* | |
| Forced draft fans | Sturtevant—60,000 cu. ft. per min. at 6.4 in. static pressure | Sturtevant—125,000 cu. ft. per min. at 9 in. static pressure |
| Number per boiler | 1 | 2 |
| Drive | Sturtevant turbine and gear. 115 hp. turbine | Sturtevant turbine and gear. 263 hp. turbine |
| | *Primary Air Fans* | |
| Primary air fans | Sturtevant Co. 4-24,000 cu. ft. per min. at 18 in. static pressure. 1-22,000 cu. ft. per min. at 40 in. static pressure | Sturtevant Co. 54,000 at 25 in. static pressure |
| Number | 5 for six boilers | 4 for three boilers |
| Drive | General Electric turbine and gear. 4-125 hp. turbine. 1-230 hp. turbine | General Electric turbine and gear. 307 hp. turbine |
| | *Dust Collectors* | |
| Dust collectors—type | American Blower Co. Cyclone | Cottrell precipitator |
| | *Raw Coal Handling Equipment* | |
| Coal towers—capacity each, tons per hr | Main Electric Co.—350 | |
| Number | 2 | |
| Conveyors, capacity each tons per hour | Dodge Mfg. Co.—350 | |
| Number | 5 groups of 2 conveyors each | |
| | *Raw Coal Handling Equipment Continued* | |
| Bunker, capacity tons | 5,000 | |
| Outdoor coal storage capacity, tons, (future) | 48,000 | |
| | *Pulverized Coal Equipment* | |
| Pulverizers, type | Combustion (Raymond) Air swept (preheated air) | |
| Capacity, tons per hour | 2-15 | |
| Number | 4-25 | |
| Drive | Motor | |
| Transporter | 1 per mill, motor driven | |
| Feeders—Number per boiler | 10 Main<br>10 Auxiliary | 20 Main<br>20 Auxiliary |
| Weigh bins, capacity each, tons | 10 | |
| Number | 2 | |
| Storage bins, capacity, each tons | 100 | 1-115, 1-135 |
| Number, per boiler | 1 | 2 |
| | *Main Generating Units* | |
| Capacity, kw | General Electric Co. 60,000 | General Electric Co. 160,000 |
| Number | 2 | 1 |
| Generators | 3-phase, 25 cycle, 11,400 volts | 3-phase, 25 cycle, 11,400 volts |
| Speed rev. per min | 1,500 | 1,500 |
| Exciter, type | Shaft driven | Shaft driven |
| Capacity, exciter (kw.) | 200 kw., 250 volts | 250 kw., 250 volts |
| Generator ventilation, type | Closed system | |
| Steam conditions at turbine throttle | 350 lb. gage<br>700 deg. fahr. total temperature | 375 lb. gage<br>725 deg. fahr. total temperature |
| | *Auxiliary Turbo Generators* (Direct Current) | |
| Capacity, kw. (DeLaval turbine, Crocker-Wheeler generators) | | 500 |
| Number | | 3 |
| Generator | 250-volt d-c. three-wire, 900-rev. per min. | |
| Steam conditions at turbine throttle | 350 lb. gage, 700 deg. fahr. total temp. | |

| | UNITS NO. 1 AND 2 | UNIT NO. 4—Continued |
|---|---|---|
| | *Auxiliary Turbo Generators (Mill House)* | |
| Capacity, kw. De Leval Turbine—General Electric Generator | | 1000 kw. |
| Number | | 1 |
| Generator | 3-phase, 25-cycle, 2300 volts, 750 rev. per min. | |
| Steam conditions at turbine throttle | 350 lb. gage, 700 deg. fahr. total temperature | |
| | *Main Condensers and Auxiliaries* | |
| Condenser, type | Wheeler—Single pass | Ingersoll-Rand—Single pass |
| Tube surface, sq. ft | 45,000—Condenser<br>2,500—Air cooler | 90,000 |
| Number per turbine | 1 | 1 |
| Circulating pumps—capacity each, G. P. M | Wheeler<br>45,000 | Ingersoll-Rand<br>80,000 |
| Number per condenser | 2 | 2 |
| Drive General Elec. Turbine and gear | 300-hp., 6270-rev. per min. 3-stage condensing turbine | 1200-hp., 7700 rev. per min. |
| Hotwell pumps—capacity each, gram per min | Wheeler<br>1,350 | Ingersoll-Rand<br>2,000 |
| Number per condenser | 2 | 3 |
| Drive Sturtevant Turbine and gear | 76.5 hp. turbine | 75 hp. turbine |
| Air pumps—type | Wheeler<br>Steam jet | Ingersoll-Rand<br>Steam jet |
| Number | 1 for each unit | 12 Primary Ejectors and 4 Secondary Ejectors |
| | *Boiler Feed Pumps* | |
| Capacity each gals. per min | Dean Hill<br>1200 gals. per min. | Dean Hill<br>2000 gals. per min. |
| Drive General Elec. Turbine and gear | 505 | 1000 hp. turbine |
| Number | 4 | 3 |
| Discharge head | 500 lb. | 630 lb. |
| | *Ash Handling Equipment* | |
| Type of systems | Sluicing, pump, and hoisting | |
| Ash Gantry Maine Elec. Co | 162 tons per hour | |
| Drive | 100 hp. motor | |
| Ash Pumps | | |
| 2—10 in. Morris Machine Work centrifugal pumps | | |
| Manganese lined | Cap. 3200 gals. per min. against head of 35 ft. | |
| Drive | 125 hp. motors | |
| | *Generator Air Coolers* | |
| | Turbines No. 1 and No. 2 and frequency changer<br>General Electric—water cooled | Turbine No. 2<br>Griscom-Russell water cooled |
| | *Frequency Changer* (General Elec. Co.) | |
| Capacity | 40,000 kw. | |
| Current characteristics | 60 cycle end, 3-phase, 13,800 volts | |
| Current characteristics | 25 cycle end, 3-phase, 11,400 volts | |
| Speed | 300 rev. per min. | |

*Transformers*

For excitation to 60-cycle end of frequency changer:
1—18,500 kv-a., 3 phase, 11,400/3300 volts, 25 cycle. (General Electric Company)
For supply to 60-cycle end of frequency changer
3—15,000 kv-a. 3 phase, 28,980/13,800 volts, 60 cycle. (Pittsburgh Transformer Co.)
Station Power:
3—4000 kv-a., 3 phase, 11,400/2300/440 volts, 25 cycle. (Pittsburgh Transformer Co.)
Interstation Ties:
2—18,000 kv-a., 3 phase, 11,400/34,500 volt, 25 cycle. (General Electric Company)

OIL CIRCUIT BREAKERS AND DISCONNECTING SWITCHES

| | Quantity | Capacity | Type |
|---|---|---|---|
| For 27,600-volt, 60-cycle feeders (General Electric Co.) | 9 | 600 | Adjacent phase dead tank |
| For 13,800-volt, 60-cycle supply to frequency changer (General Electric Co.) | 4 | 1,200 | " " " " |
| | 1 | 2,000 | " " " " |
| For 11,400-volt, 25-cycle equipment—Sections 1 and 2 (General Electric Co.) | | | |
| Generator and bus ties | 18 | 4,000 | Segregated phase dead tank |
| Frequency changer | 3 | 3,000 | " " " " |
| Feeder selectors | 26 | 1,200 | " " " " |
| Feeders | 26 | 800 | " " " " |

## OIL CIRCUIT BREAKERS AND DISCONNECTING SWITCHES—Continued

| | Quantity | Capacity | Type |
|---|---|---|---|
| For 11,400-volts, 25 cycle equipment, Sections 3 and 4: | | | |
| Generator and bus ties | 8 | 5,000 Amperes | Segregated phase dead tank |
| Interstation tie selectors | 4 | 3,000 " | " " " " |
| " " " | 4 | 2,000 " | " " " " |
| Interstation feeders | 2 | 2,000 " | " " " " |
| " " | 2 | 1,200 " | " " " " |
| Feeder selectors | 6 | 1,200 " | " " " " |
| Feeders | 10 | 800 " | " " " " |
| For 2300-volt, 25-cycle Station Power Equipment (Westinghouse Elec. & Mfg. Co.): | | | |
| Transformer and bus ties | 13 | 1200 Amperes | truck type |
| Feeder selectors | 10 | 1,000 " | " " |
| Feeder selectors | 8 | 600 " | " " |
| Feeders | 5 | 800 " | " " |
| Feeders | 13 | 400 " | " " |
| Feeders | 32 | 200 " | " " |
| For 2300-volts, 25-cycle, Mill House Equipment: | | | |
| Generator (General Electric Co.) | 1 | 500 Amperes | cell mounting |
| Group feeders (Westinghouse Elec. & Mfg. Co.) | 8 | 400 Amperes | truck type |
| Feeders (General Electric Co.) | 40 | 300 Amperes | cell mounting |

## REACTORS

For 11,400-volt, 25-cycle equipment (Metropolitan Device Corp.) Sections 1 and 2

| | Quantity | Kv-a. | Amperes | Per cent reactance |
|---|---|---|---|---|
| Generators | 6 | 1200 | 3040 | 6 |
| Frequency changer | 3 | 402 | 2030 | 3 |
| Bus ties | 12 | 2000 | 3040 | 10 |
| Feeders | 72 | 180 | 600 | 4.5 |
| For 11,400-volt, 25-cycle equipment. Sections 3 and 4: | | | | |
| Generator (Metropolitan Device Corp.) | 6 | 1336 | 4060 | 5 |
| Interstation ties " " " | 6 | 595 | 1500 | 6 |
| Interstation ties (General Electric Co.) | 6 | 180 | 900 | 3 |
| Feeders (Metropolitan Device Corp.) | 30 | 405 | 900 | 6.8 |
| For 2300-volt, 25-cycle station power equipment | 6 | 57 | 1200 | 5 |

## SWITCHBOARDS

Generator and frequency changer—Remote control electrically operated, bench-board type (General Elec. Co.)
H T Feeders—Remote control electrically operated vertical board type (General Elec. Co.)
Auxiliary power control—Remote control electrically operated, vertical board type (General Elec. Co.)
440-Volt A. C. Station power main—Remote control electrically operated vertical board type (Westinghouse Elec. & Mfg. Co.)
440-Volt A. C. Station power, distribution—Manually operated oil circuit breaker type (Westinghouse Elec. & Mfg. Co.)
250-Volt D. C. Station power—Remote controlled electrically operated circuit breakers, vertical board type (A. & J. M. Anderson Co.)

## BATTERIES (E. S. Battery Co.)

1—For main station light and power—250-volt, 2240 ampere hour lead lined wooden all type
2—For control—250-volt, 132 ampere hour, glass cell type

## MOTOR GENERATOR SETS

For D. C. control battery charging—4-25-kw., 250-volt, shunt wound

## HIGH-TENSION TESTING EQUIPMENT

| | |
|---|---|
| 1—Kenetron set | 200/50 kv., 25/1 ampere |
| 1—Test transformer | 400 kv-a., 25 cycle, 4600/80,000 volts |
| 1—Test transformer regulator | 200 kv-a., 25 cycle, 2300/2300 volts |
| 1—Mercury arc rectifier | 9000 volt, 6.6 ampere direct current |
| 1—Tracer current motor generator | 1000 volt, 500 watts |

## Discussion

**M. S. Sloan:** The paper by Messrs. Grady, Lawrence and Tapscott describes the largest single generator unit operating on, and the most recent station of, The New York Edison system. The paper states that while this comparatively new station was started as a 25-cycle station, present plans indicate that future development of The New York Edison system will be at 60 cycles, the initial plan for the station being consistent with the development of The New York Edison Company as it had existed as a separate corporate entity and with its local development program, while the plan to make future extensions at the higher frequency is a logical expression of present conditions. The actual development of the station to date and the future plans in the matter of frequency fit very nicely into the actual and prospective load conditions of the system.

The change of plan in the matter of frequency is one detail of our program of distribution development which started with and was a result of the bringing under unified management and control five companies in the Metropolitan area and serves as an illustration of the engineering and economic advantages which result from logical operative consolidation of properties.

It is scarcely necessary to point out to a body of engineers the considerable expense, both capital and operative, involved in maintaining two frequencies within an area as closely defined as that of New York City.

This economic waste is fundamental and intrinsic and not associated with any question of ownership or control. It is significant, however, that it took substantial identity of ownership and unified control to effectuate unification of frequency.

One measure of the cost of multiple frequencies is found in the fact that 200,000 kw. of frequency conversion equipment had been installed in order to enable the operation of these two frequencies as one system, partially to gain the benefits of diversity, to make reserve capacity more fully available and to enable the partial utilization of the most efficient generating equipment on the system.

Obviously no one would contemplate the establishment or the maintenance of two different frequencies unless there were sound engineering and technical reasons for so doing. Most engineers realize that in generation the advantages of 60 cycle as compared with 25 cycle are very slight while, on the other hand, the utilization advantages of the higher frequency are so great as to constitute almost essential requirements. Certainly this is true in alternating current lighting and measurably true in direct power applications. The reasons then for the original development and continuance of 25-cycle generation lay in its conversion to direct current either for general distribution or for traction systems—I here leave out of consideration the earlier long distance transmissions.

A synchronous converter, then, was for our Metropolitan Area the main reason for extending 25-cycle generation. Recent developments have removed this compelling consideration.

In recent years, perfectly good 60-cycle rotary converters have been developed for both what is commonly known as Edison distribution and the somewhat higher voltage traction use. In addition, the more recent experience with large mercury rectifiers has dispensed with the necessity for synchronous converters at normal city traction voltages and at the voltages used on interurban and main line electrification.

Extensive practical experience with the low voltage alternating-current network has demonstrated that in first cost and efficiency it is the ideal system of distribution and that continuity of service and closeness of voltage regulation are assured facts. It offers the most rapid method of expanding the distribution system to meet the growing needs of the consumer and relieves, to the highest degree, the congestion of the city streets.

Utilization development has brought into more general use variable voltage elevator drive thus relieving one of the previously insistent demands for direct-current.

The more modern developments of radio and therapeutic equipment and certain types of domestic refrigerating appliances all have combined within the last half a dozen years to create a positive customer demand for 60 cycle service. For these reasons it has been determined that the development of The New York Edison system shall be by a systematic expansion of 60-cycle, alternating-current, closed network system of distribution.

After exhaustive study by our own engineers we were able to offer to the Board of Transportation of the City of New York, for the subways now approaching completion, 60 cycle service delivered at its various substations under a contract extraordinarily favorable to the city not only in the matter of price but also in the flexibility and liberality of its various provisions as to prompt expansion or cancellation. This could have been done only by utilizing for that service the general distribution system.

The engineers of the Board of Transportation and their consultants made an equally exhaustive and painstaking study which found the use of 60 cycle either through synchronous converters or mercury rectifiers to be entirely feasible on this undertaking which contemplates the use of over 200,000 kw.

These various considerations have demonstrated the necessity and the practicability of a single standard of frequency toward which the development of The New York Edison System must trend. It is obvious that interconnections, whether with immediately neighboring companies or with distant hydroelectric plants, can be accomplished only at the prevalent frequency.

**W. S. Gorsuch:** I would like to ask whether any special features of feed-water treatment are required for a boiler having a capacity of approximately 1,000,000 lb. of steam per hour?

The reason for adoption of the size of boilers and turbine in the last extension of the plant is of special interest, particularly with regard to the relation of unit size and the features of the electrical distribution system. I would like to know whether the future developments in the electrical system influenced the final decision as to the size of boilers and turbine?

It would be of interest if the authors would describe the method of handling the steam from the steam-driven auxiliaries in the feed-water system.

**W. B. Kouwenhoven:** 1. Mention is made of the striking reduction in the floor area and cubical contents of the recent addition to the electrical galleries. Will the authors describe the features of design to which they attribute this marked saving in electrical construction, inasmuch as they state in their paper that there are but few special features which are not common to all modern isolated phase galleries, and no immediate economies over previous layout occurred?

2. Would the discussors of the station expect a further high reduction in electrical gallery construction costs by the adoption of 60-cycle units at higher voltage than is used at present with the 25-cycle generators, and what difficulties in the station layout would they expect such an innovation to cause?

**C. B. Grady:** Answering the questions by Mr. W. S. Gorsuch, (1) The Hall System is used; (2) In our initial installation at East River we purchased the largest 25-cycle turbo generator units which either of the large manufacturers would offer at that time. These were 60,000-kw., single shaft units. The same request was made of the manufacturer at the time of the last installation and the proposition of 160,000-kw. units was accepted at that time. The anticipated developments in the electric distribution system did not influence the capacity of these units as at the time of their purchase there were no anticipated changes in the 25-cycle system; (3) The exhaust steam from all of the station steam driven auxiliaries is discharged into a common header. This header is connected to each second

stage heater in the four stage heating cycle of each of the three main units.

**R. H. Tapscott:** Referring to questions by Professor W. B. Kouwenhoven, (1) The statement regarding reduction in floor area and cubical contents is on a per kilowatt basis. The paper describes the reduction in number of switches required for the bus ties and feeders as well as the elimination of bus tie reactors. With the largest size generator the number of substation feeders per feeder switch was increased from two to three. The total number of switches, therefore, used for 160,000 kw. was 40, requiring 0.215 sq. ft. of floor area per kw. capacity and the number in the initial installation for 60,000 kw. was 33, occupying 0.48 sq. ft. of floor area as mentioned; (2) Layouts have been made for 60-cycle units both on the basis of distributing at generator voltage and distributing at double generator voltage. At generator voltage the gallery space would be about the same for 60 cycles as for the last unit installed for 25 cycles. At the increased voltage the gallery space would be about the same as for 25 cycles, but additional space would be required in the gallery basement for the installation of step-up transformers. The total building requirement will probably be approximately the same as in the 25-cycle layout.

# Present Day Hydro Power Practise in Central Europe

BY A. V. KARPOV[1]

Member, A. I. E. E.

*Synopsis.—This paper represents the impressions of a European trip made during the summer of the year 1929 and gives a comparative study of the conditions of European development in so far as they are either of a particular interest or different from the conditions in the United States.*

*The advance made in Europe in the low head developments is attributed in a large part to the advanced work made in the European hydraulic laboratories and to the cooperation between the laboratory and the manufacturer of hydraulic equipment and power plant designer.*

*The advances made in the design of the large units of Propeller and Kaplan turbines are discussed.*

*The low head developments are stressed as the most interesting, and a short description is given of the plants in the region of the upper Rhine and the international interconnection system of this region.*

*The extensive pumping schemes of this region are briefly described.*

*An attempt is made to outline the power house design tendencies and the new ideas in protecting the river bed from erosion.*

*The more interesting work done in the hydraulic laboratories is described.*

*A short comparison between the mixing and placing of concrete as done in Europe and in the States is given.*

* * * * *

## Present Day Hydro Power Practise in Central Europe

An inspection trip through Germany, Switzerland, Italy, and France, was made in the summer of 1929, for the purpose of studying the hydro power practise in Central Europe. During this trip, a number of hydro power plants under construction and in operation, turbine manufacturing plants and hydraulic laboratories were visited, and consultations with many authorities on their respective subjects were arranged.

Impressions of the trip are covered in the following reports:

I. Turbine design.
II. Low head developments.
III. Interconnection and improvements in water utilization.
IV. Pumping problems.
V. Power house design.
VI. Energy destroying.
VII. Hydraulic laboratories.
VIII. Cavitation laboratories.
IX. Concrete Work.

Only developments comparable in size to those in the United States were considered and all discussions are limited to such type of developments.

### I. Turbine Design

The modern turbine design is confined to these four types: Pelton, Francis, propeller, and Kaplan.

The general tendency of the present day European practise is to narrow the field of application of the Francis turbine.

Only a few years ago, the Francis turbine was a very universal type, being used for very low heads, as well as for medium and high heads. Today the propeller and Kaplan turbines are used entirely, instead of Francis turbines, for low head developments. At the same time, the Pelton turbines, by increasing the number of jets and runners, are used for much lower heads than before. That leaves to the Francis turbine a much smaller field, in the medium head developments only.

The curves of Fig. 1 give an approximate idea of the heads and specific speeds for which these types of turbines are used.

In interpreting these curves it is to be kept in mind that for the propeller and Kaplan turbines and for the

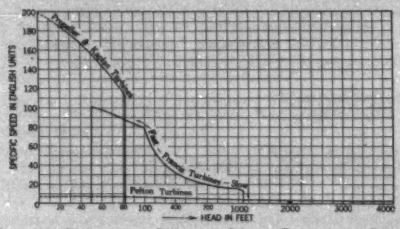


Fig. 1—Curves of Specific Speed Limits for Single-Runner Propeller, Kaplan, Francis, and Pelton Turbines

fast Francis turbines, the curves show approximately the upper limit and for the slow Francis and Pelton turbines approximately the lower limit of specific speeds for a given head.

*Propeller and Kaplan Turbines.* The most interesting of the present day European designs are the propeller and Kaplan turbines. Strictly speaking, both of these types are propeller turbines, the principal difference between them and the Francis type of turbine being that the water is guided by the stationary part of the turbine in such a way that the water flow becomes axial before the water column strikes the runner blades, (Fig. 2).

1. Designing Eng., Hydraulic Dept., Aluminum Company of America, Pittsburgh, Pa.

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30-139

The principal difference between the propeller and Kaplan turbines lies in the adjusting arrangement of the runner blades of the Kaplan turbine. The runner blades of a propeller turbine are solidly connected to the hub and the turbine shaft, and cannot be adjusted. The runner blades of a Kaplan turbine can be adjusted for different operating conditions by means of a special mechanism built into the hub of the runner, (Fig. 2).

No particular limitations apply to the size, shape, and number of runner blades of a propeller turbine. As for the Kaplan turbine, the size and shape of the runner blades are such as to avoid any mechanical interference among adjoining blades and form proper hydraulic channels for the passing water; moreover, the number of blades must be kept low so that the adjusting mechanism is simple and small enough to be placed in the proper sized runner hub.

The main advantage of the propeller and Kaplan turbines is the high specific speed for which they can be built, which makes possible a considerable saving in the cost of the electrical equipment.

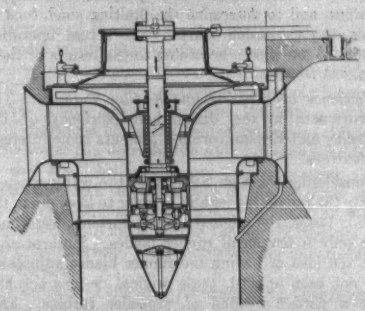

Fig. 2—Sectional Elevation of a Kaplan Turbine

The reduced space necessary for the units results in appreciable savings in the cost of the power house structure.

Also, better efficiencies can be obtained and, a matter of importance for low head developments, the efficiency will be influenced less by the variations of head.

The advantages of these types of turbines are such that at present up to the heads to which they can be safely built, they replace the Francis turbines entirely.

*Cavitation.* The most important factor that at present excludes the use of propeller and Kaplan turbines for heads above about 80 ft. is the cavitation. The cavitation problem became of such importance in the propeller and Kaplan turbine design that special cavitation laboratories were built and a thorough study of this problem is going ahead in many places. This study and the laboratory work cleared to a certain extent this rather obscure problem and the results of these studies are applied today not only to propeller and Kaplan turbines, but to Francis turbines as well.

Cavitation occurs when the pressure drops in some parts of the turbine so that it is lower than the evaporation point corresponding to the water temperature.

The phenomenon of cavitation consists in the formation of bubbles of vapor supplemented by air which has been in solution in the water. These bubbles, which are formed on the surface of the runner in the low-pressure areas, cause the drop of efficiency, destruction of the runner material, known as "pitting" or "corrosion," and runner vibrations.

It seems that any roughness of the material, visible and invisible cracks, and even changes in the structure of the material due to concentrated internal stresses, may produce or increase existing cavitation.

Cavitation, even at a very small degree, will start the destruction of the material, which will intensify the cavitation, bringing forth further destruction, as well as the decrease of the efficiency and the increase of vibrations. In a properly designed turbine no cavitation must occur at all.

In the old fashioned Francis turbines, the water was smoothly guided, and the pressure drop from guiding vanes, where the water entered the turbine, to the draft tube was very gradual. The point of highest pressure corresponded to the point where the water entered the turbine and the pressure decreased until the lowest pressure was reached at the point where the water left the runner and entered the draft tube. To prevent cavitation in such design, it was only necessary to have the pressure at the draft tube entrance higher than the evaporation pressure.

The pressure drop at the draft tube entrance depends very closely on the draft tube head and efficiency, and on the velocity at which the water enters the draft tube. If these conditions were properly chosen, the cavitation danger was prevented for such turbine design.

In the more advanced Francis turbine designs, and particularly in the fast running Francis turbines which were first introduced in the United States, the conditions are different. The water is rather forced and not smoothly guided as in the old designs. Under these conditions the pressure does not change gradually from the wicket gates to the draft tube and the point of lowest pressure may be transferred from the draft tube entrance to some point on the runner. In such designs, it is usually possible by proper change of the shape of the runner and by decrease of the draft tube head to eliminate the cavitation danger.

Conditions are different in the propeller and Kaplan turbines, where the point of lowest pressure is always above the draft tube entrance, being located somewhere on the runner blade.

Fig. 3 shows the characteristic pressure distribution on the surface of a Kaplan turbine runner, the section being taken at the Line *C–C*. The figures along the surface of the blade and the pressure curves are to be considered as coefficients only. The actual pressures

depend on the water velocity and draft tube head. For this particular shape of the Kaplan runner, the point $K$ represents the point of the lowest pressure. The pressure at this point is always lower than at the draft tube entrance and will decrease rapidly with the increase of the specific speed.

In a turbine of that type, a sufficient pressure at the draft tube entrance is no assurance whatsoever against cavitation troubles.

The propeller and Kaplan turbines, with the increase of the water head, very soon approach the limit at which even a zero draft tube head will be insufficient to prevent cavitation. Today about 80 ft. will represent for these turbines the upper limit of the water head for zero draft tube head. By lowering the runner below the low water elevation, an increase of the water head could be obtained, but probably at high cost only.

Another method is now under consideration. It

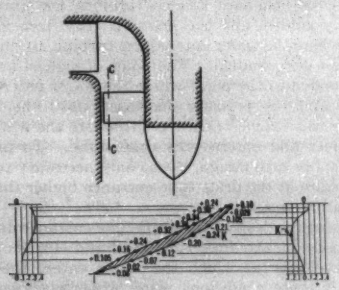

Fig. 3—Pressure Distribution at the Surface of a Kaplan Turbine Runner Blade

consists of dividing up the head and using two turbines in series, so as to have the first turbine working against the total pressure under which the water enters the second turbine.

By the very nature of the modern design, the turbine must be kept very close to the limits at which cavitation will occur, since the economical design requires a high specific speed turbine that is set reasonably high, but at the same time free from cavitation. This can be accomplished only if the proper design is supported by a very careful fabrication to prevent the cavitation danger.

To meet these conditions, the manufacture of such turbines is at a very high standard in the leading European turbine manufacturing plants. The tendency is to have all the parts of the turbine which come in contact with moving water perfectly machined. This tendency, together with the experience that was gained in the Kaplan turbine design, brought out the up-to-date designs of the large size propeller turbines in which the runners are made of a separate hub and blades that are bolted together. Such a design not only makes possible a better fabrication and removes the internal stresses unavoidable in large steel castings, but increases considerably the size of runners that can be shipped by railroad, by shipping the runner in separate parts which are bolted together at the power house.

There are special machines for machining Kaplan and propeller runner blades, mostly built as copying machines, the surface of the blade being machined to represent an exact but increased copy of a small model of the runner blade. The erection of such machines, of very large size, was in progress at two leading European plants during the past summer.

Cavitation studies were made mainly on account of the propeller and Kaplan turbines. These studies at the same time are beneficial for the Francis turbines. At one of the leading plants that possesses a cavitation laboratory, the up-to-date practise is to test models of new Francis turbines, as well as propeller and Kaplan turbines, and to determine the limiting conditions at which the cavitation starts. The actual operation conditions are chosen according to the results of these tests.

*Efficiency of propeller and Kaplan Turbines.* The improvement in the design and efficiency of the propeller and Kaplan turbines presents some interesting features.

Considering the high velocity of the water when it strikes the runner blades and in order to keep down the friction losses, the original Kaplan turbines were built with only a few small runner blades. Since at that time the idea of having the runner blades adjustable had not been applied, these original designs actually were a particular kind of propeller turbine. This arrangement gave satisfactory results for certain loadings and a very rapid decrease of the efficiency by decreased or increased loadings. The water coming down in a propeller turbine, particularly with a runner which has only a few small blades, is not guided in any way, and only for certain loading conditions corresponding to the shape and angle of the runner blades, fairly good efficiency can be obtained. These are the conditions of low eddy losses, owing to a fairly uniform and undisturbed flow of the water through the whole turbine, including the entrance guiding and regulating vanes, turbine runner, and draft tube. Changes in the loading results in an increase of the non-uniformity of the flow, rapid increase of the eddy losses, and a corresponding rapid decrease of the efficiency.

Tests proved at the early stages of the development that a rather large sized hub is necessary for undisturbed flow and high efficiencies.

Making the blades adjustable and locating the adjusting mechanism in the hub resulted in the ingenious present day Kaplan turbine design with its

very flat efficiency curve on a wide range of loadings.

It is natural that in the flat range of the efficiency curve, the maximum efficiency that corresponds to the lowest eddy losses, falls somewhere in the middle part of the efficiency curve.

In a propeller turbine, the number of blades can be increased and the blades can be extended so that the water will be partly guided. This will increase the friction losses, but may decrease the eddy losses. With

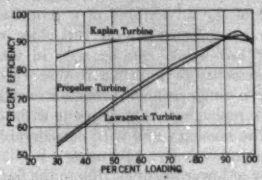


Fig. 4—Comparative Efficiency Curves of Kaplan, Propeller and Lawaczeck Turbines at Varying Loads

the increase of the size of a turbine, the eddy losses grow more rapidly than the friction losses and for large turbines, the maximum efficiency of a propeller turbine can be greater than the maximum efficiency of a Kaplan turbine. Under certain conditions, the further extension of the runner blades that will afford better guidance for the water can decrease the eddy losses so considerably that a still better efficiency can be obtained.

The Lawaczeck turbine is built on this principle and so far as the maximum efficiency is concerned, the results of efficiency tests made on the Lawaczeck turbines in Lilla Edet, Norway, are unsurpassed by any turbine of similar size.

The decrease of efficiency for changed loadings is very rapid in any type of propeller turbine, although, depending upon the design, it can be less rapid than in the original designs of Kaplan turbines with a few small non-adjustable blades. But the point of maximum efficiency of a properly designed propeller turbine will be very close to the maximum loading as against the Kaplan turbine where this point will move over to the middle part of the efficiency curve.

Fig. 4 gives approximate comparative efficiency curves for Kaplan, propeller, and Lawaczeck turbines, of about 10,000 hp., which confirm these points.

Another interesting result of the propeller turbine development and the extensive efficiency tests made in connection with this development, is the proper recognition of the influence that the outer ring of a turbine runner has on the efficiency. A large part of friction losses is due to the presence of this ring, which moves at right angle to the direction of the movement of the water.

In propeller and Kaplan turbines, this ring is entirely eliminated and the tendency is to eliminate such rings even in the big Francis turbines.

Fig. 5 shows a large runner built up from separate pieces bolted together, without the outside ring. This runner is designed to substitute a more conventional low head Francis runner with an outside ring and shows how far the European manufacturers are willing to go in this direction.

*Hunting of propeller and Kaplan Turbines.* A very unfavorable peculiarity of the first large size Kaplan and propeller turbines was their unsteadiness and the tendency to hunt. Tests indicated that this tendency is due to the irregularity of the water flow in the draft tube that increased with the increase of the size of the turbine, the shortening of the draft tube, and the decrease of the radius of the draft tube elbow. A very successful cure of this trouble was found by building a partition or baffle in the draft tube, starting close to the runner and following the axis of the draft tube as indicated in Figs. 12 and 17. This partition arrangement not only decreased the hunting tendency very considerably, but at the same time increased the efficiency, particularly at partial loadings.

The results obtained with these partitions encouraged future research in this direction and different partitions in the draft tubes and in the scroll cases were tested. The tests proved conclusively that vertical partitions properly built into the draft tube below the elbow and in the scroll case, not only do not show any bad influence, but for large size turbines even

Fig. 5—Large Sized Turbine Runner Without Outer Ring

improve the behavior of the turbine. This proved to be of importance in solving structural problems in building power houses for large propeller and Kaplan turbines. The vertical partitions in such turbines are built out as piers to support the power house structure.

*Draft Tube Shape.* Due to the fact that in the low head developments the efficiency of the draft tube is much more responsible for the over-all efficiency of the installation than in the higher head developments, a large amount of laboratory research

is done in this direction, with rather surprising results. The old fashioned elbow draft tube properly shaped and somewhat extended in horizontal direction seems to be superior for this kind of developments to the many fancy shapes which were advocated so much in the past. Practically all the latest larger low head developments that showed remarkably high efficiencies, as well as the new designs, are made with an elbow type draft tube.

*Inclined Wicket Gates.* The latest improvement in propeller and Kaplan turbine design is the inclined arrangement of the wicket gates (Fig. 6). This arrangement not only gives a considerable saving in the over-all sizes of the turbine, but in some cases improves the efficiency. The same inclined arrangement of wicket gates can be applied to fast running low head Francis turbines.

*Vertical and Horizontal Shaft Turbines.* The introduction of propeller and Kaplan turbines increased very much the tendency for vertical shaft turbines, as far as Francis, propeller, and Kaplan turbines are concerned. The Pelton turbines are not influenced by this development and still have horizontal shafts.

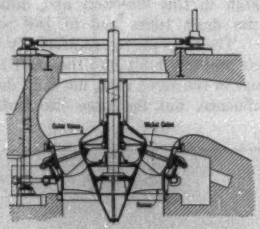


Fig. 6—Inclined Wicket Gates Arrangement

The trend that started quite a number of years ago to use vertical shaft turbines for high and medium head Francis turbines, was not very pronounced in the low head developments. On the contrary, the low head developments that were designed only a few years ago with fast running Francis turbines, had a decided trend for horizontal shaft turbines. The main reason was the possibility of using a number of turbines on one shaft, which allowed an increase in the specific speed of the turbines. At the same time, if couplings were provided on the shaft, the number of turbines in operation could be made to correspond to the amount of water available and in this way to operate the Francis turbines at favorable efficiency.

The horizontal shaft multiple turbine unit recently installed in the power house "Pfrombach" in Bavaria with eight horizontal Francis turbines, one single-phase and one three-phase generator on the ends and an electrical regulating set, represents an extreme step in this direction.

This design was prompted by an unwillingness to use propeller or Kaplan turbines and by the peculiarity of loading of the power house, which has to supply single-phase 16⅔ cycles and three-phase 50 cycles alternating current. If this power house were redesigned today, vertical shaft propeller and Kaplan turbines and a rotating single-phase—three-phase converter would probably better solve the same problem.

*Replacement of Older Turbine Designs.* A remarkable picture of the advantages of a propeller or Kaplan turbine as compared with the older designs of turbines for low heads can be seen in the recently made replacements of multiple runner vertical shaft turbines, by a single runner propeller or Kaplan turbine. These replacements were made with only minor changes in the masonry and with considerable increase of the maximum capacity. By using a Kaplan turbine, the efficiency at lower loadings, due to the flat efficiency curve of the turbine, is still higher than the efficiency of the original turbine. The saving in space by use of the inclined arrangement of the wicket gates is particularly adaptable for such replacements.

*Regulation of propeller and Kaplan Turbines.* In order to make the amount of water entering a propeller turbine correspond with the load conditions, the same process is used as in Francis turbines. The water entering through the scroll case passes first the fixed guiding vanes and then the movable regulation vanes or wicket gates. The governor of the turbine actuates the servo motors which move the wicket gates, causing the increase or decrease of the amount of water passing through the turbine.

An additional regulation, consisting in turning the runner blades, corresponding to the change of loading conditions, is necessary for the Kaplan turbines, a fact that has brought out quite a number of new problems. A poor result, so far as the efficiency is concerned, is obtained from the separate regulation of either the wicket gates or the runner blades.

For proper regulation of the turbine, the angle of the runner blades has to correspond to the position of the wicket gates. These corresponding positions are influenced by the variations of the head.

The regulation can be accomplished either by simultaneous operation of the wicket gates and runner blades, or by making the regulation in two stages: the first stage or the main regulation by operating of the wicket gates, and the second or adjusting operation by operating of the runner blades so as to bring them to the proper position. It is possible to make the main regulation by operating the runner blades and the adjusting by operating of the wicket gates.

In all present designs, the main regulation is accomplished by the governor acting upon servo motors and changing the position of the wicket gates so as to keep the number of revolutions constant at the different

loadings. The subsequent adjustment is made by the operation of the runner blades.

In the earlier designs of Kaplan turbines the actuating mechanism for the adjustment of the runner blades was regulated from time to time by hand. In the up-to-date designs, it is operated automatically by the governor.

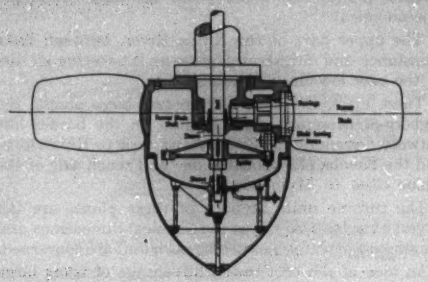

Fig. 7—Cross Section Through the Hub of a Kaplan Turbine Runner

The cross section of a recent design of a Kaplan turbine runner is shown on Fig. 7. The runner blades have an extended shaft end which is supported on two bearings. Between these bearings a lever arm is fastened to the shaft and is connected by means of rods

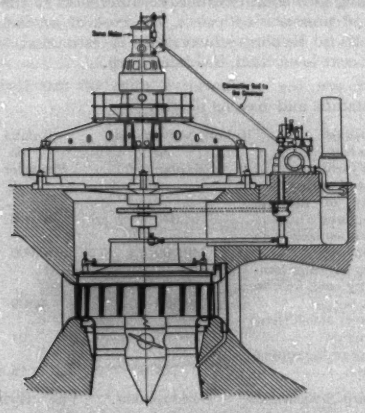

Fig. 8—Elevation of a Kaplan Turbine with the Servo Motor Above the Generator

to a spider. By moving the spider up and down, the blades of the runner are turned in one or in the other direction. The spider is solidly connected to a regulating shaft which can move up and down in the hollow shaft of the turbine. The regulating shaft is guided by two vertical sleeves, one above and one below the spider. The whole arrangement is oil tight and is kept filled with oil. The regulating shaft is moved by means of a compressed oil servo motor.

In the smaller Kaplan turbines, the servo motor that moves the regulating shaft is located above the generator.

Fig. 8 shows a general view of such a turbine and Fig. 9 the details of the servo motor. In this design the regulating shaft is continued through the hollow generator shaft and is connected with the piston of the servo motor. An indicating rod that is connected with the top of the regulating shaft is extended above the servo motor and connected by means of a system of levers with the governor and a slide valve. The angle of the runner blades is indicated by the position of the indicating rod, the movement of which is transferred to a special designed governor. The governor is arranged in such a way that if the angle of the runner blades does not correspond to the position of the wicket gates,

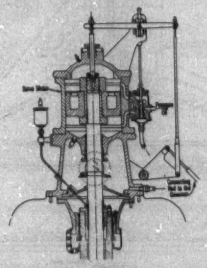

Fig. 9—Details of the Kaplan Turbine Arrangement of the Servo Motor Above the Generator

the sliding valve is actuated and the servo motor moves the regulating shaft until the necessary correspondence between the two factors has been accomplished. In order not to move the runner-blades at every slight movement of the wicket gates, the runner-blades governor is made so that it has a certain time lag with reference to the governor that actuates the wicket gates. Owing to this time lag the runner blades adjustment follows only the major regulating movement of the wicket gates and does not follow the minor swings of the wicket gate regulating mechanism. This regulating arrangement has a number of following drawbacks on account of which it is not very well suited for large size turbines:

1. The servo motor piston rotates in a stationary cylinder.
2. The long regulating shaft represents a heavy weight that is to be moved by each adjustment.
3. The hollow generator shaft is to be very heavy in order to accommodate the regulating shaft.

For large Kaplan turbines, the latest design shown

in Fig. 10 with the servo motor located between the turbine and generator shaft is expected to be a considerable improvement. In this design the regulating shaft is much shorter and since the piston of the servo motor rotates together with the cylinder no relative rotation movement between the piston and cylinder occurs. The hollow generator shaft has to accommodate only two oil pressure pipes that convey oil to the servo motor. These pipes rotate together with the generator shaft. The central pipe is solidly connected to the regulating shaft, and the indicating rod, connected to this pipe above the generator, indicates the angle of the runner blades, and this indication is transferred to the governor by means of a lever system. The rotating oil pressure pipes have a cap arrangement above the generator that permits the pressure oil to enter from stationary pipes to the rotating pipes. The servo motor is actuated by a governor that changes

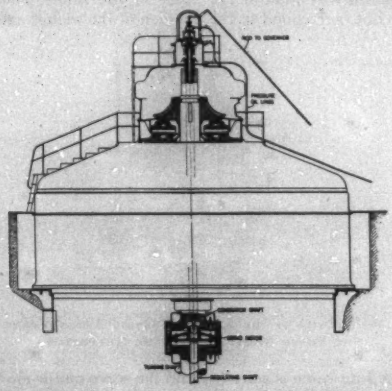

Fig. 10—Details of the Kaplan Turbine Arrangement of the Servo Motor Between the Turbine and Generator Shafts

the amount of pressure oil below and above the piston of the servo motor until an adjustment of the runner blades corresponding to the position of the wicket gates takes part.

All these arrangements do not take into consideration the influence of the different water heads and have to be set for some mean water head.

In general, it seems that the regulation problem of Kaplan turbines is still in an embryonic stage. Quite a number of improvements are possible to get the proper synchronization of both regulating mechanisms on a predetermined basis for different operating conditions.

In keeping in line with the general tendencies in governor design, the governors on the latest Kaplan and propeller turbine designs are mostly electrically driven instead of by a belt or a gear drive.

## II. Low Head Developments

Probably the most interesting of present day European developments are those for less than 80 ft. head.

The introduction and rapid increase in size of the propeller and Kaplan turbines changed considerably the economical aspects of these developments and made possible plants that a few years ago were considered uneconomical.

The upper part of the Rhine River, between Lake Constance and Strasbourg, gives an interesting picture of the new low head possibilities.

There are under construction two large plants, the Ryborg-Schworstadt plant located on the border line between Germany and Switzerland close to Rhinfelden, and the Kembs plant located on the French side of the Rhine close to Mulhouse.*

The turbine units in both of these plants are the largest ever built so far as the physical dimensions and the amount of water handled by each unit are concerned.

An idea of the economical advantage of using large sized Kaplan turbines for low heads can be gained by comparison of the Laufenburg and the Ryborg-Schworstadt plant. Both plants are very similar in size and capacity, the Laufenburg plant being located a short distance above the Ryborg-Schworstadt plant. The Laufenburg plant is of an older design and was built before the war. It contains a large number of Francis turbines.

Taking into consideration the differences in the prewar and present day prices, the cost of an installed kilowatt in Ryborg-Schworstadt is estimated to be 30 per cent lower than in Laufenburg.

Here are the comparative data of the Ryborg-Schworstadt and Kembs plants:

| Power House | Ryborg-Schworstadt | Kembs |
|---|---|---|
| Head in feet | 35 | 54 |
| Kind of turbines | Kaplan | Propeller |
| Number of units | 4 | 5 |
| Capacity of unit in horsepower | 35,000 | 36,000 |
| Installed capacity in horsepower | 140,000 | 180,000 |
| Quantity of water handled by each unit in cu. ft. per sec. | 10,500 | 6,800 |
| Number of revolutions per minute | 75 | 94 |
| Diameter of the runner in feet | 23.0 | 18.4 |

*Ryborg-Schworstadt Development.* The Ryborg-Schworstadt plant is located in a dam built across the Rhine. The general arrangement is shown in Fig. 11.

The cross section through a Kaplan turbine is shown on Fig. 12.

The water enters the concrete scroll case of each

*The author briefly described these plants in *Power* of April 1, 1930.

turbine through three passages formed between concrete piers, and passes through guiding vanes and wicket gates into the runner. After leaving the runner, the water enters the draft tube which has a steadying partition and a supporting pier. The piers in the intake and draft tube are used to support beams and slabs and carry the power house load.

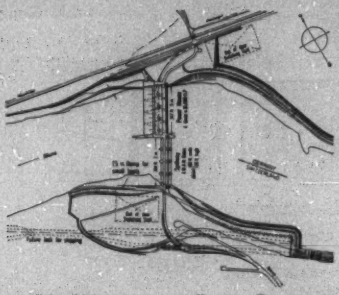

Fig. 11—Ryborg-Schworstadt Power Plant. General Plan

The thrust bearing load is carried down in solid masonry partly by the guiding vanes of the turbine.

The concrete fill indicated by lighter cross sectioning is used only at a part of the power house where the solid gravel foundation of the river bed was washed away and the soft natural fill had to be replaced by concrete.

The rest of the power house is built as shown by the heavier cross sectioning.

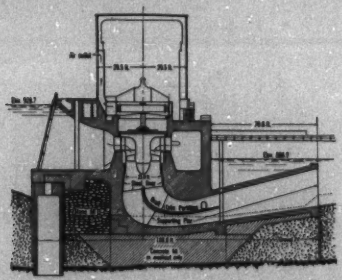

Fig. 12—Ryborg-Schworstadt Power Plant. Cross Section at the Center Line of a Unit

The unusual feature of this design is the absence of head gates in front of the turbine.

In normal operation the only way to stop the turbine is to close the wicket gates and by applying brakes to bring the runner to a stop in spite of possible leakage.

For emergency repair work, stop log provisions are made.

Another interesting feature of this plant is the main gates in the dam.

From the maximum total flow of the Rhine River that can be as high as 200,000 cu. ft. per sec., about 35,000 cu. ft. per sec. can be discharged through the power house and the rest is taken care of by four gates. These gates have a clear opening of about 80 ft. wide by 39 ft. high and are of the M. A. N. (Maschinenfabrik Augsburg Nurnberg) design.

The section through such a gate and the plan view of it are shown on Fig. 13.

The gate consists of a separate upper and lower part. The lower part of the gate is stiff enough to carry the water pressure, but the upper part of the gate has a stiffening beam at the top only; the bottom is flexible. The water presses the flexible part of the gate against the stiff lower part. A rubber strap fixed to the lower part of the gate and sliding against the upper part insures a water tight joint.

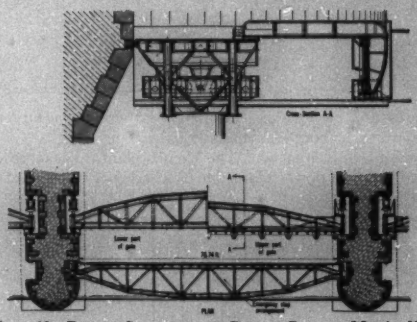

Fig. 13—Ryborg-Schworstadt Power Plant. M. A. N. Gates

The water tightness at the bottom is assured by a wooden beam pressing against a steel plate sill. At the sides of the gates, the tightness is assured by flexible steel plates which are pressed against guiding structural steel members.

The raising and lowering of the gates is done by an overhead electrically operated crane and the gates are operated by lowering the upper part of the gate or by raising the lower part of it, and finally by lifting the whole gate out of the water. This arrangement gives a perfect water control and at the same time, by letting the water flow above the gate or below it, a removal of all floating rubbish, as well as of the sand and gravel accumulated at the bottom of the gates, is possible.

Since at this size of the opening no stop logs can be used, the emergency closing of the gate is accomplished by lowering a number of steel frames handled by an auxiliary crane in the specially provided slots. These steel frames are covered with sheet metal and the water

tightness at the bottom, between the individual frames and at the sides is assured by wooden beams, which are permanently connected to the steel frames.

This design is becoming very popular for large sized

Fig. 14—Kembs Power Plant. Plan of the Canal

gates and designs are considered for sizes even larger than the Ryborg-Schworstadt gates.

*Kembs Development.* The Kembs plant is the largest and the first power plant out of a series of eight plants

Fig. 15—Kembs Power Plant. Location Plan

proposed on the shipping canal, Grand Canal d'Alsace (Fig. 14) which are to be built between Basel and Strasbourg as part of the German reparation payments. Fig. 15 shows the location of the Kembs plant and the temporary tail race.

The plan (Fig. 16) and the cross section (Fig. 17) of the Kembs power house shows a design quite different from Ryborg-Schworstadt.

A customary design of a dam with the necessary gates and spillways and the power house proper would require a much larger widening of the canal at the power plant.

The present day design was worked out, taking ad-

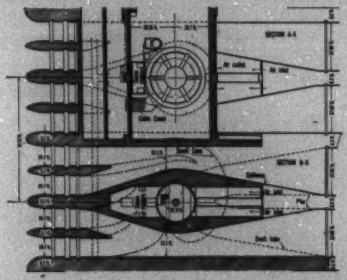

Fig. 16—Kembs Power Plant. Plan of Power House

vantage of the fact that the main regulating gates are located in the dam at the Rhine River and that the amount of water flowing through the canal is limited.

Corresponding to each unit of the power house, there are eight intakes which are opened and closed by head gates. Four of these intakes are on a lower elevation and lead the water to the concrete scroll case of the turbine. The four intakes at the higher elevation lead

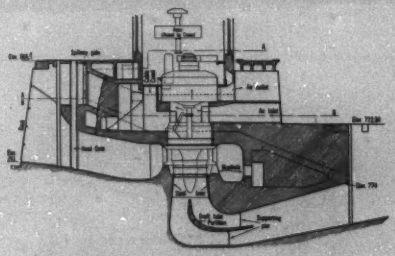

Fig. 17—Kembs Power Plant. Cross Sections at the Center Line of a Unit

the water below the main power house floor to the overflow spillway which is indicated in Fig. 16 with dotted lines.

The turbine is completely separated from the spillway by the central concrete pier, as shown on section *B-B* (Fig. 16). By closing the lower intake gates and opening the upper intake gates of a unit, the water will flow at the outsides of the central pier and any repair

work that has to be done on the unit can be done without any interference from overflow water by lifting the rotor of the generator and by subsequent lifting of the turbine runner.

The outlet of the spillway and the draft tube are brought together and the spillway will be shaped in such a way as to improve the output of the turbine in times of high water and decreased heads.

The supporting piers at the intakes and draft tube and the draft tube partition are provided in a way somewhat similar to the Ryborg-Schworstadt design.

Provisions for emergency stop logs are made in front of the intakes and at the end of the draft tubes and spillways.

Both the Ryborg-Schworstadt and the Kembs developments leave the impression of being very thorough and careful designs which can be brought out only by a very close cooperation between the turbine and power house designers and by an effective support of proper hydraulic laboratories.

*Propeller or Kaplan Turbines.* For present day low head developments, there are three possible choices of turbines:

1. Propeller turbines only.
2. Kaplan turbines only.
3. Propeller and Kaplan turbines.

The Kembs development is an example of the first choice, and the Ryborg-Schworstadt the second. The Lilla Edet power plant in Norway with two propellers (Lawaczeck) and one Kaplan turbine is a good example of the third choice.

The propeller turbine is simpler, cheaper, and can be designed to have at a loading close to 100 per cent, a very high efficiency, but at smaller loadings the efficiency will drop off very rapidly.

The Kaplan turbine is complicated, more expensive and, having a flat efficiency curve at a large range, will generally have a slightly lower maximum efficiency than the propeller turbine.

A good illustration of the difference between the efficiencies of a Kaplan and a propeller turbine is the fact that for units of about 40,000 hp., the amount of water that is necessary to turn idle a propeller turbine will deliver about 10,000 hp. in a Kaplan turbine. At conditions approaching full load, the amount of water that will deliver about 39,000 hp. in a propeller turbine will deliver less than 38,000 hp. in a Kaplan turbine. These differences in the two types of turbines in connection with local conditions will govern the proper choice.

In the Kembs power house, with a larger number of units and gradual changes in the amount of water, it was thought that by varying the number of units in operation it will be possible to have them work most of the time in the favorable range of the efficiency curve and the simpler and less expensive propeller turbines were decided upon.

In Ryborg-Schworstadt each unit is owned by a separate concern and, it is expected to work all four units all the time and change the loading of each unit according to the available water flow.

Under these conditions it was thought advisable to use the more complicated and more expensive Kaplan turbines for all four units. At the same time these conditions made it possible to eliminate the head gates, and in this way to compensate partly for the higher cost of the Kaplan turbines.

The Lilla Edet power house probably represents the average conditions better. There the idea is to run the propeller units always at the point of maximum efficiency and to have all the regulation taken care of by the Kaplan unit.

A good insurance against changes of the conditions assumed at the original design can be had by building the propeller turbines in such a way that a Kaplan runner can be inserted and the turbine run as a Kaplan turbine or vice versa.

## III. Interconnection and Improvements in Water Utilization

Most of the European power plants are connected to some distribution system and carry, partly at least, public utility load with its daily and seasonal variations.

The steam power plants of such systems take care of the deficiency in water power, but at the same time far reaching provisions are made for the best possible utilization of the available water flow and of adjustments to the variable load conditions.

The extensive use of water pumping schemes and the connection with chemical plants are the most important and interesting means of regulation.

The region of the upper Rhine shows the highest stage of development. Here the Rhine power plants, the power plants of Southern and Western Germany, Austria, and Switzerland, and through Switzerland, the French plants, form one of the largest international interconnected systems of the world.

The hydro plants of the upper Rhine have practically no storage and have to utilize the available water flow or waste the water. Due to the regulating influence of Lake Constance, the daily variation in water flow is small, but the seasonal variations are rather large. Since most of the water comes from the Alps, the largest flows occur in summer time and a scarcity of water and power is most noticeable in the winter time.

The whole region is so operated as to avoid any waste of water in plants having no storage capacity. Not only the seasonal or daily load variations are taken care of, but even the mid-day dropping off of the load is provided for.

This is achieved mainly by:

1. Regulating the load of steam plants.
2. Regulating the load or shutting down hydro plants having available storage capacity.
3. Starting and stopping water pumping in the

higher reservoirs on the German and Swiss sides of the Rhine.

4. Regulating the load of chemical plants.

The pumping problems are to be discussed separately.

So far as the chemical plants are concerned, let it be suffice to mention that in some cases they are directly owned by the power plant and some of them can take on or drop off as high as 20,000 kw. at one-half hour notice.

An interesting detail of the recent German practise toward better water utilization is the use of ground water in localities where such water is abundant. Depending upon the local conditions, a certain time lag exists between the maximum river flow and maximum ground water flow, as well as between the minimum river flow and the minimum ground water flow. Due to this time lag, even a comparatively small amount of ground water can have a good regulating effect.

## IV. Pumping Problems

Quite a number of possibilities for regulating and improving the output of power plants can be obtained by including a pumping scheme in the development.

In the past, pumping was not used to a large extent, but its use is increasing rapidly and the probabilities are that in the future it will be used very extensively.

The over-all efficiency of any pumping scheme seldom can exceed 60 per cent. On account of this low efficiency, the pumping schemes that utilize the waste water in most cases are the ones that show the best economical advantages. The schemes in which water that could be directly utilized is pumped into reservoirs will be justified only if the difference in price is large enough between the power delivered from the artificially stored water and the power that could be delivered by direct prime mover generation.

In order to get the full benefit of pumping, the pumping installation ought to be part of a large interconnected system, where the combinations of different kinds of high and low head plants with and without storage capacity create conditions that will make pumping advantageous.

The different pumping schemes actually used and proposed can be subdivided into three types and will be illustrated by a very brief description of developments that fit into each of these types. The division is as follows:

1. For daily regulation mainly. Murg and Schwarzenbach development near Forbach, Baden.

2. For seasonal regulation mainly. Waeggital development near Zurich, Switzerland.

3. For increase of the output of a power plant at high water and low water seasons. Proposed by Dr. Eng. Lawaczeck for plants with extremely variable head.

Both the Murg and Schwarzenbach and the Waeggital developments are parts of the upper Rhine interconnection systems and are located in the hills on the German and Swiss sides of the Rhine respectively.

*Murg and Schwarzenbach Development.* This development has two storage reservoirs located at different elevations. The higher reservoir delivers the water to the power house under an effective head of 1180 ft., and the lower reservoir under 460 ft.

The power house has correspondingly two sets of turbines and the water is led to the power house by two sets of penstocks.

The pumps are coupled to the horizontal shafts of the high head turbines and are driven electrically, running the main generator as a motor. The pipe connections are made in such a way that the pumps take the low head reservoir water through the low head penstocks and pump it through the high head penstocks into the high head reservoir.

At peak load conditions, the high as well as the low head units are delivering energy and the pumps are disconnected. At times of moderate energy demand only the low head units deliver energy. At times when the demand is smaller than the energy that the system can supply, the pumps are connected with the high head units and pump the water from the lower to the higher reservoir, drawing the electrical energy from the system.

The whole operation is so regulated that, besides the daily load variations, a seasonable load variation is taken care of by filling up the higher reservoir in times of high water flows and drawing it down in times of low water flows.

*Waeggital Development.* In this development the total maximum head is 1500 ft. The reservoir is an artificial lake of about 5.2 billion cubic feet capacity. The head is utilized in two steps.

The first step is formed by the power house "Rempen" with a maximum head of about 850 ft. By means of a tunnel and a set of penstocks, the water is led from the lake to the Rempen power house, after which it passes through the turbines into a tail race that is formed by a small regulating pond, which also has an appreciable natural inflow.

The second step is formed by the power house "Siebnen" with a maximum head of about 650 ft. The water is led from the Rempen power house regulating pond by a set of pipes and penstocks to the Siebnen power house and discharged into the river.

The pumping equipment is located in the Rempen power house and consists of a set of independent electrically driven pumps. Each pump corresponds to a main turbine generator unit and the pipe connections are made so that each pump takes the water from the Rempen regulating pond and pumps it through the penstock of the corresponding turbine into the lake.

The main purpose of this development is to increase the supply of power in winter time when the demand is large and the amount of water falls off.

The two plants are operated together in winter only

During the summer months the Siebnen plant is shut down entirely so far as delivery of power is concerned. The electrical generators of this plant are run as synchronous converters to improve the electrical conditions of the system.

The Rempen plant at peak load delivers power to the system; the rest of the time it pumps back the water which was used in peak load hours and pumps all the natural inflow of the Rempen regulating pond into the Waeggital lake.

In this way during the summer the lake elevation is raised, the lake receiving besides its natural inflow all the inflow of the Rempen regulating pond.

In winter at times of heavy load demand both power houses are delivering power and at times of lighter power demand a part of the water is pumped from Rempen pond back into the lake.

*Lawaczeck Scheme for Developments with Very Variable Heads.* This scheme was proposed recently for rivers in which, in times of high flow, the amount of water increases considerably and the tail race elevation rises close to the intake elevation.

For such developments it is proposed to install small reservoirs which may be concrete reservoirs at an elevation higher than the highest river elevation. The water is to be pumped into such reservoirs when the river rises; that will create an additional water head and the turbines shall be run with water under this artificial head. In connection with this scheme special turbine pumps are proposed.

*Types of Pumps.* The pumps that are in actual use or that are proposed for different schemes can be divided as follows:

Independent motor driven pumps.

Pumps that are connected with the turbine generator units.

Special Lawaczeck pumps.

*Independent Motor Driven Pumps.* Since, for the motor driven pump, the number of revolutions of the motor can be chosen so as to be favorable to the pump requirements, this kind of pump has certain advantages that are particularly noticeable if the pumping is to be done for long periods of time. If synchronous motors are chosen to drive such pumps, an improvement of the electrical conditions of the system can be obtained at the same time.

The pumps of the Rempen power house are of this kind.

*Pumps Connected with the Turbine Generator Unit.* In recent years, the use of pumps coupled with the main unit is gaining much favor. From the operating point of view, such an arrangement presents a certain advantage.

If the pump is connected to the main unit by means of a coupling, then the pumping can be started only after the main generator, which has to run as a motor, is synchronized with the system.

If in emergency the main unit is called upon to deliver power, then the coupling is to be disengaged, and the generator, being already synchronized and connected to the system, can be loaded to full capacity in a short time. In this way, by means of a quick acting coupling, the main unit that is used for pumping acts as a spare unit which can be put under load very quickly.

This arrangement was first adapted to horizontal shaft units, for which it is well suited. The plan view of the pump arrangement of the Murg and Schwarzenbach power house is shown on Fig. 18. Two turbine pumps are connected by means of a gear reduction and an electric coupling to the shaft of the main unit. The electric coupling can be disengaged practically instantaneously and the generator loaded up to the whole load in a few seconds.

The experiences with the horizontal shaft arrangement were so successful that a pump for vertical shaft units was brought out on the market. As shown in Fig. 19, the pump is connected to the unit by means of a hydraulic coupling. The weight of the pump rotor and of the part of the hydraulic coupling connected to

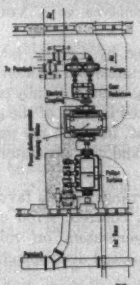

Fig. 18—Pump Connected to a Horizontal Shaft Unit

the pump is carried by a thrust bearing placed below the pump.

*Special Lawaczeck Pumps.* These pumps were proposed with the idea that at high water flows the amount of water is abundant and that if the pump has to be run only at this time the efficiency of the pumping outfit can be fairly low. Fig. 20 shows a section through a Lawaczeck pump unit installed in a submerged weir. The unit consists of directly connected pump and turbine runners. For the small heads available in such an arrangement the number of revolutions of a unit is small and the pressure developed by the pump is low. By using a battery of such units with the pumps connected in series, the necessary higher pressure can be developed only at a low efficiency.

As these pumps are to be used for only a short time every year their simplicity and low cost are of much more importance than their efficiency.

## V. Power House Design

The following discussion is concerned with designs with vertical shaft turbines:

It is impossible to put down any general rules that would cover all the latest designs, but a few tendencies can be noticed.

One seldom meets the two-floor arrangement in which the power house has an easily accessible main generator

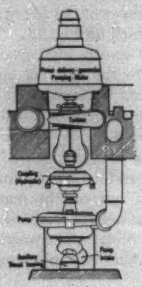

Fig. 19—Pump Connected to a Vertical Shaft Unit

floor that is covered by a crane, and a lower turbine floor not easily accessible and without the crane service. The one floor arrangement is usually preferred, in which the turbine is located in a pit of the generator floor, or else an arrangement, in which the main floor is at the turbine elevation and the generators are located on raised pedestals.

The one floor arrangement is favored for low head developments with concrete scroll cases and the arrangement with generators on raised pedestals is favored for medium head development with steel scroll cases.

The auxiliary turbine equipment in both cases is served by the main crane.

The unsupported length of the building columns can become quite long at one side of the building in such designs. By having a separate generator floor with liberal openings in it and with the turbine equipment located on the turbine floor below these openings, the advantages of the one floor arrangement can be had without the disadvantages of the unequal length of the building columns.

Structurally complicated and uncertain designs are very seldom used and the tendency is to build up the power house as a combination of simple elements.

In the larger low head developments this is accomplished by the liberal use of supporting piers built into the scroll case and draft tube, which results in a design consisting of a plain system of slabs and beams supported on these piers.

Such designs are used in the Ryborg-Schworstadt and Kembs plants.

For medium head developments, the arrangement of the power plant Aufkirchen on the Mittlere Isar in Bavaria is very satisfactory from an operating as well as from a structural point of view, and is typical of many recent designs.

This power house has only a main turbine floor and the generators are raised above the elevation of this floor on a pedestal common for all generators.

The weight of the generators and the thrust bearing loads are carried down by means of arch barrels running the whole width of the generator pedestal. The arch barrels are supported by piers that are located between the scroll cases of the separate units.

The whole design is structurally sound and the power house has practically no dark and inaccessible places. Every piece of equipment can be handled by the main crane.

The troubles which many plants have experienced in past years with runners, caused some engineers to provide for the possibility of removing the turbine runner independently from the generator. For larger turbines this is accomplished by locating the generator at a higher elevation and increasing the length of the shaft between the turbine and the generator. This longer shaft has two couplings between the turbine and generator with a short piece of shaft in between. After unbolting these couplings and removing the short piece of shaft, the turbine runner can be lifted independently from the generator rotor.

Such design increases the over-all height of the power house and some auxiliary lifting devices are necessary to handle the turbine runner and to bring it within the reach of the main crane.

## VI. Energy Destroying

The question of erosion of the ground at the toe of dams, as well as of the damage that may be done to the

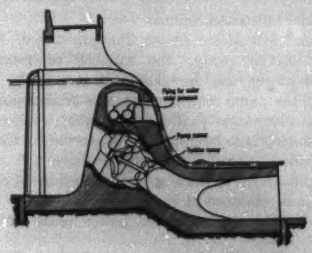

Fig. 20—Lawaczeck Turbine Pump Unit

river or canal bed by the overflow water coming down the spillway has been seriously studied in the last few years. In cases where the dam is not built on rock and the river or canal bed is not formed in rock or lined with concrete, this question is of particular importance. In order to prevent any erosion, two quite different methods have been adopted recently.

The Energy Destroyer of Baudirector Kennerknecht represents the one way of handling this problem, and the indented sill of Dr. Eng. Th. Rehbock the other.

The Energy Destroyer is built and operated in the Innwerke near Munich, Bavaria. The idea is to let the water flow down in two separate pipes at considerable velocity and to combine both water columns on the lower elevation in a reservoir that is formed in such a way that a mutual destruction of the energy of both water columns will take place and the water will flow over the reservoir at moderate velocity without any danger to the river or channel bed. The Energy Destroyer of the Innwerke has now been in operation for a number of years and works very satisfactorily. Being connected with the upper pond by means of a siphon, it regulates automatically the water level of the upper pond.

The idea put into the indented sill design is that the energy of the water leaving the spillway at a considerable velocity is effectively destroyed on a short distance of the tail race by the forming of a water roller. In order to prevent any erosion in the place where the water leaves the toe of the dam, conditions are to be created which will move the erosion of the river bed at a safe distance from the toe of the dam. The indented sill, which consists of a number of concrete teeth placed at the toe of the spillway, fulfills these requirements and the model tests at the laboratory in Karlsruhe give a most convincing picture of its action.

## VII. Hydraulic Laboratories

Any attempt to get an idea about the high spots of the present day hydro power developments in Europe brings out the important part that the hydraulic laboratories are taking in these developments.

In Europe and particularly in Germany and Switzerland, there is a very efficient system of hydraulic laboratories supported by technical universities, states, and turbine manufacturers. These laboratories can be divided in the following three types:

1. River hydraulic laboratories which are working mainly in the line of investigation of behavior of rivers under different conditions, the influence of hydraulic structures such as dams, spillways, etc., on the behavior of the river, movements of river beds, and erosions of river and channel beds, river regulation problems, etc.
2. Turbine laboratories in which the work is mainly concentrated on turbine testing problems, cavitation, pitting, water flow in pipes, scroll cases, draft tubes, etc.
3. Naval laboratories that are mainly working on the problems connected with ship design.

The laboratories of the technical universities are of all three types, the state laboratories are mostly river and naval laboratories, and turbine manufacturing concerns have turbine laboratories.

Considering only the river and turbine laboratories, it is to be noted that the progress in hydro development in Europe is due to the close and most beneficial cooperation and friendly competition which exists among these different laboratories.

The laboratories connected with the technical universities and states have more time and a better opportunity to do new development and research work, to check over and correct the work of other investigators, and to make special investigations necessary for the proper design of different hydraulic structures.

The work of the laboratories connected with the turbine manufacturing concerns is necessarily rather limited by the pressing every day problems that arise in connection with the designs in which the particular concerns are interested. Only at irregular intervals when the pressure of the immediate work is released can such a laboratory attempt to do any new development work. The division of work among these different laboratories and free exchange of information are responsible for the present day high standing of the low head developments in Europe.

Here are a few of the more interesting problems in connection with the laboratory work:

*Scale of Models.* Two different opinions predominate in the question of the scale on which models such as rivers, channels, locks, dams, etc., should be made and tested.

One opinion that is best represented by the Hydraulic Laboratory of the Prussian State in Berlin, is that the models have to be as large as possible; the other opinion, best represented by the Hydraulic Laboratory of the Technical University of Karlsruhe, is that the models are to be reasonably small depending on the character of the problem to be studied.

The Berlin Laboratory in logical development of its idea went so far as to start to build an out-of-doors laboratory outside of Berlin, in order to remove the limitations that are put on the scale of the models by the size of a building. In this laboratory models as large in scale as 1:40 are built and tested.

In order to work on still larger scales, this laboratory goes so far as to build and test models with different horizontal and vertical scales.

The Karlsruhe Laboratory stresses the importance of the refinement of measuring and observation methods and believes that a small model can be tested out much more thoroughly by making a larger number of tests under different conditions, a procedure that would be prohibitive on account of time and cost in a large scale model.

Both laboratories have the support of outside technical opinion. The Berlin Laboratory is starting a number of model tests on river regulation problems in Soviet Russia which are to be run on out-of-door models of large scale. The Karlsruhe Laboratory is finishing a special building where the regulation problems of the Rhine River are to be solved on models of much smaller scale (1:200). The tests are to be run on a number of separate models, each representing consecutive stretches of the Rhine River about 10 km. long.

*Water Measuring Devices.* In testing full sized turbines, the exact measurements of large amounts of water are necessary. The existing methods are cumbersome and unsatisfactory, and research in new water measurement devices is going on.

At the Technical University in Munich a thermoelectrical device is being developed, which, if successful, promises to be quite an improvement. The idea consists in having a wire in a glass tube heated by electric current and the temperature of the wire measured by a thermocouple. If inserted in running water, the device can be gaged so as to give the water velocity as a function of the water temperature. By inserting a number of such devices, for instance in a penstock, the mean velocity of the water and the quantity of it could be determined quickly and easily by measuring the water temperature and the potential of the thermoelectrical couple.

## VIII. Cavitation Laboratories

The importance of cavitation and the necessity of cavitation studies led to the development of special cavitation laboratories.

The purpose of the cavitation investigation is to determine the exact conditions of draft tube head and water velocity at which the cavitation will start in a particular turbine.

By determining the efficiency of the turbine by the usual methods at different draft tube heads and drawing the efficiency curves, an approximate idea of the conditions at which the cavitation starts can be gained by the drop of the efficiency curve.

Very sensitive measuring methods are necessary to determine the exact point at which the cavitation starts, since the efficiency curve drops at the beginning rather gradually.

Other methods seem to give better results.

The cavitation laboratory of the Escher Wyss Company in Zurich uses very successfully the stroboscopic method. The model of the runner can be observed during the test through a glass window; the observer covers his head and the glass window with a dark cloth as in an old-fashioned photographic camera and illuminates the runner by an electric lamp, which is electrically connected with the runner by means of a commutator and gives one flash for each revolution of the runner. When observed by means of this lamp, the runner appears immovable irrespective of the number of revolutions it actually makes. So long as no cavitation occurs, the water appears perfectly clear. The exact moment at which the cavitation starts can be determined because of the small bubbles of vapor and air that appear along the outer circumference of the runner as a slight fog. With increase of the speed or with the increase of the draft tube head, the bubbles increase in size and number until finally the water becomes very turbulent and opaque.

In such tests a full sized draft tube head must be available which usually forces the location of such a laboratory on a higher floor and the extension of the draft tube down to the lower floors.

*Laboratories and Low Head Developments.* The laboratory cooperation is particularly important in low head developments. An old fashioned Francis turbine can be designed on a drafting board and the performance of the turbine designed in such way can be very closely predicted without any model tests.

A propeller or Kaplan turbine can be properly designed only if the preliminary drafting board design is modified and improved in accordance with model tests.

The conditions under which cavitation can be avoided can be determined only if the chosen shape of the blade is tested in a cavitation laboratory.

The turns of the blades of a Kaplan turbine corresponding to the position of the wicket gates, the shape and size of the draft tube partitions and of the supporting piers in the draft tube and spiral case can be determined by model tests only.

Not only the turbines, but the design of the entire power plant is to be supported by laboratory tests. The large amounts of water to be handled and the inability to determine without tests the influence that the proposed structures will have on the behavior of the river, are making the laboratory help of utmost importance. The expenses and time loss that are involved in laboratory tests are saved in more economical structures and better designs resulting from such tests.

*Design of the Ryborg-Schworstadt Power Plant.* A good general idea about the way in which more important low head designs are handled and about the amount of cooperation between the power plant designer, turbine manufacturer, and hydraulic laboratory can be gained by considering the way in which the design of the Ryborg-Schworstadt development was worked out.

First, a preliminary study of the development was made and the approximate location of the proposed dam and power house were determined. This information was given over to the Karlsruhe Laboratory where a complete model of the part of the Rhine River involved in this development was built. Extensive series of tests were made in the laboratory to determine the proper location of the dam and power house, the amount of river protection necessary above and below the dam, the conditions to be met to protect the shipping interests, the possibilities of sand and gravel accumulation at the intake, the influence of the cofferdams, and so on. At the same time the three turbine manufacturing concerns that were chosen to deliver the Kaplan turbines, J. M. Voith in Germany, Escher Wyss & Co. and Atelier des Charmilles in Switzerland, made preliminary designs of the turbines, built models of them, including scroll cases and draft tubes, and tested the models to determine the efficiency, the cavitation limitations, the runner blades adjustments, the shape and location of the dividing partitions and supporting piers, etc.

The results of tests made in Karlsruhe, as well as

tests made by the turbine manufacturers, were put before all parties and the necessary modifications in the preliminary design were discussed and decided.

In this way the preliminary design was modified a number of times until the best possible combination was found and the final design that is now in construction was decided upon.

## IX. Concrete Work

The progress made in the past few years in the United States in proper control, mixing, and handling of big masses of concrete, has not yet reached Europe. Observations made in Germany and France showed that the concrete work was mostly done in an old fashioned way.

In the United States, the uniformity of the concrete work and the predetermined strength and density of the concrete are assured by:

1. Proper proportioning and mixing of the aggregates.
2. Strict maintenance of the necessary water-cement ratio.
3. Transportation of the concrete and disposing of it in forms in such a way as to prevent any segregation of the aggregate.

These important considerations are very often neglected in Europe. The work is mostly conducted on an arbitrarily chosen cement-sand-broken stone ratio and no strict water-cement ratio is maintained, the amount of water being left to the discretion of the foreman. In line with this absence of scientific control, the tendency that is so pronounced in the States to reduce the number of mixing plants and to have the mixing done in large mixers and in properly equipped and controlled plants is also absent. Small mixers under the direct control of the foreman in charge of the particular part of the job are mostly used. As a result, the concrete work is poor, from the American point of view.

In a properly conducted American job, the concrete is sound and equally dense throughout the whole thickness, but the outside will look rather rough, showing usually the marks of the forms. If for some reason a top coating of concrete mortar is desired, it can be applied properly only by using some instrument to roughen up the surface of the concrete after the forms are stripped.

In most of the European jobs, the concrete is porous and of non-uniform quality and a top coat of mortar can usually be applied on the green concrete without any preparation. This top coat is one of the most important parts of a European job. The applying of the top coat is a highly specialized operation, which is controlled only by the personal knowledge and experience of the cement finisher. He not only personally determines the ratio of fine and coarse sand and cement, but in most cases the mixing is made by hand and in small quantities, under his personal supervision. After mixing, the top coat is applied by hand and troweled by steel trowels.

Such a job will have at the beginning an unusually smooth and neat appearance. But, in a comparatively short time, the top coat will crack and loosen and fall off. The appearance of concrete work only four or five years old in some cases is appalling, particularly after last year's severe winter.

Besides the poor quality of the concrete work, the very long time necessary to finish a development in Europe probably depends partly on these many irregularly operated individual mixing plants. As they cannot be properly controlled and regulated, their combined output is much smaller than it could be if all the mixing were concentrated in one or a few larger plants and the concrete handled in large quantities and more regularly.

### Acknowledgment

The very hospitable, helpful, and frank way in which different developments were shown to the writer, as well as the free way in which interesting and valuable information was given, are to be noted.

The trip itself was made possible by the assistance and support which the writer received from Messrs. E. S. Fickes, J. W. Rickey, and C. H. Moritz, of the Aluminum Company of America.

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## Discussion

**F. A. Allner:** Mr. Karpov's observations on the status of hydraulic research work in Europe are of great interest to engineers who have to deal with low and medium head developments.

There has been until very recently a lack of adequate laboratory facilities in this country, especially of those required for the study of the cavitation problem. For this reason one of the major hydroelectric companies in the East found it necessary to build a cavitation laboratory of its own immediately adjacent to an existing development of about 55 ft. head, where turbine models, complete with settings as proposed for another low head project on the same river, are now being tested for cavitation behavior.

Facilities have also been provided for making tests on model structures, such as, spillway sections, sluice gates, flashboards and other similar structures.

It is possible to test a 16-in. turbine model in this laboratory under a full operating head of 50 to 55 ft. and vary the draft head on the runner from 10 ft. submergence to 10 ft. draft head. These wide limits are essential in making the tests for cavitation. Cavitation is determined by two independent methods: First, a graphical method wherein an efficiency curve is drawn for constant operating conditions, with the exception that the draft

head is varied. The draft head at which cavitation starts can be determined by a sudden dropping of efficiency. The second method, used more recently by the cavitation laboratories in Europe, is the visual method for which more positive results are claimed. In order to use this visual method, the laboratory at Holtwood has been designed with an observation chamber just below the turbine setting, with glass windows in the draft tube at about the elevation of the turbine runner. Through the use of a stroboscope, it is possible to see the water leaving the runner blade and also to see the formation of air bubbles in the draft tube in the vicinity of the runner.

The laboratory normally uses about 50 cu. ft. per sec.; the exact quantity being measured by a Venturi meter tube, which has been calibrated in place by a weir as well as by the Allen salt velocity method. The power is absorbed by a 300-hp. electric dynamometer specially designed and built for vertical operation by the General Electric Company. To maintain constant conditions for a given test, the laboratory has been provided with a large head tank of approximately 350 sq. ft. area and with a pond of even larger surface area for the tailrace. Both water elevations are maintained constant by using long spillway sections.

We are obtaining valuable information concerning cavitation through this laboratory, so that we hope to be able to predict the highest elevation at which the runners at the new project may be set without encountering pitting.

By locating the runner as high as is indicated from the results of the cavitation tests, substantial economies can be secured in the cost of structures and in the amount of excavation required in the river bottom, not only under the power house itself but also in the tailrace downstream.

**A. V. Karpov:** Last year when I was making the necessary arrangements for my European trip and discussing my plans with friends, most of them thought that such a trip would give a considerable amount of information, but one of them was very skeptical. His line of reasoning was that a single manufacturer in the States produces more horsepower in hydraulic turbines than a whole European country and under such conditions what could be learned in Europe that is not already known in the States.

When I called his attention to the extensive laboratory work that is going ahead in Europe, his reply was that the extensive laboratory work was necessary because of the lack of practical experience and that in the States the manufacturers are backed with such a wealth of previous experience that they can achieve better results with a moderate amount of laboratory work.

In Europe I had the opportunity to discuss with one of the outstanding men in the field of hydraulic laboratory research the difference in amount of hydraulic laboratory work done in Europe and the United States. His opinion, based not only on his knowledge of the conditions in Europe, but also on the experience of a recent American trip, is very characteristic:

"Engineers in different countries are very much alike and try to bring their work to conclusion as quickly as possible. In the States they are supported in this desire by the easy way in which money can be spent in a rich country and instead of building and testing a model on a small scale, they go ahead and build a model to a scale 1 to 1 and test it.

If the test is satisfactory, the model stays as a finished work; if the test is unsatisfactory—well—then more money is spent and the necessary changes are made until everything seems to be satisfactory.

In Europe the money does not come so readily and much more strict technical proofs are required in order to get the money.

The only way to furnish such proofs is to make model tests and they are made not to the scale 1 to 1 but to a much smaller scale.

Incidentally, the necessity to make a small model usually results in a better development because if some one works on a small scale model, he, as a general rule, is not satisfied if everything looks all right at the surface, but out of all the possible combinations he tries to find the one that is the most satisfactory and in most cases it is a vast difference between something that is taken at random and is just satisfactory and a thing that is worked out thoroughly and arrived at by exclusion of all the "just satisfactory" solutions and accepting only the best.

Of course, if you have a model to the scale of 1 to 1 no research of any magnitude can be done and very seldom improvements are made even if the necessity of them is realized."

This opinion shows in a nut shell the difference between the present hydro power practise in Europe and in the States.

Most of the countries of Europe are in the stage that we in the States, or at least in the eastern part of the States, are just approaching:

The more favorable sites are developed and the new developments have to be made at sites that in the past were considered uneconomical and can be developed only if improvements are possible that will make the developments more economical.

One point of general interest, is the more individualistic way in which large developments are often handled in the States. In Europe, if you will try to follow the history of a large development, you probably will notice a greater spirit of cooperation between different parties taking part in the development which brings the necessity of much stricter proofs for each statement in order to have them accepted by all parties concerned.

The cavitation problem gives a very vivid picture of the different points of view in Europe and in the States.

A comparatively short time ago, the American practise in water power machinery was more advanced and superior to the European practise.

In the high head developments the American designed Pelton turbine was leading. In the field of the medium and low head developments, the American designers were the first to realize the importance of high specific speed turbine runners for the economical exploitation of such developments. The conservative Francis turbine design was changed, the runner diameter was made smaller and the modified higher specific speed runner was developed in this country. The development of the runner cut down considerably the initial cost of the medium and low head developments, but brought a new difficulty that was not encountered in the older designs. This difficulty, known as the cavitation phenomenon, with the resulting pitting, was increasing with the increase of the specific speed and proved to be in many cases very disastrous.

No real scientific laboratory work has been done in the States and a general mistrust against research in still higher specific speed runners developed and was so pronounced that the work in this direction was very much hampered and the American designers did not pursue the logical evolution of the idea of high specific speed turbines. All the subsequent research along these lines was made in Europe and culminated in the successful introduction of propeller and Kaplan turbines.

The credit for a scientific investigation of this matter and for the establishing of the first turbine cavitation laboratory is due Dr. D. Thoma, who, after considerable theoretical work, built the laboratory in 1924 as an addition to his hydraulic laboratory in Munich and formulated the conditions under which the cavitation tests on models have to be run in order to be applicable to full size turbines.

The fact that European turbines built in later years are practically free from cavitation troubles and the very remarkable development of large propeller and particularly Kaplan turbines in Europe in the last 10 years, is the direct result of the scientific investigations made in a number of cavitation laboratories in Europe.

Today, when ordering a turbine in Europe, the manufacturer can supply exact information about the limiting conditions under which, for the particular kind of turbine, the cavitation will occur and the whole design can be based on this information. In the States the manufacturer has only the idea that under high

setting and high specific speed cavitation will occur, but he is unable to give exact information as to when it will occur. Under these conditions the power house design is based on an argument, the manufacturer trying to persuade the customer to use against his better judgment low settings and low specific speeds and in this way to increase very considerably the cost of the whole development. It may sound as a joke, but actually developments involving hundreds of thousands of horsepowers are settled in one or in the other way depending on how convincing the manufacturer is in his arguments. The results are the extravagant expensive developments or the cavitation troubles and they can be seen in very many places in the States.

Another interesting point in the European developments which I tried to bring out in my paper, is the handling of the concrete work. Our way of controlling the mix and the handling of the concrete is much superior, and the equipment used in Europe can hardly be compared with the equipment used in our high grade jobs. Here I believe the credit is due the Portland Cement Association, not only for its very advanced research work but also in a larger degree for its consistent educational campaign. No doubt the results of the research made in concrete work in the States are known the world over, but the practical application of this research lags considerably, due to the absence of a powerful and progressive organization to spread the theoretical knowledge in the field.

In the presentation of my paper, I aimed to stress the more important principal points, instead of giving an abstract of the paper itself. The most important point, to my belief, is that at present only the industries that realize the importance of high grade research and make an honest effort to carry such research are going ahead.

That sounds like a platitude, but the comparisons that I drew seem to justify the necessity of repeating once more this simple truth.

The main reason for the presentation of my paper was to stress our shortcomings in theoretical and laboratory research work. The absence in the States of a cavitation laboratory was considered as a very serious drawback in the progress of hydro-power developments and Mr. J. W. Rickey, Chief Hydraulic Engineer of the Aluminum Company of America, called a conference of hydraulic turbine users and manufacturers, on November 4th and 5th, 1929, in Pittsburgh, Pa., to discuss the question of creating such a laboratory in the States. The fact that just lately two such laboratories were completed, the one by a large turbine manufacturing concern and the other by a large turbine user, is very gratifying. If the work in these laboratories, and in others that probably will follow, is vigorously pushed ahead, it is to be hoped that the States will again lead in low head hydraulic machinery, with the result that a large number of new sites can be successfully developed.

# Automatic Stations

## ANNUAL REPORT OF THE COMMITTEE ON AUTOMATIC STATIONS*

*To the Board of Directors:*

In accordance with established precedence, your Committee on Automatic Stations submits a review of the past year's development and application of automatic stations.

The committee terminates its third year of activity having kept in step with, and encouraged the rapid advancement in, the development of automatic equipment. Automatic equipment is assuming a most important role in every branch of the electrical industry. Along with these activities the committee has established, so far as possible, coordination of its own functions. This has been made possible by the farsighted organization perfected during the first year of the committee's existence and has accomplished in part the compilation of technical data in the form of subcommittee reports. It has also made possible the first technical session on automatic stations, in the presenation of six technical papers at the Summer Convention of 1930.

The application of various types of automatic equipment has become so extensive that no attempt has been made to cover the multiplicity of uses, it felt that the general phases have been considered in the arrangement of the technical papers for the Summer Convention and the subcommittee reports contained herein.

The committee has suffered a great loss in the untimely death of Walter H. Millan of St. Louis, Missouri, on November 13, 1929. Mr. Millan was Chairman of the Committee on Automatic Stations for the years 1928-1929. His death removes from among us an engineer of distinction, a loyal friend, and a sincere supporter of the ideals of the American Institute of Electrical Engineers.

### Developments

Numerous developments have been completed during the past year; many of these are concerned principally with telemetering systems while others have been undertaken with a view to simplicity and standardization. The automatic control of power rectifiers has reached a high degree of perfection, particularly in the field of railway electrification.

Some development has taken place in the use of carrier current for operating remotely located switching equipments and in accomplishing telemetering. There seem to be possibilities in this field.

### Operating Experiences

Considerable operating data have been collected in the past years, not only by the Committee on Automatic Stations but by other national organizations. Although operating experience is and always will be an important factor, it now seems that with the increasing stabilization of operating performance, it will be possible to look upon this as a matter of routine.

### Standards

Standards No. 26, Automatic Stations, has again been reviewed by the committee. Recommendations for revisions in the list of device function numbers and in the table of minimum protection for power apparatus have been forwarded to the Standards Committee.

It is recommended that Standards No. 26 be reviewed and revised annually by the Committee on Automatic Stations.

### Standardization of Symbols

A subcommittee, (Messrs. C. Lichtenberg and M. E. Reagan), was appointed to investigate and determine to what extent standard A. I. E. E. symbols were being used on diagrams for automatic stations. This subcommittee reported that these symbols are being used very generally. It was determined, however, that the present symbols are inadequate, and it is recommended that the succeeding Committee on Automatic Stations review this subject and propose additional and revised symbols.

### Technical Papers

The following six papers are being presented under the auspices of the Committee at the Annual Convention, Toronto, Canada, 1930:

1. *An Electron Tube Telemetering System*, by A. S. Fitzgerald.
2. *Development of a Two-Wire Supervisory Control System, with Remote Metering*, by R. J. Wensley and W. M. Donovan.
3. *Centralized Control of System Operation*, by J. T. Lawson.
4. *Automatic Power Supply for Steel Mill Electrification*, by Robert J. Harry.
5. *1000-kw. Automatic Mercury Arc Rectifier; of the Union Railway Company, New York*, by W. E. Gutzwiller and O. Naef.
6. *Miniature Switchboards*, by Philip Sporn.

### Meetings and Papers

In connection with the presentation of technical committee annual reports, the presentation of technical papers, and the discussion thereof, the Committee recommends that:

*COMMITTEE ON AUTOMATIC STATIONS:
F. Zogbaum, Chairman,
P. H. Adams, H. C. Don Carlos, Otto Naef,
Caesar Antoniono, Joseph Hellenthal, M. E. Reagan,
L. D. Bale, E. L. Hough, Garland Stamper,
G. O. Brown, Chester Lichtenberg, L. J. Turley.
S. J. Lisberger.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

1. The reports of technical committees be presented at the special sessions of the committee held during the Annual Convention.

2. Discussion of papers to be presented at technical sessions be scheduled just as papers are now scheduled.

3. Advance copies of papers for technical sessions be in the hands of those selected to discuss them at least seven calendar days before the papers are to be presented.

### Communications from Other Committees

This committee received from the Committee on Instruments and Measurements, for comment, a set of definitions covering the various phases of telemetering. These definitions were reviewed and comments forwarded.

### Unfinished Business

The following topics have been under consideration, but no final reports have been rendered:

1. Fire Protection.
2. Economical Construction.
3. Unusual Operations.
4. Load Dispatching.
5. Wire Designations.
6. Suppression of Noise.

### Subcommittee Reports

Two comprehensive subcommittee reports were prepared and are contained herein as follows:

### Automatic Substation Ventilation*

The purpose of substation ventilation is to maintain within economical and safe limits the temperature rise of electrical apparatus installed therein. This is best accomplished by using outdoor air as a medium on the natural or forced draft principle. During early installations with small capacity electrical machinery and with ample space allowance in buildings, natural ventilation predominated. There were a few exceptions where high temperature rises required more adequate ventilation by the use of blowers or fans. With the gradual growth and development of larger units and the concentration of greater kilowatt capacity within a given area or volume (especially in basements and the crowded metropolitan areas) the problem of effective ventilation became more serious and led to a more scientific application of the various elements.

Practically each installation requires special consideration. The problem of suitably arranged and properly sized inlets and outlets; the location of air ducts for the best directed means of reaching typical suction areas on rotating type machines; the requisite as to quantity and velocity of cool air, together with preventive means of recirculation, are factors involved in the study of realizing the most effective ventilation.

With manually-operated stations, the temperature rise of ambient air caused from recirculation, together with the entire room temperature, must be governed for comfort of operators to meet summer or winter conditions. With partially or totally enclosed rotating units, an effective means has been found in controlling recirculation by conveying the heated air direct to outdoor outlets.

Sound-proofing of buildings and attempts at noise prevention with automatically controlled substations have developed the more elaborate system of forced draft. It is a matter of spending energy to handle the necessary volume of air against the resistance of bafflers, sound absorbing material, circuitous routes of air duct lines, and air filters, or washers.

Many valuable articles have been published covering actual installations with complete data on the various methods employed to ventilate effectively both machine and substation building to which reference is hereby directed.

*Contributed by L. J. Turley.

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## GUIDE TO SPECIFICATIONS FOR AUTOMATIC SWITCHING EQUIPMENTS*

In the application of automatic switching equipments, certain fundamental factors apply equally well to all service classifications; others are necessarily specific. This guide is prepared with the desire to aid in the selection of the type of equipment with proper operating characteristics for a given service. This is given in outline form to call attention to the factors to be considered in this selection.

In general, the various devices comprising the automatic switching equipment should be chosen to meet the interrupting rating, short time rating, continuous and overload rating for the particular service.

### GENERAL

I. Selection of equipment for automatic service varies slightly from that chosen for manual control.

A. Usually smaller units nearer load centers.
   1. Better voltage regulation.
   2. Saves distribution losses.
   3. Saves feeder copper.
   4. Smaller real estate and buildings.

B. Determination of loads and load centers. (In laying out plans of system, several schemes should be considered. Refer to published data. See A. E. R. A. Eng. *Proceedings* as example for railway work).
   1. Survey and analysis of load requirements.
   2. Spot load centers.
   3. Scheme and type of machine. (See "Machines" under F.)
   4. Spare units or portable substation.

C. Economic study.
   1. Determination of total investment and annual charges for the several schemes, including transmission, conversion, and distribution.
   2. Calculation and tabulation of losses.
   3. Considerations of factors such as:
      a. Ratio of unit size to total capacity.
      b. Desirability of multiple unit stations.
      c. Standardization on one size of unit.
      d. Availability of station site.
      e. Overhead or underground transmission and distribution.
      f. Electrolysis mitigation.
      g. Telephone and radio interference.
      h. Type of building.
   4. Decision based on combined study of economics and practical considerations.

D. Characteristics of system.
   1. Effect of a-c. conditions.
      a. A-c. line regulation should be within recommended limits. (See A. I. E. E. Standards.)
      b. Regulation may determine type of conversion unit employed.
   2. Agreement of efficiencies of equipment with service requirements.
   3. Effect of power factor on the power price rate.
   4. Amount and character of maintenance.

E. Transformers.
   1. Considerations in selection of power and auto-transformers.
      a. Installed cost.
      b. Weight—foundations.
      c. Space.
      d. Efficiency.
      e. Fire hazard.
      f. Type.
         (1) Single-phase.
         (2) Three-phase.
         (3) Spare.
      g. Method of cooling.
         (1) Air.
         (2) Oil.
         (3) Water.
      h. Windings.
         (1) High-voltage taps for regulation adjustments.
         (2) Low-voltage taps for starting equipment.
         (3) Tertiary windings.
         (4) Connections (Δ-Δ, Y-Y, etc.).

F. Machines.
   1. Synchronous converter.
      a. Needs stable a-c. supply.
      b. Inherently a unity power-factor machine.
      c. Usually needs no special equipment to parallel with other similar units.
      d. Inherently a fixed voltage machine except when of the booster type or equipped with other means of varying the a-c. supply voltage.
      e. May require brush operating mechanism.
   2. Steel tank mercury arc rectifier.
      a. Inherently a slightly lagging power-factor machine.
      b. Requires auxiliaries for
         (1) Vacuum system.
         (2) Temperature control.
      c. Needs no special equipment to parallel with other similar units.
      d. Inherently a fixed voltage machine except when equipped with separate means of varying the a-c. supply voltage.
   3. Synchronous motor generator.
      a. May operate at leading or lagging power factor.
      b. Usually needs auxiliary apparatus to parallel with other similar units.
      c. Inherently a variable d-c. voltage machine.
      d. Generator may be provided with separate excitation.
   4. Induction motor-generator.
      a. Inherently a lagging power-factor machine.
      b. Usually needs auxiliary apparatus to parallel with other similar units.
      c. Inherently a variable d-c. voltage machine.
      d. Generator may be provided with separate excitation.

In choosing the type of unit, consider:
   (1) Installed cost.
   (2) Weight—foundations.
   (3) Space.

*Contributed by C. Lichtenberg and M. E. Reagan.

(4) Efficiency.
(5) Ventilation and cooling means.
(6) Fitting machine characteristics to the service.
(7) Noise.
(8) Stability of a-c. supply.
(9) Service reliability.
(a) Heating.
(b) Commutation.
(c) Sensitivity to short circuits, etc.
(10) Safety features.
(11) Power-factor correction.
(12) Indoor or outdoor.
(13) Fly-wheel effect.
(14) Amortisseur windings.
(15) Amount and character of maintenance.

5. A-c. generator.
a. Vertical or horizontal.
b. Speed (rev. per min.).
c. Synchronous or induction.
d. Exciting systems.
(1) Individual exciter per unit.
(2) Common exciter for all units.
(3) Exciter bus.
(4) Type of exciter drive.
(a) Direct connected.
(b) Belted.
(c) Geared.
(d) Motor.
(e) Auxiliary prime mover.
e. Voltage regulation.
(1) Fixed field.
(2) Voltage regulator.
(a) Individual regulator for each unit.
(b) Common regulator.
f. Brakes.
(1) Oil operated.
(2) Air operated.
(3) Water operated.

6. Synchronous condenser.
a. Self-cooled.
b. Enclosed.
c. Water cooled.
d. Hydrogen cooled.

7. Rotating machine accessories.
a. Bearing thermal relay.
b. Synchronous speed device.
c. Grounding protective relay.
d. Overspeed device.
e. Rheostats.
(1) Hand operated.
(2) Electrically operated.

G. Switching Equipment.

1. Control power. (In general the source of control power chosen should be a reliable source obtainable at minimum cost.)
a. A-c. control: Particularly applicable to less complicated installations. Generally simplest and most inexpensive, making use of control battery and associated charging equipment unnecessary. Special features may be necessary to incorporate in control in order to prevent momentary shut-down on voltage dips.
b. A-c. and d-c. operation with tripping battery: Simple and inexpensive arrangement for average installations but requiring a certain amount of battery equipment. Recommended minimum tripping battery voltage is 48.
c. D-c. operating and tripping battery: Generally ideal arrangement from control standpoint for more complicated stations but results in some additional complication and maintenance due to amount of battery equipment required.
d. D-c. with pneumatically operated main circuit devices: Special adaptation used for railway service which has advantage of using standard, pneumatically operated devices used in car equipments, but has the disadvantage of requiring a continuous supply of compressed air and compound equipment.

2. The arrangement and construction of the a-c. bus and mounting of the oil circuit breakers may be of any of the following types:
a. Indoor.
(1) Safety enclosed trucks.
(2) Indoor metal clad.
(3) Cubicles.
(4) Masonry or brick cells.
(5) Welded or riveted angle iron framework.
(6) Pipe framework.
b. Outdoor.
(1) Outdoor metal clad.
(2) Outdoor oil circuit breakers.
(3) Switchhouses.
(4) Welded or riveted angle iron framework.
(5) Pipe framework.

The choice of the above is governed by the following considerations:

a. Installed cost.
b. Station construction and arrangement.
(1) Floor space.
(2) Head room.
(3) Time available for initial installation.
(4) Self contained unit construction.
(5) Future additions.
(6) Adaptability to move to new installations.
c. Operating features.
(1) Phase isolation.
(2) Circuit isolation.
(3) Interchangeability of units.
(4) Readily removable feature.
(5) Test position of breaker.
(6) Grounding and testing arrangement for breaker.

3. A-c. incoming lines.
a. Two or more lines for reliability.
(1) Parallel lines.
(2) Preferred emergency.
(a) Synchronous sources.
(b) Non-synchronous sources.
(c) Non-preferential sources.
b. Trip on unbalance, low voltage, reverse power, etc.
c. Reclose on reestablished voltage.

4. A-c. feeders.
a. Stub-end feed.
(1) Trip on overcurrent.
(2) Reclose periodically a definite number of times with time delay.
b. Multiple stub feed.
(1) Trip on overcurrent, reverse power, etc.
(2) Reclose periodically a definite number of times with time delay.

(3) Automatic synchronism check and automatic synchronizing.

5. D-c. feeders.
   a. Stub feed and stub-multiple feed.
      (1) Trip on overcurrent, undervoltage or short circuit.
      (2) Reclose after time delay on reestablished normal conditions.
      (3) Ratings and reclosing values.

H. Methods of starting machines.
1. Transformer taps.
2. Starting compensator (two- or three-step).
   a. Short-time rating.
   b. Oil or air cooled.
3. Star-delta.
   a. Extended windings.
4. Series reactor.
   a. Short-time rating.
   b. Oil or air cooled.
   c. Per cent normal starting current.
5. Full voltage.
   a. Per cent normal starting current.

I. Protection. (For table of minimum protection refer to A. I. E. E. Standards No. 26.)

J. Metering. (For table of minimum metering refer to table in this report.)

K. Station construction.
1. Site available.
2. Facilities for installing.
3. Temporary or permanent station.
4. Portable station.
5. Type and number of units.
6. Provision for future units or addition.
7. Heating requirements.
8. Noise-proofing.
9. Architectural harmony.
10. Ventilation. (See automatic Subcommittee Report on above subject.)

L. Inspection and maintenance. (Refer to Automatic Substation Maintenance which forms a part of this report.)

II. Automatic railway substations

A. Characteristics.
1. Choice of d-c. voltage (600-1500-3000).
2. Rising, flat, or drooping machine characteristic.
3. Ability to withstand frequent short circuits.

E. Starting and stopping indications.
1. Low-voltage starting and undercurrent stopping.
2. Overcurrent starting for additional units.
3. Time switch.
4. Supervisory control.

III. Automatic Mining Substations.

A. Characteristics.
1. Choice of d-c. voltage (275-550).
2. Rising, flat, or drooping machine characteristics.
3. Ability to withstand frequent short circuits.

B. Starting and stopping indication.
1. Local or remote control.
2. Overcurrent starting for additional units.
3. Time switch.

IV. Automatic synchronous condensers.

A. Characteristics.
1. Quantity of corrective kv-a. needed (leading and lagging).
2. Excitation systems.
   a. Direct-connected exciter.
   b. Voltage regulator.
   c. High-speed excitation.
3. Means for reducing starting kv-a.
   a. Bearing oil pressure.
   b. Starting motor.

B. Starting and stopping indications.
1. Start on high and low voltage and stop on undercurrent.
2. Power factor starting.
3. Time switch.
4. Supervisory control.

V. Hydroelectric generating stations.

A. Types of prime movers.
1. Reaction turbines.
2. Impulse turbines.
3. Propellor type turbines.
   a. Hand adjusted.
   b. Automatically adjusted.
4. Vertical or horizontal.

B. Hydraulic control.
1. Servo-motor without speed-head.
   a. Oil operated.
   b. Water operated.
   c. Electrically operated.
2. Governor.
   a. Speed-head drive.
      (1). Motor
      (2). Belt
      (3). Gear.
   b. Starting and stopping device. (63s).
   c. Synchronizing motor.
   d. Limit stop motor.
   e. Accelerating device.
   f. Position switches.
   g. Latch for closed gate.
   h. Automatic oil pressure system.
   i. Miscellaneous valves, by passes and drains.

C. Starting and stopping indications.
1. Float switch.
2. Frequency relay start and underload stop.
3. Time switch.
4. Supervisory control.

D. Method of synchronizing.
1. Self-synchronizing.
   a. Ratio of unit to system size.
   b. Amortisseur windings.
2. Automatic synchronizing.
   a. Reasonable speed control at no load.

VI. Automatic lighting substations.

A. Characteristics.
1. Two- or three-wire (250-125).
2. Method of voltage regulation.
   a. Pilot wire from load centers.
   b. Reenergizing dead system.
3. Balancer sets.

B. Starting and stopping indications.
1. Low-voltage starting and undercurrent stopping.
2. Overcurrent starting for additional units.
3. Time switch.
4. Supervisory control.

VII. Automatic a-c. substations.

A. Starting and stopping indications.
1. First unit in service continuously.
2. Overcurrent starting and undercurrent stopping for additional units.

VIII. Street lighting circuits.

A. Types.
1. Series.
2. Multiple.

B. Types of control.
  1. Time clock.
  2. Resonant remote audio frequency system (500 cycles).
  3. Carrier current system.

IX. Automatic d-c. industrial substations.
A. Characteristics.
  1. Two-wire 250-volt.
  2. Method of voltage regulation.
    a. Constant bus voltage.
    b. Ability to withstand short circuits.
B. Starting and stopping indications.
  1. Local or remote control.
  2. Overcurrent starting of additional units.
  3. Time switch.

X. Automatic battery charging equipments.
A. Characteristics.
  1. Choice of voltages (to suit battery).
  2. Types.
    a. Motor-generator.
    b. Static rectifiers.
    c. Station bus.
B. Methods of charging.
  1. Trickle charge.
  2. Floating charge.
C. Starting and stopping.
  1. Continuous operation.
  2. Start and stop with main unit.

XI. Supervisory control.
A. Characteristics.
  1. Supervisory control systems employed to operate and obtain remote supervision of equipment located at a greater distance than it would be economical to carry individual wires for each device.
  2. Control wires.
    a. Construction.
      (1) Overhead.
      (2) Underground.
    b. Type of conductor.
      (1) Individual conductor.
      (2) Multi-conductor cable.
    c. Inductive interference.
    d. Ground detector.
    e. Suitable resistance and insulation.
    f. Duplicate sets of wires.
  3. Storage battery.
    a. Charging equipment.
    b. Ungrounded usually.
  4. Control equipment.
    a. Control keys arranged in form of system diagram on dispatcher's board.
    b. Interposing relays.
    c. Alarm lamps.
  5. General.
    a. Audible or visual indications.
    b. Alarm to signify any apparatus change.
    c. Indication showing equipment to which line wires are connected.
    d. Remote metering.
    e. Remote synchronizing.

## Automatic Substation Maintenance

The advent of the automatic substation has brought about a change in maintenance and maintenance methods. The work has become more or less specialized, and a different type of man is required to care for this type of station. The amount of maintenance and inspection necessary to keep the equipment in proper operating condition varies with the type of equipment and its application, and with the local conditions. It is quite obvious that a hydroelectric station located away from the dirt of the city will not require nearly so much cleaning and blowing out as a railway converter station located on a busy street in the heart of the city. It is also evident that the more complicated stations will require more maintenance work than the simpler type.

This advice is based upon maintenance experience in railway converter stations and all charts and schedules cover this type of equipment. Maintenance of other types of equipment, however, parallel the railway type very closely and the only variation will be in the type of charts used and the amount of maintenance necessary.

It is assumed that the operating company has a competent crew of maintenance men well versed in general maintenace practises and thoroughly familiar with the sequence of operation of the stations which will be placed in their care. These men may be broken up into two groups—the inspectors and the regular maintenance crew. The inspectors should be men who have proved themselves especially adept in working out the causes of trouble and visualizing the conditions which could produce the troubles which they are to locate and cure. The inspector should visit the stations every two or three days, depending upon the severity of service, and make a casual inspection of the equipment. This casual inspection should consist of reading meters, taking readings on operation indicators, checking oil levels and giving the station a visual check throughout. The inspector should also be charged with the investigation of any troubles which may arise in the operation and should have complete charge of the testing and calibrating of all protective devices.

The members of the maintenance crew should be trained maintenance men and helpers working in pairs, the maintenance man doing all the inspecting and adjusting and the helper handling the air hose and taking care of the brushes and wiping down the equipment. The frequency with which this maintenance crew visits the stations will depend entirely upon the severity of the service on the station and also upon local conditions regarding dust and dirt. In general, however, it is found that a thorough blowing out and cleaning up accompanied by a general inspection about every two weeks is sufficient. It must be understood, however, that this is only a general average and that this amount of work must be increased or decreased according to the individual needs of the station.

The type of inspection reports and charts varies with the individual operating company, but in general, they all follow the same lines. There are two general forms of inspection charts in common use. One type is merely a numerical list of the devices with suitable blank spaces to be filled in by the workman. This report is very much in detail and calls for answers of the "Yes" and

"No" variety and has a slight tendency to destroy the individuality of the maintenance man; in general, it is better to let the maintenance man use his own judgment as to cotter pins, contacts, and general mechanical conditions of the various devices. Another disadvantage in this report is that with the various devices listed in numerical order, it means that to follow the report down from top to bottom, the maintenace man must keep moving from one piece of equipment to another, numerically and not according to physical location, and unless the report is followed very closely, some pieces of apparatus may be missed.

The type of inspection report or chart shown in Fig. 1 consists of a general plan of substation, with the switchboard placed flat on the floor. All pieces of equipment are shown in their relative positions by small numbered squares and the inspector or maintenace man using this chart may start at one end of the switchboard and check each panel as he goes. A common practise is to have the maintenance man use different colored pencils for checking off the equipment which he has inspected and cleaned. In this manner, if one man checks a certain panel upon which trouble is found later, he can be held accountable for not having discovered and eliminated the trouble on his previous inspection. This type of chart is also useful in that the superintendent of substations, in looking over these reports, can pick out at a glance, the devices that have caused trouble, as this is indicated by a "T" placed in the square representing the device. If the inspector or maintenance man has checked the device and found it o. k., he so indicates by a check mark in the square; but if he finds that there is trouble in this particular piece of apparatus, he places a "T" in the square, turns the inspection report over, indicating the device number, describing the nature of the trouble and what was done to remedy it. This makes a quick and convenient method of locating troubles on the chart and does not necessitate the reading of all of the details.

It is impossible to give any definite instructions regarding the amount of maintenace work necessary to keep a chain of automatic substations in the proper operating condition, as the quantity of the work is entirely dependent upon the severity of the service to which the equipment is subjected and also upon the local conditions regarding dirt, dust, dampness, etc. However, it will be found from six to eight months' experience in caring for a chain of automatic stations, just how much individual maintenance each station will require, and a schedule may be arranged accordingly.

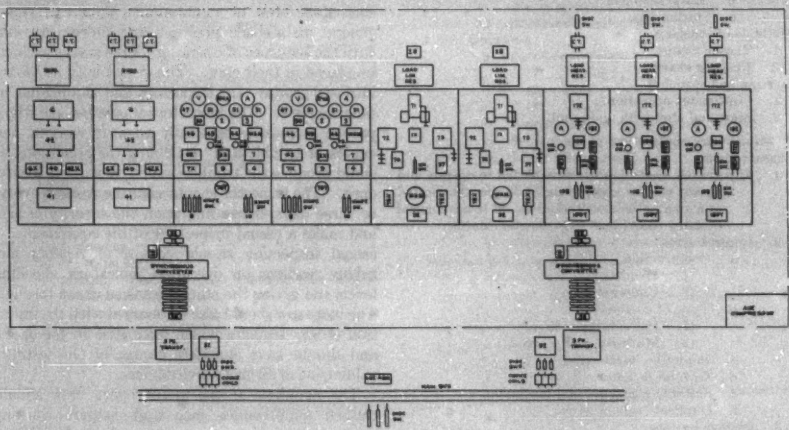

Fig. 1—Substation Inspection Chart

In addition to the regular maintenace work of inspecting, cleaning, and blowing out, there is a certain amount of routine testing and inspection that should be laid out and followed carefully over each year's period of operation. This type of work consists of the testing and calibrating of the various protective devices, the maintenance and inspection of bearings, and the testing of transformer oil. A sample schedule for work of this kind is given below; and while it must be understood that this schedule will not apply to all applications, it can nevertheless be used as a basis for starting an inspection and testing program:

D-c. reverse-current relays, and a-c. reverse power and machine overspeed: Test and calibrate every six months.

D-c. overload, a-c. reverse phase, and low voltage: Test and calibrate every six months.

Bearings of converters and auxiliary rotating equipment: Change oil and flush reservoirs every six months. Take out and inspect converter and motor-generator set bearings once a year, and touch up spots that show signs of slipping or cutting.

Transformer oil: Samples of oil from the oil insulated transformers should be taken every six months and tested for dielectric strength by actual test with an oil testing transformer. If the oil tests low, it should either be changed at once or else run through a dehydrating machine.

Oil in oil breakers: The amount of attention which the oil breakers in a station require is solely dependent upon the number of operations per day and the severity of the loads which they interrupt. For that reason, no *hard and fast rule* can be applied to the number of inspections required. In general, however, it may be said that the oil should be changed and the contacts inspected and adjusted every three to six months. In case the breaker does not perform very many operations it is often possible to extend this period considerably, but this can be proved only by experience.

Thermostats, grid resistance and bearing: Since they operate around 100 deg. cent., bearing thermostats are very easily tested by placing them in a deep pot of oil heated by a Bunsen burner or tinner's furnace. Grid thermostats, however, present a different problem as their operating temperature is usually around 300 deg. cent. This prohibits the use of oil, as it will boil below that temperature. However, a very inexpensive furnace for testing these thermostats may be made similar to that shown in Fig. 2.

This oven is merely a heavy sheet-iron cone, lined with asbestos and designed to fit over the top of an ordinary tinner's stove. Suspended from the closed top of this cone is another sheet-iron cone of smaller dimensions which forms a chamber for heating up the bulb of the grid thermostat, at the same time keeping it away from the direct flame of the tinner's stove. Small openings are left in the outside cone to carry away the flame and gases. The inner chamber maintains practically an even temperature, so that readings obtained from the thermometer will be equivalent to the temperature to which the grid thermostat bulb is subjected. The grid thermostats and bearing thermostats are probably the most abused of any of the protective devices in an automatic substation because, due to the difficulty of testing them, inspectors and maintenance men often allow them to remain in an improperly calibrated condition for some time without discovering that they are out of calibration. For this reason, they should be tested at least every six months in order to insure the safeguarding of machine bearings and the load-limiting resistors.

Feeder resistance measuring relays: In most applications, it is sufficient to check the calibration of these relays every six months. This work is commonly accomplished by the use of a resistance capable of carrying the measuring current and equal to the resistance of the load upon which it is desired to reclose.

The remaining protective devices can be checked during the general inspection and cleaning-up period; no special time for this work is necessary.

Insulation tests should be made on the station equipment every six months. By insulation test is meant that all control wiring, all high-voltage bus work, and all electrical apparatus should be subjected to an insulation test with a megger. In addition, on all 600-volt installations, the switchboard risers and supports should be tested for grounds and also for potential. The same applies to the cast-iron framework which supports the grid resistors. Occasionally a bank of grid resistors will be found which has broken down its insulation and

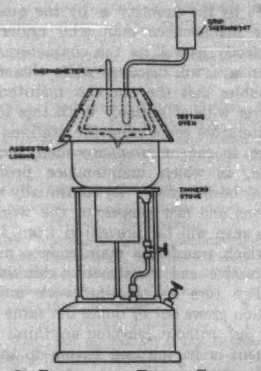


Fig. 2—Furnace for Testing Thermostats

placed potential on the cast iron end frames. This is a dangerous condition, since workmen may accidentally ground these end frames and cause a bad burn-out. The subjecting of the control wiring to an insulation test often discloses some peculiar condition which would not have been discovered except through the medium of serious trouble. The use of a megger on the control wiring will often disclose minor grounds caused by collections of copper and carbon along wiring and equipment which at the time of inspection could cause no trouble but might at some future time develop into an arcing ground or short circuit which would cause serious damage. When these faults in control wiring exist an elimination process should be started by taking off connections and progressing slowly down the control wiring until the fault is located. This can be accomplished by following the schematic diagram and checking off the points as they are disconnected and cleared.

If they are to find troubles quickly and properly adjust the various relays, it is essential that the

inspectors and maintenance men be supplied with the proper instruments. A set of meters is useful for this purpose. These meters are compact and may be carried in a small leather carrying case. One is a d-c. voltammeter with the following ranges: 0-15, 0-150 volts with external resistor for 600 volts, and 0-3, 0-15 amperes. The other is a triple-scale a-c. voltmeter 0-150, 0-300, and 0-600 a-c. volts. Instruments of this kind can easily be carried from station to station and will always be available for testing and inspection work. Furthermore, the fact that the maintenance men have these instruments available will lead them to investigate immediately any condition which may not seem exactly right to them, while if it is necessary to secure the proper instruments from headquarters to investigate the condition, the chances are that it will be postponed and forgotten.

Automatic substations maintenance should be judged not so much by the quantity as by the quality of the work. The maintenance man who understands his station perfectly, as well as the characteristics of the individual relays, will discover while cleaning up the station troubles that the average maintenance man will pass over without notice. With this in mind, all available literature concerning the stations should be turned over to the maintenance men, and frequent classes held, in which maintenance problems and methods may be discussed. By continually bringing up new problems and new phases of the work in these classes, the men will be prevented from falling into that rut which transforms maintenance men from a state of creative and constructive thinking into one in which they turn out routine work mechanically. This condition grows out of doing the same work, day in and day out, without learning anything new about the equipment or having any reason to think deeply about its scheme or operation.

So long as the work is instructive and the men are learning through the medium of their experience in the stations, the quality of the maintenance work will be found to be of high degree, but as soon as this drops into a slow, grinding routine, a let-down in the quality of the inspection and the maintenance will be apparent.

## Bibliography

In order to provide additional information for those interested, it has been the practise of this Committee to publish each year a bibliography on automatic stations. This has been done again this year and the list has been brought up to the year 1930. This bibliography is attached to this report as Appendix No. 1.

## APPENDIX NO. 1

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TABLE OF MINIMUM INSTRUMENT AND METERING EQUIPMENT

| | Syn. converter | | | Syn. motor-generator | | Gen. | Cond. | Rect. | Trans. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rwy. 600-volt | Edison 250-volt | Mining and industrial | Edison 250-volt | Mining and indus. | Syn. hydro. | syn. | Merc. | Static | A-C feeders | Balancer sets | Syn. motor |
| A-c. ammeter | | | X§ | X | X | X | X | | X* | X* | | X |
| A-c. voltmeter | | | | | | X | X | | | | | |
| Reactive volt-ammeter | X | X | X§ | | | | | | | | | |
| Field ammeter | | | | X | X | X | X | | | | | X |
| Main d-c. ammeter | X | X | X | X | X | | | X | | | X‡ | |
| Main d-c. voltmeter | X | X | X | X | X | | | X | | | X† | |

*Single ammeter with three-phase switch or three-phase ammeter.
†To read full d-c. voltage and voltage from either side to neutral.
‡With zero center scale in neutral.
§Either one.

1. Contributed by Main Library of the General Electric Co.

1929

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# Electrical Communication

## ANNUAL REPORT OF THE COMMITTEE ON COMMUNICATION*

*To the Board of Directors:*

This Committee supervised the preparation of quite a number of papers during the year, among them being fifteen papers on technical subjects which were finally presented to the membership during the Winter and Summer Conventions. Over two hundred communication papers on various subjects were presented before the A. I. E. E. in the different sections of the country during this period.

The various branches of electrical communication engineering have made considerable progress during the year as is indicated by a summary of the principal developments referred to in the following report:

### Telephone Service Improvements

During the year 1929, considerable progress was made in improving telephone service and extending its scope. The growth in the number of telephones in the United States was approximately 900,000, the largest number for any one year, representing an increase of about 4.6 per cent. The total number of telephones by the end of 1929 was approximately 20,230,000. The number of daily toll conversations increased 9.5 per cent to a total of about 3,520,000.

The acceleration in the use of telephone service by the public has been accompanied by increased programs of construction of telephone plant and equipment involving an increase in expenditure of approximately $445,000,000 or 11.8 per cent in investment during the year.

As a result of the efforts of operating and staff organization there has been improvement in local exchange telephone service. The telephone companies have opened schools for the instruction of private branch exchange switchboard operators who are the employees of subscribers. Since about one-fifth of all telephones receive service through private branch exchanges, this plan seems well justified. In addition, the operating companies are supplying an increasing number of experienced operators for private branch exchanges.

Mechanical and electrical troubles have been reduced a measurable extent and the handling of information calls has been improved by means of better equipment and improved methods.

The introduction of improved operating practises and facilities, permitting the use of simplified methods of operation similar to those employed for local business, has substantially speeded up the handling of toll service. More recently, as a further step in realizing improvements in the quality of the toll service as a whole, and particularly between widely separated points, there has been developed a general basic routing plan designed to offer the highest practicable standards of service as regards the speed, accuracy and transmission efficiency in the handling of toll messages. This plan, known as the General Toll Switching Plan, provides essentially for the basic layout and design of the toll plant in a manner which will limit the number of switches required in routing toll calls and provide generally improved transmission standards for toll connections.

### Telephone Plant

The extension of toll cable continued even more rapidly during 1929 than for the previous year. Approximately 3700 miles of loaded inter-city cable were added to the system together with about 1300 miles of short-haul toll cable, making a total of 5000 miles for the year and a total of toll cable both long- and short-haul for the United States of about 20,000 miles. The greater part of this mileage is in the north-eastern section of the country, but extensions are being made rapidly in the south and west. Continuous cable plant now extends from Bath, Maine, to Charlotte, North Carolina, and westward over several routes as far as Iowa City, Iowa. An extensive mileage in operation on the Pacific Coast has been made continuous from San Francisco to Fresno. About 74 per cent of the toll wire mileage is now in cable as compared with 53 per cent five years ago. These cables, which carry about 300 telephone circuits and as many telegraph circuits, for the so-called full-sized cable, are loaded at intervals of about a mile, while repeater stations are placed about 50 miles apart.

Some of these long distance cables have been placed underground while others are suspended aerially. There are many situations where the aerial type of construction satisfactorily meets requirements and it is not so expensive as the use of conduit with manholes at regular intervals. Recently there have been introduced in this country two methods for securing more economically the advantages of the underground cable where the rate of growth does not require the frequent placing of additional cables. In one of these methods a cable, protected by means of impregnated paper, jute, and steel tape covering, is buried in the ground without

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*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.*

conduit. In the second method a single fiber conduit is laid and the lead covered cable is drawn into it. In both these new methods manholes are placed only at points where loading coils are to be inserted. This results in the reduction of the number of manholes as compared to previous practise from about eight per loading section to only one.

In the application of these new methods special trench digging and filling machines are employed and under certain conditions a tractor plow has been effective in opening a trench.

Pressure testing of cable with gas to indicate leaks in the sheath is now coming into general use in connection with the installation and maintenance of toll cables.

A special high-speed cable delivery truck for use on private right-of-way has been developed to replace caterpillar type tractors and trailers formerly used for this purpose. Interesting features of this truck are four-wheel drive and two sets of tires for each wheel. One set of tires for the front wheels is smaller than the other and does not come in contact with a hard road surface, thus insuring easy steering in driving on highways. Under the most difficult conditions the speed of the truck is approximately 10 miles per hour compared with about 2 miles per hour for the tractor and trailer. On the road the truck has a speed of about 30 miles per hour.

### Telephone Equipment and Circuits

The use of currents of frequencies below the voice range, for calling or ringing, permits economical types of apparatus at the terminals of the circuits but requires means for relaying the signals at each intermediate repeater station. Voice-frequency signaling eliminates this relaying apparatus, and its use on toll circuits has been extended recently by the development of improved equipment for the purpose. This new equipment employs signaling current so small that the interference into neighboring circuits is negligible and provides a degree of selectivity such as practically to eliminate false operation. The new equipment is being applied on the majority of toll circuits having one or more intermediate repeaters with consequent economy in equipment and reduction in maintenance.

The increased demand for toll service has required a corresponding increase in the size of circuit groups between cities and the extension of toll circuits over greater distances, many of these new circuits being in cable. With this increase in the number of toll circuits, improvements in testing arrangements followed, and a new type of test and control board has been developed. This provides for concentrating the toll circuit apparatus before plant attendants, in the same way as at the switchboard, together with more efficient and precise testing facilities for locating faults. Other features of the new arrangements provide for circuit flexibility to care for changes in traffic loads and plant failures and in automatic indication of circuit status for the traffic and plant supervisors.

### Dial System Service and Equipment

The growth of dial system service in the United States during 1929 was rapid and is represented by an increase of dial telephones of approximately 850,000 or 24.3 per cent. Approximately 21½ per cent of the total telephones in the United States are now operated on the dial basis.

An interesting development in connection with tandem equipment of the panel type for such cities as New York, Chicago, and Boston is a new call announcer which speaks the number to the manual operators, using the same general principles of sound recording and reproduction by film as are employed for talking motion pictures. A narrow beam of light is passed through a film record of the voice to a photoelectric cell. The machine consists of 14 individual speech channels corresponding to the 10 digits and 4-party letters. These give a constant repetition of each numeral or letter with a silent interval. Connection is made automatically and in succession to the proper speech channels to make up the number wanted, the switching from one channel to the next taking place in the silent interval. The machine is common to an office and will facilitate extension of the tandem method to the more distant manual suburban offices.

### Telephone Circuits in Radio Broadcasting

The use of telephone circuits for connecting long chains of radio broadcasting stations continued to increase during the past year. On March 4, 1929, during the inauguration of President Hoover, more than 30,000 miles of telephone program circuits carried the ceremonies to 118 broadcasting stations in all parts of the country, making the occasion the largest chain broadcast that has ever occurred. The exercises were also heard by many listeners in different countries through short-wave transmission.

### Carrier Telephone Systems

The rapid extension of carrier telephone facilities throughout the United States continued during 1929. The increase in number of channel miles in service was approximately 135,000, or 57 per cent.

### Transoceanic Telephony

The development of international telephony during the past two or three years has proceeded with such astounding rapidity that about 87 per cent of the world's telephones are now interconnected by the aid of transoceanic radio telephony.

During the year a further rapid development occurred in the use made of and in the facilities provided for transatlantic telephone service. The previously existing facilities of one long-wave circuit and one short-wave circuit have been supplemented by two additional short-wave circuits, making a group of four circuits

functioning to interconnect the continental wire telephone networks of North America and Europe.

At the Winter Convention there was presented a group of four papers under the general subject of Transoceanic Telephone Service which discussed, in some detail, these new short-wave facilities and their relation to the older facilities.

Two important extensions of international commercial telephone service during the year were the opening of service between Madrid and Buenos Aires on October 12, 1929, and between New York and Buenos Aires on April 3, 1930. These additional short-wave radio telephone systems have made possible the connection of the telephone networks of Europe and of North America with those of Argentina, Uruguay, and Chile and should be an important factor in influencing commercial and political relations between the continents.

### Ship-to-Shore Telephone Service

Experiments of ship-to-shore radio telephony, which have been made from time to time since 1920, resulted in commercial service from the United States to the *S. S. Leviathan* on December 8, 1929, and from Great Britain to the *S. S. Majestic* in the middle of February, 1930. Experiments have also been made with other ships and it is expected that commercial service will be extended as fast as the necessary ship installations can be made.

This ship-to-shore service is being given in the short-wave range and requires the provision of a number of wavelengths for covering the different distances and different conditions due to time of day.

The coastal transmitting and receiving stations in the United States are located on the New Jersey coast, about 60 miles south of New York, the transmitter at Ocean Gate and the receiver at Forked River. Pending the completion of the transmitting station, a station located at Deal Beach, New Jersey, is being employed. These stations are connected with New York by wire line and the technical control of the circuit, as well as the traffic operation, takes place in the long-distance telephone building in New York.

### Telephone Communication with Airplanes

The Bell Telephone Laboratories has for some time been conducting experimental and development work on the difficult problem of two-way telephone communication between airplanes and the ground. In this work two airplanes are employed which are equipped with apparatus designed to make accurate measurements and tests while the plane is in the air. Tests have shown that satisfactory two-way telephony is possible between airplanes and practically any telephone connected with the United States. In several of the tests commercially satisfactory communication was maintained between an airplane here and telephone stations in Europe. This involved radio transmission from the airplane to the Bell Telephone wire system in the United States, the transatlantic radio and the regular telephone wire system in Europe.

Largely as a result of this work two-way radio telephony for plane-to-ground communication has advanced to the point where commercial apparatus is now becoming available and regular transport planes of several lines will soon be equipped with it. This should add greatly to the safety and reliability of air transportation. In addition to the pilot receiving weather and landing conditions reports and other data, he can in return keep the dispatcher informed of his position and of the weather conditions along the airway.

### International Technical Conference on Radio

The fact that in radio the nations of the world share a common transmitting medium makes it important that there be international understanding on the technical standards which are to be met in order to minimize interference. There occurred at the Hague last September the first meeting of a newly organized international technical committee, known as the International Technical Consulting Committee on Radio Communication, or, more briefly, the CCIR. The meeting was attended by some two hundred government and company technical experts from the principal nations of the world.

The findings of the committee are purely advisory, but will undoubtedly have weight throughout the world, since they represent the best world opinion obtainable upon the subject. Without going into the details, it is interesting to note that constructive proposals were adopted upon the following subjects: (1) methods for comparing the frequency standards of the different nations; (2) accuracy with which stations should be expected to hold to their frequencies; (3) the frequency intervals at which stations should be assigned.

### Radio Telegraph

Commercial marine radio service was established at New York City and Sayville, L. I., with ships at sea on May 15, employing modern short-wave service as well as the usual intermediate and long-wave lengths. An additional marine station has just been completed near West Palm Beach, Florida, and was opened to general public service on February 28.

Commercial transcontinental radio telegraph service connecting the Atlantic and the Pacific Coasts was inaugurated on November 15. This service not only joins the ship-to-shore services centering at San Francisco and New York City, but also extends the Pacific Coast point-to-point and Honolulu radio circuits to New York, connecting with radio telegraph services already established, to South America and those contemplated.

An additional commercial transoceanic radio telegraph service was established between New York and Lima, Peru, on December 11. This service is conducted jointly by the Mackay Radio and Telegraph Company, operating at Sayville, L. I., and the All American Cables, Inc., operating at Lima, Peru.

### Carrier Telegraph Systems

The past year has witnessed a rapid growth in the application of carrier telegraph in this country. Approximately 200,000 channel miles of carrier telegraph have been placed in service, representing an increase of about 44 per cent for the year.

Progress has been made during the year in increasing the number of carrier telegraph channels which it is possible to obtain from both open-wire and cable circuits. Furthermore, carrier telegraph and carrier telephone systems have been combined in a way to provide considerable flexibility in obtaining different ratios in the number of telephone and telegraph channels which it is possible to obtain from a given group of line circuits.

For open-wire lines suitable for the transmission of carrier frequencies, trials are under way which indicate that the number of carrier telegraph channels which it is possible to obtain from one pair of wires may be increased from 10 to a maximum of 36. One pair of wires may also provide a combination of one carrier telephone channel and 24 carrier telegraph channels, or two carrier telephone channels and 12 carrier telegraph channels.

There was a continued increase in the application of carrier current telephony and telegraphy for the efficient use of existing plants in America and Europe, especially in Spain, France, and Italy, Australia and other localities. In Australia and New Zealand notable advances have been made in carrier current communication where the great distances are peculiarly adapted to this type of operation.

### Cable Telegraphy

The Western Union Telegraph Company successfully completed duplexing experiments at Bay Roberts, Newfoundland, on the Bay Roberts-Horta, and on the Azores duplex loaded cable, the development and laying of which were noted in the 1929 report. A duplex balance was obtained satisfactory for operation at 1400 letters per minute. This is somewhat higher than the speed for which the cable was designed and is several times as high as the duplex speed of any previous long cable. An ultimate speed greater than 1400 letters in each direction is possible. The artificial line for balancing the cable, as well as the cable itself, is of unusual design, in that in addition to matching the inductive loading of the cable, it was also necessary to take into account various factors which are neglected in balancing for low speed operation.

A severe earthquake was registered on most of the seismographs of the world on the afternoon of Monday, November 18, 1929, which was the cause of ten submarine telegraph cables off the east coast of North America being severed. Nearly all were broken at more than one point. The location of the epicenter, as determined from earthquake records, was given by the Dominion Observatory, Ottawa, as 44° 30′ North Latitude 57° 15′ West Longitude, and the time 3.32 : 8 p. m. Eastern Standard Time. Some of the breaks did not occur at the time of the earthquake, but several hours later which would seem to indicate that there were further tremors. No less than eight cable repair ships were immediately dispatched to make the necessary repairs. Fortunately the cable companies have duplicate cables and alternate routes so international communications were not affected to any great extent.

### Airways Communications

The San Francisco-Los Angeles weather reporting network established last year on an experimental basis through cooperation of the Weather Bureau, the Daniel Guggenheim Fund for the Promotion of Aeronautics, and the Pacific Telephone and Telegraph Company, has since been taken over by the Airway Division of the Department of Commerce. Through the cooperation of the Department of Commerce and the telephone companies, similar systems have been established along the New York-Chicago airway. An even more extensive system has been put in operation for the Transcontinental Air-Transport along its air-rail route across the continent. In these systems, telephone typewriter circuits connect the meteorological collection and distribution centers. This information is relayed to planes in the air by means of radio telephone apparatus.

### Printing Telegraphy

During the past year, over one hundred of the concentration equipments for printing telegraph circuits mentioned in the last year's report have been scheduled for installation and at least ten are already in operation. The operating economies expected from the use of the concentrators have been more than realized.

The increase in the number of telephone typewriters used in the Bell System was very marked during the past year. Approximately 7000 machines were added, representing a growth of about 140 per cent during the year. The number of circuit miles used in telephone typewriter service has increased by approximately 280,000 or 64 per cent during the year. The difference in the rate of growth between telephone typewriters and circuit miles is due to the rapid growth of the telephone typewriter service in local areas, where the connecting circuits average only about five miles each.

Recently, experimental telephone typewriter exchange service was installed in telephone company offices in New York, Boston, Chicago, and some adjacent cities, and the practicability of this type of commercial service was demonstrated. Telephone typewriter instruments are in a large measure as adaptable as telephone instruments and can be interconnected through special switchboards in much the same manner. A subscriber, wishing to be connected to another one in the same city or in a distant city, communicates with a switchboard operator using his telephone typewriter, and the operator makes the connection to and signals the called subscriber. After the called subscriber answers, messages are passed between the subscriber

in much the same manner as over a telephone system, except that a written record is obtained at both stations. Arrangements can also be made so that one station can be connected to a number of others and broadcast information to them.

In the private branch exchange field, a number of different types of installations of telephone typewriter switching systems were made. Several automobile manufacturing companies, for example, have found these systems very efficient for production control in their factories and warehouses. Another example is the installation used by the credit bureau of one of our large cities.

### Automatic Stock Quotation Boards

The past year has seen the introduction on a fairly wide commercial basis of automatic stock quotation boards in brokers' offices for electrically recording market prices. Some of these boards are controlled from a central point over telegraph circuits; others are operated locally from keyboards installed in each broker's office. One type of board is designed to display the last dozen or more sales so as to indicate the trend of the market.

On May 21, 1929, the first Teleregister type of automatic stock quotation board was placed in service in a broker's office in New York City. Since that time the demand for this service has been so great that within nine months approximately 20 per cent of the board rooms in New York City were receiving automatic service of some form.

With this particular type of equipment, all boards in a city or in a zone which may have a radius of several hundred miles are operated from a central transmitting station.

### Mechanical Conveyers for Telegrams

A new type of conveyer wherein the telegram is carried on its edge on a moving belt in a narrow trough has been developed by the Western Union Telegraph Company for collecting telegrams from operating positions in large offices. This conveyer is called a "V Belt Conveyer" and takes its name from the shape of the trough in which the messages are carried. The belt runs along the back edge of the operating table and is readily accessible to the operator for depositing received telegrams thereon; a series of V belts carry the telegrams to a central point where the messages are routed to outgoing wires.

### Municipal and Protective Signaling

There has been considerable extension of electrical traffic signals. The newer devices show a decided shift toward the "New Jersey" cycle, green, amber, red, green.

In congested districts there has been a considerable increase in progressive signals. With these a vehicle starting at one end of a street protected with a green light may travel through to the end without being delayed by a red light provided speed is kept within predetermined limits. There has also been a considerable increase in signals controlled by the vehicle. These are set to show green normally on the more traveled route and are reversed by vehicles running over a switch or magnet in the street. These have not yet been made satisfactory for congested districts since they do not make suitable provision for pedestrians, but improvements are being made to overcome this and other disadvantages.

The most important change in municipal fire alarm systems during the past year is a tendency to adopt improved current supply arrangements. One such type of arrangement is the single battery with trickle charger using copper oxide rectifiers or similar charging devices in place of duplicate batteries charged alternately by motor generators. Another type of improvement is the sealed type storage cell which is rapidly replacing the loose top cell. Similar improvements are being adopted for police signal systems.

The use of telephone typewriter systems by police organizations has gained headway. There are more than ten such systems now in service, including installations for the New York City police organization and the Pennsylvania State Police, each containing as many as 100 telephone typewriter stations.

### Television

During the year there has been extensive progress in fundamental development.

This has included work on the application of television both to wire and radio systems. Television in colors was first demonstrated last June over a short wire circuit. This employs a new type of photo-electric cell responsive to all the colors of the visible spectrum, an improvement on the former type, which was sensitive only at the blue-green end. Special argon tubes combined with neon tubes previously used, together with color filters and new arrangements of apparatus, are employed. Moving as well as stationary objects can be clearly seen in their natural colors.

### Sound Pictures

The growth in the use of sound picture systems in theaters continued and sound projection equipment is now universally applied in important motion picture theaters In the recording field improvements have been made in sound quality as the result of improved pickup devices, by refinements of electrical circuits, by better optical systems in the case of film recording, and refinements in photographic processes for handling films. Rerecording has become quite general in studio practise and special rerecording equipment has been developed. Both disk and film methods of sound recording continue in favor with the producers.

In projection, improvements in sound quality have resulted from improved optical systems and pick-up devices, and improved loudspeakers and driving mechanisms generally. Acoustic treatment of theaters to

secure better conditions for sound projection in theaters are found to be substantially different from those for direct audition in assembly halls.

A paper describing the technique and apparatus of sound picture recording and reproduction entitled *The Electrical Engineering of Sound Picture Systems* was presented at the Pacific Coast convention, at Santa Monica, California, September, 1929, by Messrs. K. F. Morgan and T. E. Shea.[1]

## Foreign Telephone and Telegraph Matters of Interest

While the Communication Committee has made no complete record of communication developments in other countries, the following items which have been brought to the attention of the Committee are believed to be of interest:

In Europe, in 1929, 25 new international long-distance circuits were put into service between places not previously connected with each other. In some cases, there were services between two cities, in other cases between some principal city in one country and numerous cities in another country, and in other cases, numerous cities in two countries. This, the most rapid expansion of international long distance telephony which has ever taken place in Europe in one year, was made possible by the underground cables which have been laid within the last four years, during which period the number of important European cities connected internationally increased from 17 in 1925 to 76 up to the middle of 1929. The increase in service has been accompanied by a corresponding improvement in quality of transmission, and in density of traffic.

The Anglo-Polish service was extended into Poland to Cracow, Lodz, Poznan, and other towns. The Lodz exchange was connected by long distance with the Swiss telephone system. Nine additional departments of France were given telephone service with Switzerland so that the whole of that country, with the exception of Corsica, is now connected with the Swiss network. In addition, telephone communication between Copenhagen, Genoa, Milan, and Turin has been established via Switzerland.

Telephone service between Great Britain and Finland, Paris and Finland, Rome and London, Switzerland and Italy, Hungary and Denmark, and Hungary and Poland is now available. Service between Stockholm and Reval, Esthonia, via Helsingfors, Finland, has also been established.

In October, 1929, telephone service was opened between two of the Canary Islands (Gran Canaria and Teneriffe) over a submarine cable nearly 40 nautical miles in length. This is a single-core, non-loaded cable with a copper tape return and is designed for the ultimate operation of six two-way carrier telephone channels in addition to the voice frequency channel and a direct-current telegraph circuit. The cable is in some places nearly 2 miles below the surface of the ocean.

A 20-nautical-mile telephone cable was laid between Algeciras, Spain, and Ceuta, Morocco, to supplement the cable placed between these points in 1924. This cable is designed for one telegraph circuit, one voice frequency telephone and six carrier telephone channels.

A 12-quad non-loaded cable, 37 nautical miles in length, was placed between Buenos Aires, Argentina, and Colonia, Uruguay. This cable is operated on a 4-wire basis in connection with 2-wire open-wire circuits from Colonia to Montevideo. The pairs have been equalized to 5000 cycles which has made it possible to secure very satisfactory results in broadcasting from Montevideo opera and other programs given at Buenos Aires.

In September, the new underground Paris-Lyon-Marseilles telephone cable was opened for service. It is 800 km. long and contains 130 circuits. In October, the new Italian underground cable linking Naples with Florence was inaugurated. The year also saw the underground telephone cable between Vienna and Graz extended to the Jugoslavian frontier, and the new East Prussian submarine cable laid between Leba and Pillau.

The Czechoslovakian Government during the year placed an order for a 120-kw. broadcasting station at Prague. So far as is known, this is the largest station which has been planned up to the present time in Europe.

1. A. I. E. E, Trans., Vol. 49, January 1930, pp. 105-116.

# Electrical Machinery

## ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL MACHINERY*

*To the Board of Directors:*

The Committee on Electrical Machinery takes pleasure in submitting the following report on its work during the past year. The report is divided into two sections, the first dealing with organization and policies, and the second with the progress of the art.

### Part I.—Organization and Policies

The Electrical Machinery Committee is organized with five permanent subcommittees, with the following memberships:

SUBCOMMITTEE ON SYNCHRONOUS MACHINERY

S. L. Henderson, Chairman, B. L. Barns, C. M. Gilt, C. F. Harding, J. A. Johnson, H. C. Louis, O. K. Marti, A. M. Rossman, O. E. Shirley, R. B. Williamson.

SUBCOMMITTEE ON TRANSFORMERS

V. M. Montsinger, Chairman, Raymond Bailey, W. H. Cooney, W. M. Dann, J. A. Johnson, H. C. Louis, J. H. Paget, J. F. Peters, Philip Sporn.

SUBCOMMITTEE ON INDUCTION MACHINES

H. B. Dwight, Chairman, A. B. Craig, J. L. Hamilton, C. J. Koch, F. Miller, C. A. Price, O. C. Schoenfeld.

SUBCOMMITTEE ON D. C. MACHINES

H. L. Zabriskie, Chairman, J. Bourath, J. L. Burnham, H. B. Dwight, Jesse B. Lunsford, A. M. MacCutcheon, E. P. Nelson, R. W. Owens, W. H. Powell, W. I. Slichter, J. G. Tarboux.

SUBCOMMITTEE ON MERCURY ARC RECTIFIERS

E. L. Moreland, Chairman, H. L. Andrews, L. D. Bale, A. E. Bettis, H. D. Braley, O. K. Marti, E. B. Paine, D. W. Proebstel, E. B. Shand, H. C. Sutton.

ANNUAL REPORT

C. M. Gilt.

The Committee has dealt with two principal subjects, standards and papers.

STANDARDS

During the year the Committee has studied many proposed changes in the existing A. I. E. E. Standards, and has recommended to the Standards Committee the adoption of alterations and additions relative to the following subjects or paragraph numbers:

*Standard No. 5: D-C. Rotating Machines, Generators and Motors*

A new definition of a two winding synchronous converter.

Revisions of paragraphs 5-356 (a) and 5-367 (a) relating to field rheostat losses.

*Standard No. 7: Alternators, Synchronous Motors and Synchronous Machines in General*

New definitions as follows:
Synchronous Reactance
Potier Reactance
Resistance Drop
Potier Reactance Drop
Potier Impedance Drop
Electrical Degree
Short Circuit Ratio
Terminal Voltage
Induced Voltage
Excited Voltage
Distortion Factor

A new paragraph relating to a method of calculation of field current at full load.

Revisions of paragraphs 7-457 (a), 7-461 (a), and 7-474 (a) relating to field rheostat losses.

*Standard No. 9: Induction Motors and Induction Machines in General*

New paragraphs relating to:
Allowable Voltage Unbalance
Definition of Breakdown Torque
Definition of Power Factor
Methods of Determining Power Factor

Revisions of:

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| Pars. 9-62 | relating to slip |
| 9-68 | relating to definitions of protected machines |
| 9-250 | relating to break-down torque |
| 9-301 | footnote relating to conventional efficiency |
| 9-310 (b) | relating to $I^2 R$ losses in the rotor |
| 9-312 | relating to brush contact loss |
| 9-313 | footnote relating to stray load losses. |

*Standard No. 13: Transformers, Induction Regulators and Reactors*

Six new definitions of types of cooling.

Revisions of paragraphs 13-1, 13-215, 13-250, 13-400, 13-402, and 13-408.

*Standard for Capacitors.* A new standard for capacitors has been prepared and recommended to the Standards Committee for printing in report form.

The Committee desires very much to secure the early adoption of "American Standards" for all of the classes of electrical machinery, and its work on standards is all directed toward this end. At the present time, the only complete machinery standard, within the purview of this Committee, that has been approved as "American Standard" by the A. S. A. is that on synchronous

*COMMITTEE ON ELECTRICAL MACHINERY:

P. L. Alger, Chairman,
E. B. Paxton, Secretary,

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| L. F. Adams, | C. F. Harding, | L. W. McCullough, |
| B. L. Barns, | S. L. Henderson, | V. M. Montsinger, |
| W. M. Dann, | L. F. Hickernell, | E. L. Moreland, |
| H. B. Dwight, | J. Allen Johnson, | F. D. Newbury, |
| W. J. Foster, | H. C. Louis, | R. W. Owens, |
| C. M. Gilt, | A. M. MacCutcheon, | A. M. Rossman, |
| W. S. Gorsuch, | O. K. Marti, | R. B. Williamson, |
| A. L. Harding, | | H. L. Zabriskie. |

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

converters, but the parts dealing with rating of Standards Nos. 5, 7, and 9 have also been approved as "American Standard." The complexity of the present organization for approving these standards, and the large number of interests that must be consulted before agreement can be secured, have made progress slow, but the recent organization of a new sectional committee on Rotating Electrical Machinery is expected to facilitate matters. This new sectional committee will be responsible for the preparation of "American Standards" on all types of rotating electrical machinery, and the Committee on Electrical Machinery is actively cooperating with it.

A number of questions in regard to standards of the International Electrotechnical Commission have been referred to the committee, and reports have been made to the Advisors on Rating of the U. S. National Committee of the I. E. C. Every effort is being made to promote agreement between the I. E. C. and the American Standards.

A series of test codes for induction, direct-current, and synchronous machines and transformers is under preparation by the Committee. These codes will give explicit directions for making performance tests on electrical machinery, so that electrical tests (especially those on combined equipments, such as waterwheel generators, motor driven pumps, etc.) can be performed in a uniform way.

### Papers

An important function of the Committee is to sponsor papers on electrical machinery, that will bring out discussion on new developments, and will properly record the progress of the art. During the past year, over 50 machinery papers have been submitted to the committee for review, and 34 have been actually presented at Institute Conventions, including twelve proposed for the 1930 Summer Convention.

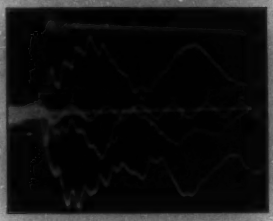
There has been an increasing number of papers available during the past few years, and the need for more time for presenting, and space for recording, these papers is pressing. The Committee would like to sponsor symposiums on several aspects of electrical machinery developments during the next year or two, such as stray load losses, motor insulation, mechanical design, lightning protection of apparatus direct connected to transmission lines, reactance definitions and short circuit calculations, and mercury arc rectifiers. At the present time, the papers spontaneously submitted to the Institute occupy most of the available time at Conventions, so that there is little opportunity to develop such symposiums. The Committee, therefore, recommends that parallel sessions be held at conventions, that more papers be accepted for presentation, and that responsibility for abridging the papers and discussions to conform with the publication policies of the Institute be delegated to the committee chairmen.

## Part II—Resume of Progress of the Art

### Transformers

Investigations into internal voltages in transformers have been actively continued during the year. The creation of high internal oscillations by lightning and switching surges of different kinds which were previously observed by sphere-gaps have been confirmed in the past year by the use of the cathode ray oscillograph. Fig. 1 shows oscillograms taken by the General

A



B

Fig. 1—Voltage Oscillations in Grounded Transformers

a. Core type b. Shell type

Wave No 1 Applied voltage
Wave No. 2 At point 50 per cent from neutral end of the winding
Wave No. 4 At point 26 per cent from neutral end of the winding
Wave No. 5 At point 78 per cent from neutral end of the winding
Wave No. 3 Timing

Electric Company on ordinary core and shell types of power transformers. Fig. 2 shows oscillograms taken by the Westinghouse Company on a 140-kv. shell type power transformer. Fig. 3 shows oscillograms taken by the General Electric Company on a power transformer of the non-resonating type.

The use of equipment for changing the ratio of transformers without interrupting the load has been extended and equipment for doing this has become largely standardized and manufactured on a quantity production basis. Improvements in simplicity and sturdiness have been made.

The recent development of the General Electric Company consists of three salient parts:

1. Two heavy ratio adjusters for 9 or 11 ratios with

an intermittent gear of high mechanical precision for turning first one and then another ratio adjuster to the next position.

2. Two oil-immersed, cam-operated contactors designed to remove the load from each ratio adjuster in succession during a change in ratio.

3. A motor operated driving mechanism including the position indicators, limit switch, and control devices.

All transformer connections are oil immersed and are so arranged that the reactance of the circuit is the same

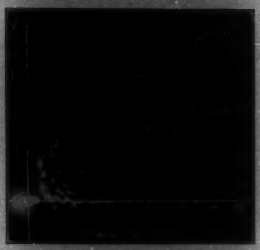


FIG. 2—OSCILLOGRAMS TAKEN BY THE WESTINGHOUSE E. & M. CO. ON A 140-KV. SHELL TYPE POWER TRANSFORMER

I Oscillations with an extremely long wave
II Oscillations with a long wave
III Oscillations with a short wave
IV Oscillations with chopped surges

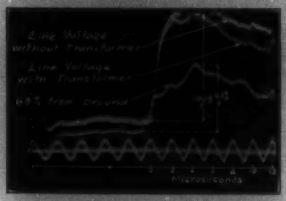



FIG. 3—NON-RESONATING TRANSFORMER

1. Voltage wave at the end of transmission line with transformer disconnected.
2 Voltage wave at the end of the transmission line with transformer connected (voltage across transformer)
3. Voltage at 63 per cent point. Crest value 63 per cent of applied voltage
Note No. 3 a practical duplicate of the shape of No. 2 in spite of the fact that the transformer was out of oil and electrostatic unbalance was created thereby

in all positions resulting in equal voltage steps. Simplicity with a minimum of connections outside the transformer tank have been the object of the design.

Fig. 4 illustrates an interesting application of up-to-date load ratio control as applied to a 20,000-kv-a., single-phase, water-cooled transformer with two secondary windings. Each winding is equipped with load ratio control for supplying individual busses. There are six of these transformers installed by the Buffalo General Electric Company forming two 60,000-kv-a. banks which were supplied by the General Electric Company.

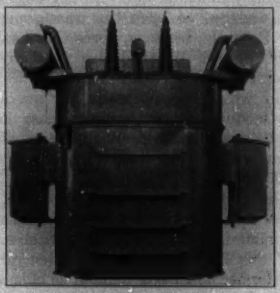


FIG. 4—A 20,000-KV-A. SINGLE-PHASE WATER COOLED, LOAD RATIO CONTROL TRANSFORMER

Built by General Electric Co. for the Buffalo General Electric Co.

A difficult problem in load ratio control was met by

the Westinghouse Company by means of a separate regulating transformer and two of their UB tap changers and a reversing switch. The transformers are used for the operation of electrical furnaces, the largest of this type constructed in this country, and are rated 6500-kv-a. single-phase, 25 cycles, 12,000/45 volts with a low voltage current of 180,000 amperes at 1¼ load. By means of the load ratio control, the secondary voltage may be varied from 30 to 60 volts in steps of approximately ½ volt each.

The use of pothead transformers, in which cables are

Fig. 5—A 60,000 Kv-a. Single-Phase Transformer

Built by Westinghouse E. & M. Co. for the Roseland Switching Station of the Public Service Electric & Gas Co.

brought into a pothead without external bushings, has increased, and many potheads have been equipped with internally mounted disconnecting switches which were not designed to open the transformer exciting current. Recently, however, three transformers have been built by the Westinghouse Company for the Public Service Lighting Commission of the City of Detroit in which the potheads are provided with internally mounted disconnecting switches designed to interrupt the transformer exciting current. The transformers are rated 2000-kv-a., three-phase, 60-cycles, 24,000/600-volts.

A number of transformers have been built with two secondaries having a high reactance between them in order to minimize the effect of disturbances. An example of this is the 100,000-kv-a. General Electric auto-transformer now being built to be connected to a 12,500-volt generator on the primary side with two secondaries rated 24,500 Y. On account of the unbalanced load conditions that may exist, the equivalent two winding capacity is 58,000 kv-a.

Among the notable transformer installations of the year are four Westinghouse single-phase, 60-cycle units installed in Roseland Switching Station of the Public Service Electric and Gas Company. Each transformer has four separate windings rated at 30,000, 15,000, 15,000 and 20,000 kv-a., self-cooled. The design permits the addition of forced air cooling equipment to obtain 50 per cent higher ratings. On the basis of half the sum of these forced air-cooled ratings the units are equivalent to 60,000-kv-a., two-coil transformers. The windings are for connection to lines at 220,000 volts star, 132,000 volts star, 132,000 volts star, and 11,000 volts delta. The weight of each transformer as shipped is 270,000 lb. and was the heaviest individual unit shipped on a single railroad car.

During the year the maximum size of transformers for use with mercury arc rectifiers has shown considerable increase. A number of 3000-kw. units have been built and one of 6500 kw. for a 650-volt rectifier is now being constructed by the General Electric Company. A new method of compounding has been developed by this company which results in more desirable voltage characteristics and causes the rectifier to function at practically unity power factor at normal load.

Transformers grounded through reactors are subject to high voltages at the neutral when lightning or switch-

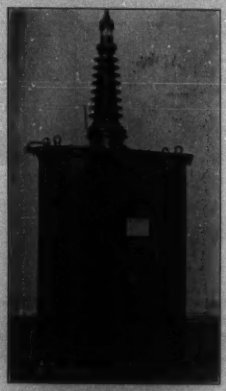


Fig. 6—Neutral Impedor

Developed by General Electric Co. to limit the voltage from transformer neutrals to ground

ing surges are applied to the line terminals. The General Electric Company has developed a grounding device called the "Neutral Impedor" for use with transformers when grounded with reactors or resistance. This device limits the voltage from neutral to ground to a predetermined value. In case such an impedor is used with a non-resonating transformer, the transient voltage distributes uniformly along the transformer winding. During the last year and a half nearly 800,000 kv-a. of transformers of non-resonating type have been built so that they can be operated with the impedor in the neutral.

Four 25,000-kv-a., 220-kv., single-phase transformers were recently shipped to the Southern California

Edison Company from the Westinghouse factory and are designed for grounding the neutral by means of a reactor. The design limits the maximum voltage of the neutral to 73 kv. above ground during a fault between line and ground. By the use of such a transformer and reactor the ground faults can be limited to a reasonably low value and the cost of installation is less than that required for transformers insulated for full voltage in both terminals.

Last year's report mentioned a standard single-phase "substation" designed for taking small power from a high-voltage line. Fig. 7 illustrates an expansion of the idea brought out by the General Electric Company to supply 150-kv-a., three-phase from a 110-kv. line.

The Brown Boveri Company has developed an interesting high-voltage potential transformer in which the core and coils are mounted in a hollow insulating bushing between a metal top and a grounded metal

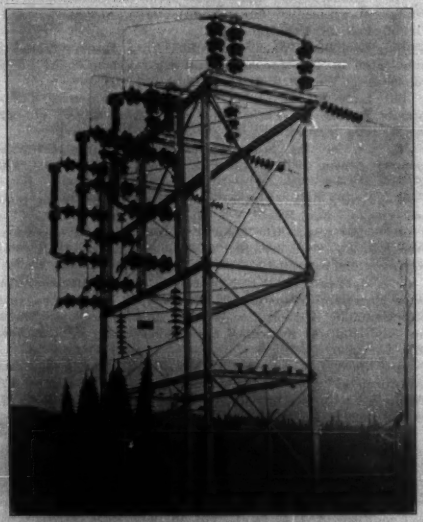


Fig. 7—150-Kv-a. 110,000-Volt Three-Phase Unit Design Outdoor Station

With type RA-1 disconnecting switch, combined fusible cut-out and current-limiting resistor, three, 50-kv-a. single-phase transformers, low-voltage switch house and steel structure. View from side of tower.

bottom tank, with the primary leads connected to the cover and bottom tank.

An interesting metering transformer combination has been supplied to the Allied Power and Light Company by the Westinghouse Company for use on a 154-kv., 60-cycle system which consists of three double secondary transformers and a three-phase open delta connected voltage transformer. The extra current transformers

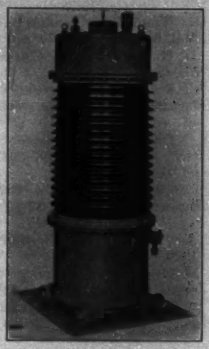


Fig. 8—150-Kv. Brown Boveri Potential Transformer with Insulation Casing

and double secondaries provide a double check and the potential transformer connection is equivalent to the use of a single-phase unit across two of the phases.

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## Synchronous Machinery

The increasing use of fabricated construction of rolled and welded steel members has continued and is becoming more and more universal except for standardized designs in which duplicate castings are used in large quantities. The so-called "dished" steel-plate end-shields have been applied to several large synchronous motors, hydrogen-cooled condensers, and marine motors. The General Electric Company has developed a line of bearing pedestals to harmonize with the appearance of the fabricated construction and has modified the design of the oil wells so that the rings operate completely enclosed, practically eliminating the escape of oil vapor. The bearing construction has been modified to secure more uniform distribution of the pressure.

The year 1928 saw a large increase in the kv-a. capacity of water wheel generators while the size of turbo-generators stayed about the same. The past year has seen the reverse process in which the capacity of single shaft turbo-generators has been increased to 166,666 kv-a. The interest in outdoor rotating machinery has increased and several of this type have been built or are in the process of construction. The successful experience with hydrogen-cooled condensers has been continued and more machines of this type are under construction.

*Hydraulic Generators.* The following is a list of some of the more interesting hydraulic driven generators installed or being built during the past year:

| Purchaser | No. | Kv-a. | Speed | Manufacturer |
|---|---|---|---|---|
| Dnieprostroy Hydroelectric Dev. | 4 | 77,500 | 88.2 r.p.m. | General Electric |
| Sao Paulo Tramways | 1 | 55,000 | 360 " | " " |
| New York Power and Light Co. | 1 | 47,000 | 81.8 " | " " |
| Aluminum Co. of America | 2 | 45,000 | 150 " | Westinghouse |
| Carolina Power & Light Co. | 3 | 45,000 | 400 " | " |
| Lexington Power Company | 4 | 40,625 | 138 " | " |
| New England Power Company | 4 | 39,000 | 138 " | " |
| City of Seattle | 1 | 33,000 | 257 " | " |
| Arkansas Power & Light Co. | 2 | 31,111 | 94.7 " | Allis Chalmers |
| Portland Oregon Electric Power Co. | 1 | 30,000 | 514 " | General Electric |
| City of Tacoma | 2 | 30,000 | 300 " | Allis Chalmers |
| Alabama Power Co. | 2 | 29,000 | 100 " | Westinghouse |
| Central Maine Power Co. | 2 | 26,667 | 138.5 " | General Electric |
| Montana Power Co. | 2 | 25,000 | 81.8 " | Westinghouse |

The 55,000-kv-a., 360-rev. per min. machine which is being built by the General Electric Company is the largest horizontal water-wheel generator which has been built up to the present time. The 47,000-kv-a., 81.8-rev. per min. generator is a vertical unit of the over-hung type with the guide and thrust bearings located together beneath the rotor.

The machines for the Lexington Power Co., New England Power Co., and the Montana Power Co., built by Westinghouse are all of the over-hung type.

The 31,111-kv-a. generator being built by the Allis Chalmers Company is also the over-hung type. The stator is of welded plate and the rotor spider is made of cast steel in four segments. The poles are bolted to the spider and the arms are shrouded to reduce windage loss.

The Brown Boveri Company has built a vertical 20,000 kv-a., 250-rev. per min. machine which is particularly interesting in that it is capable of supplying the same rated output at either 50 or 16⅔ cycles at the same speed. When operating to produce 50 cycles, the spider is provided with 24 poles dovetailed into one slot each and when delivering 16⅔ cycles there are 8 poles fitting two dovetails with an empty slot between each two poles.

Fig. 9—Upper Bearing Bracket of 77,500-Kv-a. General Electric Water Wheel Generator for Dnieprostroy Hydro-Electric Development, Russia

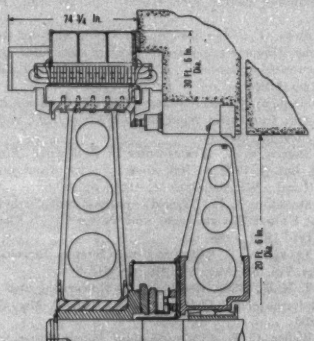


Fig. 10—Cross-Section Sketch of Allis Chalmers Co's. 31,111-Kv-a. Overhung Type Hydraulic Machine

Built for Arkansas Power & Light Company

*Steam Turbine Generators.* The size of single shaft units has increased until now the General Electric Company is building a 166,666-kv-a., 1800-rev. per min., single-shaft turbo-generator for the State Line Generating Company and the 160,000-kv-a., 1500-rev. per min., 25-cycle, single-shaft, turbo-generator built by the same company is operating in the East River

station of the New York Edison Company. The 235,000-kv-a., three-shaft generator at the State Line Plant at Chicago was placed in operation during the year.

The Allis Chalmers Company is building a 115,000-kw., 18,000-volt, 1800-rev. per min., single-shaft generator

Fig. 11—235,000-Kv-a. Three-Shaft Generator Built by the General Electric Co. for the State Line Plant of Chicago

for the Waukegan Station of the Public Service Company of Northern Illinois. The rotor is a single forging and is one of the largest yet undertaken; rough-turned; the weight is 240,000 lb. On these extremely large, long generators, external motor driven fans are being used so as to keep the span between the bearings as short as possible.

Fig. 12—240,000 Lb. Single Forging for the 115,000-Kw. Generator Rotor Being Built by the Allis Chalmers Co.

An interesting development in turbo generators has been the vertical compound type of installation developed to reduce floor space. The largest of these is that installed at the Ford Motor Company consisting of two units, each running at 1800-rev. per min. with a total capacity of 124,911 kv-a. Two units of this type are being furnished the Pacific Gas and Electric Company by the General Electric Company in which the low pressure unit operates at 1800-rev. per min. and the high pressure at 3600-rev. per min. and with a total capacity of 50,000-kv-a. Two similar machines are being furnished the Jersey Central Power and Light Company by the General Electric Company with a total capacity of 31,250 kv-a.

The Westinghouse Company has increased the size of 3600-rev. per min. units to 18,750 kv-a. Three of these machines are being built for the Louisiana Steel Products Company and two for the Virginia Public Service Company. These generators are equipped with special propeller type fans mounted on the shaft.

The Westinghouse Company has been able to make an interesting factory test on two duplicate turbo generators of 68,800-kv-a. capacity built for the Duke Power Company. The test included a "pump-back"

Fig. 13—25,000-Kw. General Electric Vertical Compound Steam Turbine Generator for the Jersey Central Power & Light Co., Being Assembled for Test

loading at 0.8 power factor full load and substantiated the present A. I. E. E. Standards which use the short circuit losses as equivalent to the load losses at full voltage and full load.

Voltage of 22,000 has thus far proved efficient, and there are five General Electric generators at this voltage which have been in successful operation for periods varying from several months to one and one-half years. Two 116,600-kv-a. and one 166,666-kv-a. generators are being built for 22,000 volts.

The use of the double winding generator is being extended and there are now 768,333 kv-a. of double winding generators of General Electric manufacture in operation or in the course of construction.

*Synchronous Motors.* The use of synchronous motors has been extended to include band saws, fans and blowers, and flour mills. The General Electric Company is now building one 3000-hp., 124-rev. per min., compressor motor which is believed to be the largest motor for this service undertaken so far. The two largest diameter synchronous motors are 25 ft.

in diameter and are supplied by the Westinghouse Company to the Columbia Steel Company for driving a billet mill and a sheet bar mill. The motors are rated 5000 hp., 82 rev. per min. at 2300 volts and when started at full voltage the starting torque is 95 per cent

Fig. 14—View in Westinghouse Shops Showing "Pump Back" Test of Two Duplicate Generators of 68,800 Kv-a. Capacity

with 330 per cent current in-rush. The torque of pull-in is 40 per cent and the pull-out is 220 per cent. The Westinghouse Company is building an 1800-hp., 150-rev. per min. motor for a piercing mill of a seamless tube

Fig. 15—The Largest Diameter Synchronous Motor. It Drives a Sheet Bar Mill for the Columbia Steel Co.

plant which develops a pull-out torque at 350 per cent of normal load.

There seems to be an increasing demand for high speed synchronous motors and the Allis Chalmers Company has recently built a 500-hp., 3600-rev. per min. motor for driving a pump. The construction of this is similar to that of a turbo generator except for special features to provide adequate starting.

The General Electric Company has built some synchronous motors with two circuits, one of which is left open when starting, to reduce the starting current when started at full voltage.

Dynamic braking has been applied for reducing the time of stopping. Some applications have been made in which the field circuit has been connected single circuit for running and two circuits parallel for stopping, giving the equivalent of double excitation during the braking period.

The Allis Chalmers Company has built a number of synchronous induction type motors for cement mill drive which give the advantage of high starting current and moderate line current during the starting period without clutches and give the advantages of the synchronous motor under normal running condition.

*Marine Synchronous Motors.* During the year the *SS. Pennsylvania* joined the *SS. Virginia* and *SS. California* in commercial operation. These 18-knot

Fig. 16—A 500-Hp., 3600 Rev. Per Min. Synchronous Motor Built by the Allis Chalmers Co.

vessels are each propelled by two 8500-hp., 120-rev. per min., self-starting synchronous motors. The Grace Line *SS. Santa Clara* was launched and will be equipped with two 6300-hp., 120-rev. per min., self-starting synchronous motors to drive the ship at 19 knots. Four 8000-hp., 143-rev. per min., self-starting synchronous motors were completed for the two Ward ships, *SS. Oriente* and *SS. Morro Castle.* The above equipment was furnished by the General Electric Company. Two ships are being built for the Dollar Line which will be the largest and highest powered of any ships built in the country for commercial service with electric drive. The General Electric Company will furnish the two 13,250-hp. synchronous motors for one ship and the Westinghouse will furnish the same drive for the other.

*Synchronous Condensers.* The Westinghouse Electric and Manufacturing Company have on order a 15,000-kv-a., hydrogen-cooled condenser for the Indiana and Michigan Electric Company and a 15,000-kv-a., hydrogen-cooled machine for the

Southern California Edison Company. The General Electric Company is building a 15,000-kv-a., 900-rev. per min., 24,000-volt, hydrogen-cooled condenser for the American Gas and Electric Company. There are now 32,500 kv-a. in hydrogen-cooled condensers of General Electric manufacture in operation and 75,000 kv-a. in construction. The largest size condensers now under construction include a 30,000-kv-a., 600-rev. per min. machine for the Public Service Electric and Power Company of New Jersey, a 30,000-kv-a., 600-rev. per min., 60-cycle unit for the Southern California Edison Company, being built by the General Electric Company, a 30,000-kv-a., 720-rev. per min. synchronous condenser being built by the Allis Chalmers Company, and one at 720-rev. per min. and two at 600 rev. per min. of the same capacity constructed by Westinghouse.

Fig. 17—The First of Two 25,000 Kv-a., 500-Rev. Per Min. Outdoor Condensers

Furnished the Toronto Leaside Station by the Canadian Westinghouse Co.

Fig. 18—3900-Kw., 13,000 Ampere Rotary Converter

Being built by Westinghouse Elec. & Mfg. Co. for Commonwealth Edison Co. of Chicago

The Canadian Westinghouse reports the installation of two 25,000-kv-a., 500-rev. per min. vertical outdoor synchronous condensers at the Toronto Leaside transformer station of the Hydro-Electric Power Commission of Ontario. These machines are of particular interest in that they are the first vertical shaft outdoor type condensers with the exciters suspended below the thrust bearing, which is located under the rotor.

*Frequency Converters.* The Westinghouse reports the installation of a second 40,000-kv-a. frequency changer of the synchronous-synchronous type for the Commonwealth Edison Company. The same manufacturer is building an 18,750-kv-a., 300-rev. per min. set for the Consumers Power Company to act as a tie-in between a 30-cycle and a 60-cycle system. It is expected that at a later date the machines may be split and each one used as a 60-cycle condenser. The 30-cycle end will then be operated with a rating of 35,000-kv-a. at 600 rev. per min.

The Toledo Edison Company has placed in operation a 35,000-kw., 300-rev. per min. General Electric synchronous-synchronous set having a 46,000-kv-a., 60-cycle, 13,500-volt motor and 41,176-kv-a., 25-cycle, 6750-volt generator.

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## D-C. MACHINES

The use of fabricated construction which has rapidly increased during the past few years has been more extensively applied to direct current machines of various sizes. The use of rolled-steel field yokes is practically universal in large sized machines.

Greater attention is being given by operating companies to ventilation of machines so as to prevent recirculation of air causing high ambient temperatures. The use of the volute housing in which the ventilation of the machine is used to force the heated air, through ducts, out of the building has been extended and the synchronous converters which the General Electric Company is constructing for the New York City Board of Transportation will be equipped with this type of ventilation.

*Synchronous Converters.* The largest 60-cycle converters for railway service, and the first to use 12 phase for this application, are under construction by the General Electric Company for the Board of Transportation of the City of New York. They will have a nominal rating of 4000 kw. at 625 volts with a 200 per cent rating for five minutes and 300 per cent rating for one minute. A 25-cycle converter for chemical work

Fig. 19—D-C. Motors Driving the 12-In. Hot-Strip Mill

The six 1250-hp. motors driving finishing stands are mounted on common bedplate. 4500-hp., 150/450 rev. per min. roughing mill motor in background. The Sharon Steel Hoop Co., Sharon, Pa.

having a current rating of 16,000 amperes for voltages from 270 to 340 is being built. It is believed that this is the largest current rating of a synchronous converter for the extremely high load factor commonly experienced in electrolytic work, although a similar machine was built several years ago for 17,000 amperes lighting service.

An extremely interesting development is a 3000-kv-a. 60-cycle 300-volt converter being built by the General Electric Company for hydrogen cooling. This machine is to be used in a chemical plant in which the complete enclosure with hydrogen cooling serves as a protection against fumes as well as secures the greater effectiveness of cooling. No operating information has been secured at this writing.

An example of the extensive use of fabricated construction is found in some 3900-kw. booster-type 60-cycle converters being built for the Commonwealth Edison Company of Chicago by the Westinghouse Company. With the exception of the pedestals, the entire machine is made of structural steel. The rolled frame and welded type of construction in the manufacture of the bedplate, commutator, spider and brush rigging can be seen in Fig. 18. The same fabricated type of construction is being used on two 5440-kw. 25-cycle field controlled converters built by the same manufacturer for the Roessler and Hasslacher Chemical Company of Niagara Falls.

*Generators and Motors.* The Westinghouse is now building a 10,000-hp. blooming-mill-drive involving a number of interesting features. The upper and lower rolls are each independently driven by a 5000-hp. motor, the pinion and pinion housing normally used to connect the upper and lower rolls being completely eliminated. The two motors are located at the same end of the mill giving improved efficiency, greater flexibility, and reduced first cost to the steel mill. The power for the drive is obtained from an induction motor-generator set having three d-c. generators operating in parallel.

The General Electric Company has built an equipment for a 12-in. hot-strip mill consisting of six 1250-hp. motors on a single base arranged on 8 ft. centers. Due to the wide range in basic speeds, from 103 to 312 rev. per min., double motors were used for three of the units.

An interesting motor-generator set has been built by the General Electric Company for the drive of a 7000-hp. and 1650-hp. reversing motor. The motor-generator set is built with three 2400-kw. generators designed to operate in parallel. Both the generators and the motors are equipped with special field windings and excitation control designed to give characteristics for a proper division of load as the five machines are connected to one bus.

*Exciters.* During 1929 there has been a definite trend toward providing large a-c. machines with individual exciters and a greater use of sub-exciters, that is, small exciters to provide separate excitation for the main exciters. Several large exciters for recent large turbo generators were provided with sub-exciters for mounting on the main turbine shaft. The advantages of the sub-exciter are lower losses, greater stability, and quick response.

Fig. 20—A General Electric 1500-Kw. Synchronous Motor, D-C. Generator Set with Volute Ventilating Housing

Where it is necessary to obtain low excitation voltage from exciters feeding a-c. generators which may be required to supply charging current to long transmission lines, differential shunt fields have been employed on the exciters. These fields are about 10 per cent as heavy as the main shunt fields and are separately excited which permits the exciter to operate below its normal residual voltage value. This is especially necessary where voltage regulators are used, as the operation of the regulator depends upon its swinging the voltage beyond

the average value which applies to the collector rings of the a-c. generators. By the use of the differential shunt fields the main rheostat can be entirely eliminated even when the excitation required is below that of the residual of the exciter.

For some machines, usually synchronous condensers, it is necessary to provide excitation voltage down to zero volts. The General Electric Company obtains this condition by providing a Wheatstone Bridge arrangement in the rheostat of the separately excited main field. With this arrangement, voltages down to zero and even in a reverse direction can be obtained without resorting to special field windings on the main exciter.

Ordinary a-c. generators when used with quick response excitation require an exciter voltage change of the order of 400 to 600 volts per second. This lower value of voltage change can be obtained with exciters without the use of laminated yokes.

In a quick response excitation system where voltage required from the exciter is greater than 750 to 1000 volts per second, eddy-currents in solid frames and in thick laminations in pole pieces materially retard the rate of change of voltage. To overcome this difficulty the Westinghouse Company has designed the exciter yoke of laminations held together by insulated end plates and the pole pieces are made of thin laminations held together by insulated rivets. This construction will permit speeds of response of from 3000 to 4000 volts per second. On one synchronous condenser installation made by the General Electric Company a maximum rate of rise on the main exciter was in excess of 7000 volts per second. These extremely high speeds are used at present on synchronous condensers only and then in only rare cases.

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## Induction Motors

One of the most significant developments of the year is the undertaking by the various manufacturers of this country, to produce a line of motors which will comply

A A

Fig. 21—The Crocker Wheeler Speed Changer (Two Views)

a. "C" type reducer viewed from high-speed side with covers removed
b. "C" type reducer view from low-speed side with covers removed

with the standardized mounting dimensions approved by the National Electric Manufacturers' Association. Some manufacturers are redesigning the motors electrically while dimensions are being changed. These new lines should appear on the market during the year 1930.

During the past year the developments of small induction motors has seen a more extensive application of totally enclosed motors, many of them being in the explosion-proof classification. The enclosed fan-cooled principle has been extended to larger motors; for

Fig. 22—Five Kw., 60/180-Cycle Single Unit Frequency Changer Eight Per Cent Regulation

example, the Louis Allis Company report the development of an explosion-proof self-ventilated motor which can be furnished in sizes up to 75 hp. and designed to withstand internal pressures up to 100 lb. per sq. in. The use of the enclosed fan-cooled motor is finding some application as a drive for fuel pulverizer mills. As an adjunct to the smaller line of induction motors the Crocker Wheeler Company has developed a new line of toothless speed changers which are reported to have an efficiency of 99 per cent at three-quarters load and 98½ per cent at full load.

The use of the capacitor motor has been extended, for some applications with the capacitor in service continuously and for others only during the starting operation. The General Electric Company has brought out single-phase capacitor motors for use in driving propeller type fans. By the use of a high resistance rotor the speed of the fan may be controlled by varying the applied voltage, as by means of taps on an autotransformer. The Electrical Machinery Company has put on the market a scheme of connecting a capacitor across the induction motor terminals during starting in order to reduce the kv-a. in-rush. After the motor is up to speed, the capacitor is disconnected from the line and is available for use in starting other motors.

For furnishing power to high speed hand tools a new type of single-unit frequency changer has been developed by the General Electric Company which is adaptable for a change of frequency from 60 to 180 cycles. It combines in a single unit the function of a frequency changer and a driving motor of the conventional two unit set. By eliminating the base, coupling, and driving motor the single unit frequency changer occupies a minimum of room.

The use of atwo circuit induction motor in which only one circuit is used for starting has been developed to reduce the current in-rush during starting.

The General Electric Company has built a 27,500-hp. induction motor which is part of a 20,000-kw. induction-synchronous frequency-changer set now in operation on the system of the Buffalo General Electric Company. Two similar sets are being built for the Union Electric Light and Power Company of St. Louis. The Canadian

FIG. 23—INDUCTION MOTOR FURNISHED THE WELLAND SHIP CANAL BY THE CANADIAN WESTINGHOUSE CO.

The top half of the frame may be removed to replace parts

Westinghouse Company is furnishing some 200-hp. motors for the Welland Ship Canal of rather special construction illustrated in Fig. 23. The object of the design is to make it possible to lift the top half of the frame and then remove the complete electrical and mechanical parts of the lower half so that spare parts could be quickly inserted in the frame.

Progress has been made in the application of polyphase adjustable speed a-c. motors for the needs of the textile industry; as an example, one manufac-

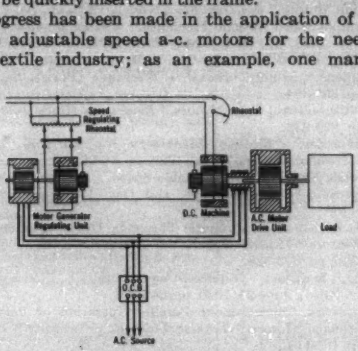


FIG. 24—DIAGRAM OF CONNECTIONS

turer has received an order for 2000 such commutator type motors having shunt characteristics and rated 3-hp. at 1650 rev. per min. maximum speed. The motors are to be used for driving full-fashioned hosiery knitting mills requiring close speed regulation and adjustable speed which is readily obtained by shifting the brush position.

A new scheme of speed control has been developed by Sargent and Lundy of Chicago, making use of an induction motor whose stator is connected rigidly to the armature of a d-c. motor and mounted on bearings so that it can be rotated. The d-c. motor may drive or be driven by a d-c. generator whose voltage is adjustable from maximum positive through zero to maximum negative so that the so-called stator may be rotated in either direction at any speed within its maximum limits. Those now in operation have been built to have a speed range of from 100 per cent to 40 per cent. The d-c. motor and generator may be only a small percentage of the total horsepower of the main motor as they supply only the difference in power required between the operating speed and synchronous speed. The capacity of the direct current machines now in operation is approximately 16 per cent of the induction motor rating.

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## Mercury Arc Rectifiers

Since January 1, 1929, a total of 78 mercury arc rectifiers sets with an aggregate rating of 179,900 kw. have been put in operation or on order in the United States and Canada. The largest part of this equipment is for railway service, but some will be used for other applications; for example, four large units each having a

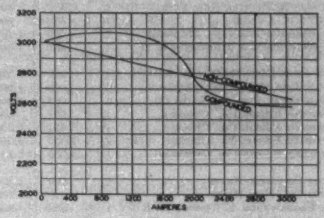


Fig. 25—Regulation Curves of Rectifiers for D. L. & W. R. R. Electrification

MERCURY ARC RECTIFIER UNITS INSTALLED OR ON ORDER IN THE UNITED STATES AND CANADA SINCE JANUARY 1, 1929

| Purchaser | No. of sets | D-c. volt | Kw. per set | Total kw. | Control | Service | Put in service | Manufacturer |
|---|---|---|---|---|---|---|---|---|
| American Gas & Electric, New York | 2 | 620 | 1,000 | 2,000 | Automatic | Railway | 1929 | Brown Boveri |
| American Gas & Electric, New York | 2 | 610 | 500 | 1,000 | Automatic | Railway | On order | Brown Boveri |
| Boston Elevated Railway | 2 | 600 | 3,000 | 6,000 | Automatic remote control | City | On order | General Electric |
| B. C. Electric Railway | 1 | 575 | 1,000 | 1,000 | Manual | Urban | 1929 | General Electric |
| Calgary, City of | 1 | 575 | 600 | 600 | Automatic | Railway portable | 1929 | Brown Boveri |
| Calgary, City of | 1 | 575 | 1,200 | 1,200 | Automatic | Railway | 1929 | Brown Boveri |
| Chicago & Joliet Electric Railway Co | 1 | 620 | 1,000 | 1,000 | Automatic | Interurban | 1929 | General Electric |
| Chile Exploration Co | 1 | 650 | 1,000 | 1,000 | Automatic | Heavy mine haulage | On order | General Electric |
| Columbus Railway Power & Light Co | 1 | 600 | 500 | 500 | Automatic | Urban | 1929 | General Electric |
| Columbus Railway Power & Light Co | 1 | 600 | 500 | 500 | Automatic remote control | Urban | 1929 | General Electric |
| Commonwealth Edison Co | 1 | 1,500 | 1,500 | 1,500 | Manual | Railway | Being erected | Brown Boveri |
| Commonwealth Edison Co | 2 | 600 | 3,000 | 6,000 | Automatic | Railway | 1929 | Brown Boveri |
| Commonwealth Edison Co | 4 | 625 | 3,000 | 12,000 | Manual | Railway | Being erected | Brown Boveri |
| Commonwealth Edison Co | 1 | 1,500 | 1,500 | 1,500 | Manual | Railway | Being erected | Brown Boveri |
| Commonwealth Edison Co | 3 | 625 | 3,000 | 9,000 | Manual | Railway | On order | Brown Boveri |
| Commonwealth Edison Co | 3 | 625 | 3,125 | 9,375 | Manual | Urban | On order | General Electric |
| Consolidated Mining & Smelting Co. of Canada | 3 | 460/560 | 5,600 | 16,800 | Manual | Electrolytic | 1929 | Brown Boveri |
| Consolidated Mining & Smelting Co. of Canada | 2 | 650 | 6,500 | 13,000 | Manual | Electrolytic | On order | Brown Boveri |
| Consolidated Mining & Smelting Co. of Canada | 1 | 650 | 6,500 | 6,500 | Manual | Electrolytic | On order | General Electric |
| Delaware, Lackawanna & Western Railroad | 11* | 3,000 | 3,000 | 33,000* | Manual | Railroad electrification | On order | General Electric |
| Delaware, Lackawanna & Western Railroad | 2 | 3,000 | 2,000 | 4,000 | Automatic remote control | Railroad electrification | On order | General Electric |
| Eastern Massachusetts Street Railway Co | 3 | 600 | 1,000 | 3,000 | Manual | Urban | 1929 | General Electric |
| Edmonton, City of | 1 | 575 | 1,325 | 1,325 | Manual | Railway | 1929 | Brown Boveri |
| Ford Motor Co | 2 | 460 | 1,000 | 2,000 | Manual | Power | On order | Brown Boveri |
| Halifax Tramways | 1 | 590 | 1,100 | 1,100 | Manual | Railway | 1929 | Brown Boveri |
| Municipality of Milan (Italian G. E.) | 1 | 550 | 1,000 | 1,000 | Manual | Urban | 1929 | General Electric |
| Montreal Tramways Co | 1 | 600 | 2,400 | 2,400 | Automatic | Railway | 1929 | Brown Boveri |
| Montreal Tramways Co | 2 | 600 | 1,500 | 3,000 | Automatic remote control | Urban | Under installation | General Electric |
| Philadelphia, City of | 2 | 630 | 2,500 | 5,000 | Manual | Subway | Being erected | Brown Boveri |
| Piedmont & Northern Railway | 4 | 1,500 | 750 | 3,000 | Automatic remote control | Railroad electrification | 1929 | General Electric |
| Public Service Co. of No. Ill., Chicago | 1 | 600 | 1,900 | 1,900 | Manual | Railway | On order | Brown Boveri |
| Public Service Co. of No. Ill., Chicago | 1 | 600 | 1,900 | 1,900 | Automatic | Railway | On order | Brown Boveri |
| Public Service Co. of No. Ill., Chicago | 1 | 1,500 | 1,500 | 1,500 | Manual | Railroad electrification | 1929 | General Electric |
| Sacramento Northern Railway | 1 | 1,500 | 500 | 500 | Automatic | Interurban | 1929 | General Electric |
| Saskatoon, City of | 1 | 575 | 600 | 600 | Automatic | Railway | 1930 | Brown Boveri |
| Toronto Hydro Electric System | 2 | 600 | 1,100 | 2,200 | Automatic | Railway | 1929 | Brown Boveri |
| Union Railway Co. of New York City | 1 | 625 | 1,000 | 1,000 | Automatic | Railway | 1929 | Brown Boveri |
| City Subways of New York | 7 | 625 | 3,000 | 21,000 | Automatic remote control | Railway | On order | General Electric |
| Totals | 78* | | | 179,900 | | | | |

*In addition one spare 3000-kw. rectifier tank (without transformer) is on order. Four of the above sets consist each of two 1500-kw. tanks operating as a unit.

MERCURY ARC RECTIFIER UNITS INSTALLED IN THE UNITED STATES AND CANADA PRIOR TO JANUARY 1, 1929

| Purchaser | No. of sets | D. c. volt | Kw. per set | Total kw. | Control | Service | Put in service | Manufacturer |
|---|---|---|---|---|---|---|---|---|
| American Gas & Electric, New York | 1 | 575 | 300 | 300 | Automatic | Railway | 1927 | Brown Boveri |
| Calgary, City of, Canada | 1 | 575 | 600 | 600 | Semi-automatic | Railway | 1928 | Brown Boveri |
| Canadian National Railways, Montreal | 1 | 600 | 1,200 | 1,200 | Manual | Railway | 1928 | Brown Boveri |
| Chicago, North Shore & Milwaukee R. R. | 1 | 600 | 1,000 | 1,000 | Automatic remote control | Interurban | 1926 | General Electric |
| Chicago & Joliet Elec. Ry. Co. | 1 | 600 | 500 | 500 | Automatic | Interurban | 1928 | General Electric |
| Columbus Railway Power & Light Co | 1 | 600 | 1,000 | 1,000 | Manual | Urban | 1927 | General Electric |
| Columbus Railway Power & Light Co | 1 | 603 | 1,000 | 1,000 | Manual | Railway | 1927 | Brown Boveri |
| Commonwealth Edison Co., Chicago | 1 | 621 | 600 | 600 | Manual | Railway | 1925 | Brown Boveri |
| Commonwealth Edison Co., Chicago | 1 | 621 | 1,200 | 1,200 | Manual | Railway | 1925 | Brown Boveri |
| Commonwealth Edison Co., Chicago | 2 | 1,500 | 3,000 | 6,000 | Manual | Railway | 1926 | Brown Boveri |
| Commonwealth Edison Co., Chicago | 1 | 1,500 | 1,500 | 1,500 | Manual | Railroad electrification | 1926 | General Electric |
| Connecticut Co., New Haven | 5 | 600 | 1,200 | 6,000 | Manual | Railway | 1927 | Brown Boveri |
| Connecticut Co., New Haven | 2 | 600 | 1,200 | 2,400 | Automatic | Railway | 1927 | Brown Boveri |
| Delaware, Lackawanna & Western R. R. | 1 | 600 | 200 | 200 | Semi-automatic | Railway | 1926 | Brown Boveri |
| Dominion Power & Transmission Co., Montreal | 1 | 600 | 600 | 600 | Automatic | Railway | 1928 | Brown Boveri |
| Duquesne Light Co | 2 | 600 | 1,000 | 2,000 | Manual | Urban | 1927 | General Electric |
| Ford Motor Co., Detroit | 1 | 250 | 550 | 550 | Manual | Power | 1925 | Brown Boveri |
| Gary Railways Co., Gary, Indiana | 1 | 600 | 500 | 500 | Automatic | Railway | 1926 | Brown Boveri |
| Lethbridge, City of, Canada | 1 | 500 | 400 | 400 | Manual | Railway | 1927 | Brown Boveri |
| Long Island R. R., New York | 1 | 650 | 1,000 | 1,000 | Semi-automatic | Railway | 1926 | Brown Boveri |
| Long Island R. R., New York | 3 | 650 | 1,000 | 3,000 | Automatic remote control | Railroad electrification | 1928 | General Electric |
| Los Angeles Railway Corp | 2 | 600 | 500 | 1,000 | Automatic | Urban | 1928 | General Electric |
| Milwaukee Electric Railway & Light Co. | 3 | 600 | 550 | 1,650 | Automatic | Railway | 1927 | Brown Boveri |
| Montreal Tramways Co | 2 | 600 | 1,200 | 2,400 | Automatic | Railway | 1927 | Brown Boveri |
| Montreal Tramways Co | 1 | 600 | 1,200 | 1,200 | Automatic | Railway | 1928 | Brown Boveri |
| H. Morgan & Co., Montreal, Canada | 2 | 265 | 132 | 264 | Manual | Power | 1928 | Brown Boveri |
| New York Edison Co | 1 | 240/260 | 570 | 570 | Manual | Power | 1925 | Brown Boveri |
| Northern Indiana Public Service Co | 1 | 1,500 | 1,500 | 1,500 | Automatic remote control | Interurban | 1926 | General Electric |
| Northern Indiana Public Service Co | 3 | 1,500 | 750 | 2,250 | Automatic remote control | Interurban | 1926 | General Electric |
| Northern Indiana Public Service Co | 2 | 1,500 | 750 | 1,500 | Automatic remote control | Interurban | 1928 | General Electric |
| North Shore Power Co., Montreal | 1 | 600 | 600 | 600 | Manual | Railway | 1927 | Brown Boveri |
| Philadelphia Rapid Transit Co | 2 | 600 | 500 | 1,000 | Automatic | Urban | 1927 | General Electric |
| Philadelphia Rapid Transit Co | 3 | 600 | 1,000 | 3,000 | Automatic | Urban | 1928 | General Electric |
| Portland Electric Power Co | 2 | 1,350 | 750 | 1,500 | Manual | Interurban | 1927 | General Electric |
| Public Service Co. of Northern Illinois | 1 | 1,500 | 1,500 | 1,500 | Manual | Railroad electrification | 1927 | General Electric |
| Southern Public Utilities Co | 1 | 600 | 750 | 750 | Manual | Railway | 1928 | Brown Boveri |
| United Traction | 1 | 600 | 500 | 500 | Automatic | Urban | 1924 | General Electric |
| Utilities Power & Light Co., Chicago | 1 | 600 | 550 | 550 | Manual | Railway | 1927 | Brown Boveri |
| Utilities Power & Light Co., Chicago | 1 | 600 | 900 | 900 | Manual | Railway | 1927 | Brown Boveri |
| Totals | 60 | | | 54,184 | | | | |

rating of 10,000 amperes at 650 volts are now on order for electrolytic use.

Two new features of particular interest have been developed by the General Electric Company and will be applied for the first time to rectifiers which are being constructed for the Delaware, Lackawanna and Western Railroad. These consist of a biased grid adjacent to the anodes which deionizes the vapor as the current passes through zero and materially reduces the tendency to arc-back; and compounding features, using static condensers in the compounding circuit, which give substantially flat compounding up to 150 per cent load, and incidentally materially improve the power factor of the rectifier unit. The biased grid consists of a grid located directly below the anode connected to a cylindrical insulated shield surrounding the anode. The shield and grid are energized from an auxiliary transformer in such a manner as to supply the grid with a potential of the desired phase relation to the anode potential. The grid thus installed acts to deionize the vapor in the vicinity of the anode each time the anode voltage decreases to zero before the anode voltage can reach a negative value.

Fig. 26—Three 5600-Kw. Rectifier Sets (Brown Boveri) for Consolidated Mining & Smelting Co. at Trail, B. C.

The General Electric Company reports continued success with the use of the graphite anode and has

standardized on such anodes for all rectifiers. The General Electric Company has also standardized on the Mycalex Anode Seal in place of the porcelain mercury seal. On the other hand the Brown Boveri Company continues the use of metal anode for all classes of rectifiers.

The Delaware, Lackawanna and Western will use rectifiers exclusively for conversion units for its suburban electrification. Thirteen 3000-volt rectifier units with an aggregate capacity of 37,000 kw. and one spare 3000-kw. rectifier tank are now on order. These units will have a rating of 150 per cent for two hours and

Fig. 27—Three 1000-Kw., 600-Volt General Electric Rectifiers

Arranged for operation on either 25- or 60-cycle supply, installed in the Fall River substation of the Eastern Mass. Street Railway Co.

300 per cent rating for five minutes and on tests have been carried far beyond these limits.

A portable substation equipped with a 600-kilowatt 575-volt rectifier unit by Brown Boveri has been completed and put in service in 1929 by the Electric Light and Power Department of the City of Calgary.

The Board of Transportation of the City of New York has placed an order with the General Electric for seven 3000-kw. rectifiers which will be used in single unit stations to supply the new subway system. While part of the supply for the subway system will be from multiple-unit synchronous converter substations, one section of the initial line will be operated from these single-unit stations which will be installed underground, adjacent to the subway tunnel.

In Europe a 400-kw. 12,000-volt rectifier has been successful in radio transmission work and several similar high-voltage sets are now on order. Rectifiers for 2125 kilowatts 465 to 475 volts have been supplied to steel mill operation. These units were designed and built by Brown Boveri, Inc. The attached tabulation indicates the rapid growth of this type of converting equipment.

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# Electric Welding

## ANNUAL REPORT OF COMMITTEE ON ELECTRIC WELDING*

*To the Board of Directors:*

Your Committee on Electric Welding hereby reports the following activities and developments in its field of activity for the fiscal year May 1, 1929 to May 1, 1930.

### Meetings and Papers

The committee arranged for a symposium on welding which was held on the afternoon of Thursday, January 30, 1930 at the Winter Convention of the Institute held in New York. This symposium comprised a total of five very interesting papers:

1. *Cathode Energy of the Iron Arc*, by Gilbert E. Doan of Lehigh University.
2. *Calorimetric Study of the Arc*, by P. E. Alexander of the Thomson Research Laboratories.
3. *Resistance Welding*, by B. T. Mottinger of Akron, Ohio.
4. *Electrically Welded Structures Under Dynamic Stress*, by Morris Stone and J. G. Ritter of East Pittsburgh, Pa.
5. *Electric Welding by the Carbon Arc*, by J. C. Lincoln of Cleveland, Ohio.

The first two papers brought forth a great deal of discussion, and should undoubtedly stimulate other scientific investigators to carry on the work begun by these authors so that our knowledge of the physics, chemistry, etc., of the welding arc will eventually be completed, resulting in better welding work being accomplished in the future. The fourth paper likewise brought forth discussion and should serve as a stimulus to others to investigate particularly the behavior of welded joints and structures under dynamic loading, to determine the fatigue resistance of such joints, materials, and structures. The fifth paper brought out some very interesting information and leads one to believe that during recent years, the carbon electrode process of arc welding has not been given the consideration of which it is evidently worthy.

### American Welding Society Activities

The American Welding Society issued three noteworthy pamphlets during the year covering:

1. Fusion Welding and Gas Cutting in Building Construction.
2. Welding Definitions and Symbols.
3. Revised Welding Manual.

The first publication is so arranged as to permit its being incorporated bodily into existing building codes for the various cities so that the use of welding as a means of shop fabrication and field erection may be applied to structural steel construction on a formal and recognized basis. The second publication sets forth rational definitions and terminology which will be of great help to the welding industry in standardizing and simplifying the production of drawings and designs for welding construction. The use of this work will also assist the industry to understand and adopt the use of welding much more quickly and accurately than would otherwise be the case. The third publication completes a set of four instruction manuals which are available either singly or in complete manual form on the subjects of Resistance, Thermit, Arc Welding and Cutting, and Gas Welding and Cutting. These publications cover their subjects thoroughly and are of great value, especially to industrial plants and to shops which are not thoroughly versed in the various processes.

### Commercial Activities

*Buildings.* During the year, the Southern California Edison Company has had under way a 12-story, 3600-ton office building which will be approximately 25 per cent arc welded. All of the wind bracing and the seismic bracing for this building is to be of welded design.

The Boston Edison Company is erecting an arc welded 15-story, 1600-ton office building which is rather a unique departure in that the shop fabrication is to be carried on by riveting and the field erection by welding.

One widely known construction company has recently stated in public announcements over its signature that it is ready to bid at competitive prices on welded construction as an alternative to riveted construction on any steel buildings.

Another interesting piece of construction work completed during the year is that of the Forest Lawn Memorial Park Mausoleum at Glendale, California, completed by the Pacific Iron and Steel Company of Los Angeles. The particular feature of interest in this building is the heaviest all-welded truss that has been produced to date, namely, one weighing 60 ton, with a span of 96 ft. and a height of 18 ft. The weight of the entire welded structure is 123 ton.

A new contribution to the building art was announced by the American Institute of Steel Construction at its Seventh Annual Convention at Biloxi, Mississippi, last November. This was the develop-

*COMMITTEE ON ELECTRIC WELDING:

A. M. Candy, Chairman,
C. A. Adams, H. M. Hobart, A. M. MacCutcheon,
P. P. Alexander, C. J. Holslag, B. T. Mottinger,
C. W. Bates, C. L. Ipsen, J. W. Owens,
Alexander Churchward, J. C. Lincoln, William Spraragen.
Ernest Lunn,

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

ment of a new type of arc welded steel floor construction known as the "battledeck" type which was demonstrated by the erection of a sample structure automatically arc welded. This particular design of floor structure, involving steel-plate material tying beams together, is expected to be revolutionary in its effect on building construction work and to produce a less expensive total structure.

*Pipe Welding.* The use of welding in the construction of pipe and the field construction of pipe lines has been extended rapidly during the past year along the lines that have become pretty thoroughly standardized. No particularly new developments have been made in this field.

*Pressure Vessels.* Probably the most interesting development in this field is the issuance by The A. S. M. E. of Code Revisions for Pressure Vessels. These are proposed for adoption by the A. S. M. E. Code for the Construction of Unfired Pressure Vessels. The proposed changes include the following provisions: for longitudinal seams double V, butt welded, 8000 lb. per sq. in.; for girth or head seams of the single V, butt type, 6500 lb. per sq. in.; for double full fillet lap or girth welds 7000 lb. per sq. in.; and for spot or intermittent girth or head welds, 5600 lb. per sq. in. The above permissible fiber stress values can be used when the welded vessel is welded in accordance with the recommended procedure for fusion welding of pressure vessels given in the Appendix; the strength of the joints may be calculated on a maximum unit working stress ($s$), at right angles to the direction of the joint.

*Machinery Construction.* The large manufacturers of electrical equipment have made a greater proportion of their machinery of welded construction during the past year than ever before. This same practise is being taken up by manufacturers of other lines of equipment. One phase of machinery construction which has been received with particular interest is the construction of jigs, fixtures, and special shop machine tools by the welding process. It has proved to be of great economic advantage not only from a first cost standpoint but also because the manufacturer is able to tool up much more quickly than is possible with the use of cast structures.

*Ship Construction.* The Truss-Weld Barge Corporation launched an 8000-barrel capacity gasoline tanker, 134 ft. long and of all-welded construction.

The Electric Boat Company at Groton, Connecticut, has completed a 100-ton cargo-deck barge 118 ft. long by 10½ ft. wide of the all-welded Ewertz patented design. In the construction of this barge, 150 tons of steel were used and approximately 18,000 linear ft. of welding was performed requiring about 3500 lb. of welding wire.

The Fore River Yard of the Bethlehem Shipbuilding Corporation delivered two colliers, 350 ft. long each, with the transverse seams of their tank tops welded and with bulk heads wherein two rows of rivets were replaced by one row of rivets and a continuous weld.

The Charleston Dry Dock and Machine Company completed a 120-ft. oil tanker, and at the Standard Steel Shipbuilding Corporation, Los Angeles, a 65-ft. yacht was completed by the arc welding process. Two merchant ships, the *Morro Castle* and the *Oriente*, were constructed at the plant of the Newport News Shipbuilding and Drydock Company, for the Atlantic Gulf and West Indies Navigation Company. The outstanding new applications on these ships are the completely welded inboard shaft alley bulk heads, masts, and bilge keels.

*Resistance Welding.* The use of resistance welding equipment in industry at large and especially in the automotive field has gone forward rapidly within the past year.

Other developments involve the use of this type of welding for the rapid production under commercial conditions of standard steel piping. However, these developments are still in the experimental stage.

## Miscellaneous

*Non-Destructive Tests of Welds.* Within the past year great advances have been made in methods for the non-destructive testing of welds. In general these come under three heads:

1. X-ray.
2. Stethoscope.
3. Electromagnetic.

*1. X-ray.* The improvement in X-ray apparatus and technique during the past few years has brought this method of examination into the commercial field, and although its application is as yet confined to fairly simple structures, it is bound to prove immensely valuable in many of the applications of autogenous welding.

*2. Stethoscope.* Due to the personal equation of the testing operator, this method is somewhat limited in its applications, and yet in certain cases, it is surprising how sensitive it is to moderately small defects. Not much can be stated regarding its commercial possibilities as it is still in the experimental stage.

*3. Electromagnetic Methods.* (a) Alternating current. This is essentially a differential method, that is, a comparison of the parent metal with the weld. These two portions are subjected to identical alternating current m. m. f., and the two secondary voltages resulting are opposed to each other, the residual being first amplified and then observed by means of an oscillograph. Experience shows that in certain simple cases, such as tubes or bars of uniform section, the characteristic indications of the oscillograph show changes of metallographic structure, such as grain size, strain, and decarbonization, as well as mechanical defects of porosity inclusions or fissures.

This method is also somewhat limited to fairly simple

structures, but in these cases gives an immense amount of valuable information.

(b) Direct current. In this case a very large direct current is passed through the welded joint and a little exploring device moved longitudinally along the joint. The exploring device is so arranged that when it strikes a magnetic field transverse to the joint, an e. m. f. is induced. The only magnetic field transverse to the joint is that due to a longitudinal component of the current which in turn will be produced only when the main or transverse current is deflected by means of some defect in the joint.

In some cases the main current contacts can be moved along the joint at the same time and at the same speed as the detector device; but the principle is the same. As in the other case, this device cannot be readily applied to all types of structures.

Practically all these devices may be applied to some of the simpler and more important types of structures; combined, they constitute a very important advance in the welding art.

During the past year the use of automatic arc welding of several different forms has increased rapidly and industry as a whole is becoming cognizant of the advantages of machine produced welds where the nature of the work is such that the necessary tooling is economically warranted.

Certain improvements in generating equipment have also been made, but these require too much detail to be discussed in this report.

## Summary

There are numerous other individual welding applitations which might be mentioned but we believe that che above summarizes the principal activities in the welding field and will indicate the rapid and increased use that is being made each year of various forms of welding and welded products.

# Electrophysics

## ANNUAL REPORT OF THE ELECTROPHYSICS COMMITTEE*

*To the Board of Directors:*

Progress in the application of results in the domain of physics has been so rapid of late that there is a temptation to make the general statement that the pure physics of one quarter century becomes the engineering of the next. This, of course, would not be true in all domains of physics, but it is more or less valid in those with which the electrical engineer is most closely connected. The mounting number of uses for devices and phenomena discovered some years ago, for example the vacuum tube, photo-electricity, and the piezo-electric vibrations of crystals, is an apt illustration of the transfer from abstract interest to practical utility. It is, then, quite to the point for the electrical engineer, in forecasting and preparing for the developments of the future, to look to the electrophysics of the present day.

The physicist is continuously acquiring increasing clarity of view in connection with principles already to some extent applied. A better understanding of the present viewpoints with regard to these principles may also be of value to the engineer in further applications.

Keeping these two ideas in view, the present report does not confine itself to applied physics. In fact, the material in the first portion of the report, giving a general idea of the developments along the forefront of theoretical and experimental physics, may not find application for a long time to come (although this might also have been said of the advance line of physics many times previously, and belied by subsequent events). Following this general survey, the progress in particular topics of more immediate practical consequence, is summarized. The subjects thus discussed are: dielectrics, magnetism and magnetic materials, the conduction of electricity in solids, photoelectricity, thermionics, the cold discharge, vacuum tubes, gas discharges, the propagation of electric waves, and magnetic and electrostatic fields.

### The "First Line" of Physics

Spectacular advances in the various fields of electrophysics have been few during the past year, as they are in any year, but a great deal of serious, accurate, and quantitative work has been recorded in almost every subdivision.

The wave-like qualities of negative electricity were established beyond all reasonable doubt, more than two years ago; but though the recent demonstrations of electron-diffraction by crystals and ruled gratings can scarcely be said to have strengthened a case which was already unassailable, some of the photographs of diffraction-rings and diffraction-fringes published during the past year are so beautiful that they merit special mention (G. P. Thomson, Rupp, Eisenhut, Debye). A beginning has already been made in turning them to practical use in the study of thin films (G. P. Thomson, *et al*). Diffraction of electrons by liquids has been proved experimentally (Debye). The wave-like qualities of positive electricity have been demonstrated (Dempster), though as yet the evidence falls far short, in beauty and in clarity, of that available for negative electricity—a circumstance not to be wondered at, considering the difficulties of the experiments. Finally, the corresponding proof has been achieved for neutral matter (helium and molecular hydrogen, by Stern; atomic hydrogen, by T. H. Johnson). More and more it becomes evident that wherever there are particles, there are waves also; particles are guided by waves, waves are the carriers of particles.

The classical theory of electric conduction in metals, the theory, that is to say, that a metal contains an electron-gas, prevented from escaping by a potential-drop at the surface, was revived some three years ago with a modification, to wit, the substitution of the Fermi distribution-law for the Maxwell distribution-law as applied to the corpuscles of the electron-gas. Later it was modified in another way: by introducing, from wave-mechanics, the idea that the electron-gas can leak out gradually across the potential-drop even though this is so high that no electron within the metal has enough kinetic energy to surmount it. The combination of these two new ideas is being tested in work on the cold discharge, and on the refraction which a beam of electrons undergoes on entering a metal; they supply also a new incentive for accurate work on the photoelectric and the thermionic effect. Unfortunately, it appears that the mathematical complexities which are encountered in attempting to bring the theory closer to the experiments are very serious. Moreover, in the recent work in thermionics and photoelectrics, it is found that the influence of surface-conditions, films of foreign substances only one molecule deep, for instance, or indeed even scantier than would result from a complete covering of the surface by a monomolecular layer, is predominant. While such influences might be explained in part by invoking the second of the new ideas aforesaid, they have apparently nothing to do with the first. It is only too obvious that in these fields very much remains to be understood.

*COMMITTEE ON ELECTROPHYSICS:
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W. S. Gorton, Secretary,

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|---|---|---|
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*Liaison Representatives of American Physical Society*
Leigh Page, W. F. G. Swann.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*



30-124

In the study of discharge through gases, where the wave-like qualities of electricity play little or no part, the developments of the last year have mostly been continuations of prior work. Since recent refinements in technique make it possible to observe what goes on during intervals of the order of a hundred-millionth of a second, some interesting work on the electric spark is being published. It has been proved that the spark bursts forth so quickly, that rearrangements of space charge rather than drifting of ions must be accountable for its onset. The extensive work, both experimental and theoretical, of Compton and Langmuir and the latter's associates, upon the "plasma" or glowing gas of the arc-discharge, is being summarized and developed in articles in the *Review of Modern Physics*, the first of which has just appeared (April, 1930). Several valuable papers on the interception of electrons by atoms, the probability of ionization of atoms by electrons, and cognate subjects have appeared.

## Dielectrics

The report of the Committee on Electrical Insulation, Division of Engineering and Industrial Research of the National Research Council, dated July, 1929, shows that there has recently been much activity in this field. Under the auspices of this committee, a symposium on dielectrics was held in connection with the general meeting of the American Physical Society in Washington, in July, 1929. They have also prepared a comprehensive program of research for physicists, chemists, and engineers, stressing the importance of fundamental work in solving the present difficulties due to dielectric absorption, dielectric loss, and conductivity. The situation has been summarized by Professor Whitehead, chairman of the committee (A. I. E. E. Jl., **48**, 27, 1929).

Dielectric breakdown has been discussed in many papers. Halbach (*Arch. f. Elekt.* **21**, 535, 1929) has tested various solids and differentiates between two types, the so-called electric breakdown and breakdown by heat. Moon and Norcross (*Jl. Frank. Inst.* **208**, 705, 1929) have discovered and investigated a third type of breakdown. Inge and Walther (*Arch. f. Elekt.* **22**, 410, 1929 and **23**, 279, 1930) have extended their investigations on breakdown to liquids, and considered the effects of time, of application of voltage, and of the homogeneity of the field on both solid and liquid materials. Jost (*Arch. f. Elekt.* **23**, 305, 1930) has also considered the effect of time on the strength of various solids. Smurow (*Arch. f. Elekt.* **22**, 31, 1929) determined the breakdown field for sulfur in solid, liquid, and gaseous form. A general review of the breakdown of liquid insulators has been published by Gyemant (*Phys. Zeit.* **30**, 33, 1929).

In several papers (*e.g.*, *Zeit. f. Phys.* **56**, 446, 1929 and *Zeit. f. Tech. Phys.* **11**, 81, 1930) Böning has given experimental support to the idea that dielectric breakdown in solids of colloidal origin is affected by ions adsorbed on the inner surfaces of channels. A similar but more elaborate theory has recently been put forward by Murphy and Lowry (*Jl. Phys. Chem.* **34**, 598, 1930) to explain absorption and loss in such materials. This was based in part on previous work on textiles with various electrolyte and moisture contents, the electrical properties of which have been determined by Murphy, Williams, and Walker (*e. g.*, *Jl. Phys. Chem.* **33**, 509, 1929, and A. I. E. E. Trans. **48**, 568, 1929). The effect of moisture in air condensers has been investigated by Lemmon and Kouwenhoven (A. I. E. E. Trans., Vol. 49, July 1930).

Ionization in paper-insulated cables has been studied further by Dawes and Humphries (A. I. E. E. Trans. **49**, 766, 1930) and also by Brown (*Jl. I. E. E.* **67**, 968, 1929). Whitehead and Marvin (A. I. E. E. Trans. **49**, 647, 1930) have found that in a high grade paper-insulated condenser the loss can be fully accounted for by dielectric absorption. Benedict (A. I. E. E. Trans. **49**, 739, 1930) has similarly calculated the power loss from the d-c. characteristics, and investigated the effect of frequency on the charging current and energy loss in various condensers. Owen (*Phys. Rev.* **34**, 1035, 1929) determined calorimetrically the heat loss in a fiber condenser at radio frequencies and found that it is proportional to the voltage and the square of the frequency. The absorption or damping of radio wave-trains in dielectrics has been discussed by Kreutzer (*Zeit. f. Phys.* **60**, 825, 1930).

The power losses in glass have been measured by McDowell and Begeman (*Phys. Rev.* **33**, 55, 1929) as a function of temperature and frequency. The variation of the dielectric constant and power factor of rosin and castor oil with temperature and frequency was found to be qualitatively in accordance with the Debye theory by Kitchin and Müller (*Phys. Rev.* **32**, 979, 1929 and Jl. A. I. E. E. **48**, 281, 1929). Goldhammer and Sack (*Phys. Zeit.* **31**, 224, 1930) studied the anomalous dispersion in dilute solutions where the Debye theory is more nearly applicable, and found results in agreement with the theory. The law of superposition in hard rubber has been confirmed by Race and Campbell (*Phys. Rev.* **34**, 1031, 1929). Electric polarization was observed by Güllner (*Arch. f. Elekt.* **22**, 141, 1929) in gypsum but not in mica nor in any glasses, indicating that the mechanism of the process is different in different substances.

Various experimenters have measured conduction currents as dependent on voltage, time and temperature. A review of previous work in relation to the theories of conduction and diffusion in solid dielectrics, has been made by Jander (*Zeit. f. angew. Chem.* **42**, 462, 1929). Experiments on quartz and rock salt have been made by Goldhammer (*Zeit. f. Phys.* **57**, 173, 1929), on rock salt and gypsum by Salessky (*Zeit. f. Phys.* **52**, 695, 1928), on an artificial resin by Suckow (*Arch. f. Elekt.* **22**, 104, 1929), and on oil by Whitehead and Marvin (A. I. E. E. Trans. **49**, 647, 1930) and by

Nikuradse (*Arch. f. Elekt.* **22**, 283, 1929). Nasledov and Sharavskii (*Ann. d. Phys.* **3**, 63, 1929) have observed the ionizing effect of X-rays by measuring the conduction current in ceresin.

Some of the most fundamental work during recent years is reported in the book "The Physics of Crystals"[1] by A. Joffe.

As in many years past, much of the work in molecular structure as deduced from measurements of dielectric constants, centers around the Debye theory. An excellent review of this subject is given by Debye himself in his recent book "Polar Molecules"[2] to which reference should be made for the fundamentals as well as for the interpretation of the results obtained before 1929. More recent reviews, with special reference to the results for aliphatic compounds and for inorganic and aromatic compounds are those by Smyth (*Chem. Rev.* **6**, 549, 1929) and by Williams (*Chem. Rev.* **6**, 589, 1929), respectively. All of the phases of the subject are treated in papers in the *Leipziger Vortrage*[3] edited by Debye.

Values of electric moments, on which to base atomic and molecular models, are perhaps best determined by studying the effect of temperature on the dielectric constants of gases. Under these conditions the molecules are least affected by neighboring molecules; and it is possible also to separate the moment produced by the distortion of the molecule by the field, from the permanent moment characteristic of the molecule when no disturbing field is present, the latter being the more desirable datum. This method, based on the relation derived by Debye in 1912, has been applied by Sänger and Steiger (*Helv. Phys. Acta* **2**, 130, 1929 and **2**, 411, 1929), by Zahn (*Phys. Rev.* **35**, 848, 1930), and by Schwingel and Williams (*Phys. Rev.* **35**, 855, 1930), to a large number of organic and inorganic compounds. Interesting among these are $N_2O$, $CO_2$, $CS_2$, and $SO_2$ which have zero moments, indicating that the three atoms in each molecule have a symmetrical linear arrangement. Measurements of the Kerr effect and the scattering of light have been used to determine electric moments by Wolf (*Zeit. f. Phys. Chem.* **3B**, 128, 1929), by Stuart, Briegleb, and Wolf (*Zeit. f. Phys. Chem.* **6B**, 163, 1929), and by Stuart (*Zeit. f. Phys.* **55**, 358, 1929 and **59**, 13, 1929). This work is based on that of Raman and Krishnan (*Phil. Mag.* **3**, 713, 1927).

The dielectric constants and refractive indexes of many binary liquid mixtures have been studied by Smyth and his co-workers, and by Williams and his co-workers. These data permit a determination of the electric moment by a third method, using Debye's theory.

There have been many more determinations of the electric moments of various compounds and groups of compounds, and discussions of the structures based on these determinations. For these papers the reader is referred to *Science Abstracts*.

1. McGraw-Hill, 1928.
2. Chemical Catalog, 1929.
3. S. Hirzel, Leipzig, 1929.

### Magnetism and Magnetic Materials

The fundamental nature of ferromagnetism has been discussed in many papers during the year. Slater (*Phys. Rev.* **35**, 509, 1930) has recently developed the theory of the origin of ferromagnetism which had already been treated by Heisenberg and by Bloch (*Zeit. f. Phys.* **57**, 445, 1929), based on the "interaction" of electrons as pictured on Schrödinger's theory. He discussed the relation between ferromagnetism, electrical conduction and cohesion in metals. The experiments of Dorfmann, Jaanus, and Kikoin (*Zeit. f. Phys.* **54**, 277, 1929) on the Thomson effect in nickel indicate that the same electrons are responsible for conduction and for ferromagnetism. Fowler and Kapitza (*Proc. Roy. Soc. Lond.* **124A**, 1, 1929) applied Heisenberg's theory to the phenomena of magnetostriction and of the large change in specific heat and in volume at the magnetic transformation point.

Becquerel and de Haas (*Proc. Roy. Soc. Amst.* **32**, 578, 1929) have experimentally verified the relation between paramagnetic susceptibility and temperature which is predicted by the quantum theory and which is different from that derived on classical assumptions. The quantum theoretical calculation of the paramagnetic susceptibilities of the elements of the rare earth and iron groups has been improved by Van Vleck and Frank (*Phys. Rev.* **34**, 1494, 1929). Gans (*Naturwiss*, **18**, 184, 1930) has reported that at very high fields the saturation value of magnetization of permalloy decreases, due to diamagnetism. Forrer (*Jl. Phys.* **1**, 49, 1930) has investigated the ferromagnetic and paramagnetic properties of a series of alloys near the magnetic transformation temperature.

A number of papers deal with the change of resistance of metals in a magnetic field; these include measurements by McKeehan on permalloy (*Phys. Rev.* **35**, 657, 1930), Vilbig on iron, nickel and steel (*Arch. f. Elekt.* **22**, 194, 1929), Kapitza on about thirty metals in very high fields (*Proc. Roy. Soc. Lond.* **123A**, 292, 1929), and Meissner and Scheffers on gold at very low temperatures (*Phys. Zeit.* **30**, 827, 1929).

Another attempt has been made, this time by Stearns (*Phys. Rev.* **35**, 292, 1930), to detect a change in the X-ray reflecting powers of ferromagnetic materials when they are magnetized. Although the sensitivity of the test is greater than ever before, the result is again negative and indicates that ferromagnetism should be identified with the spinning electron.

The average size of the discontinuities in magnetization (Barkhausen effect) have been determined by Bozorth and Dillinger (*Phys. Rev.* **35**, 733, 1930). Preisach (*Ann. d. Phys.* **3**, 737, 1929) has confirmed the earlier work of Bozorth in showing that practically the whole change in magnetization takes place discontinu-

ously, and has also shown that the size of the larger discontinuities may be greatly changed by tension and torsion.

The properties of single crystals of ferromagnetic materials have again been the object of several researches. Kaya has found that in cobalt the hexagonal axis coincides with the direction of easy magnetization (*Tohoku Rep.* **17**, 1157, 1928). Potter has prepared a single crystal of a Heusler alloy and studied its structure by X-rays, as well as its magnetic properties. Iron and nickel crystals have been studied further by Foster (*Phys. Rev.* **33**, 1071, 1929), Gries and Esser (*Stahl und Eisen* **49**, 879, 1929), Sizoo (*Zeit. f. Phys.* **57**, 106, 1929), and Zeigler (A. I. M. E. Pub. No. 273 C 43, 1930). The sharp corners in the magnetization curve originally reported by Gerlach have been accepted as real by Sizoo and by Gries and Esser, but questioned by Foster and Bozorth (*Nature* **125**, 525, 1930).

Thin films of iron, cobalt, and nickel, deposited on non-magnetic supports, have been investigated by Howie (*Phys. Rev.* **34**, 1440, 1929) and by Tyndall and Wertzbaugher (*Phys. Rev.* **35**, 292, 1930). Howie explains many of the results of previous investigators as due to the relative thermal expansions of the films and their supports on which they were deposited at temperatures other than that at which their magnetic properties were measured.

The magnetic moment of some ferromagnetic atoms have been found to be greater in some alloys than in the pure metal. Weiss, Forrer, and Birch (*C. R.* **189**, 663, and 789, 1929) have shown again that this occurs in iron-cobalt but not in cobalt-nickel alloys. Constant (*Phys. Rev.* **34**, 1217, 1929) has shown it to occur in platinum-cobalt alloys and Kaya and Kussmann (*Naturwiss* **17**, 995, 1926) in manganese-nickel alloys.

The magnetic properties of Heusler alloys, as related to their crystal structure, have been further elucidated by Valentiner and Becker (*Zeit. f. Phys.* **57**, 283, 1929) and by Doerum (*Avh. Oslo.* No. 10, 1929) as well as by Potter as mentioned above.

Reviews of many of the aspects of magnetism have been written by Gerlach (*Jl. Phys.* **10**, 273, 1929) and by Bruninghaus (*Rev. Gen. Elec.* **25**, 197 and 237, 1929). A small important book, "Magnetism,"[4] describing the theoretical significance of the facts of dia-, para-, and ferro-magnetism, has recently been published by Stoner.

## Electrical Conduction in Solids

Conduction in solids plays a part in practically all problems with which the electrical engineer has to deal, but no entirely satisfactory explanation of the phenomenon is as yet at hand. The theory of metallic conduction which seems to promise most has been developed by Sommerfeld, and is summarized by Darrow in the *Physical Review* Supplement, Vol. 1, 1929, p. 90; by Samuel in the *Electrotechnische Zeitschrift*, Vol. 50, 1929, p. 1481; and by Houston (including his own contributions) in A. I. E. E. Trans. **49**, 30, 1930, p. 795. Houston, in the *Physical Review*, Vol. 34, 1929, p. 279, showed how a law for the dependence of resistance on temperature could be obtained from the theory.

The marked decrease in resistance as the temperature of − 273 deg. cent. (0 deg. K.) is approached may at some future time be the key which will allow us to discover the nature of conduction. Bloch (*Zeit. f. Physik.* **59**, 208, Jan. 2, 1930) considering theoretically both the energy changes and the scattering of the electrons as they collide with the atoms of the metallic crystal, found that the electrical resistance at very low temperatures should vary as the fifth power of the absolute temperature. This is checked by experimental results only moderately well, and Bloch attributes the lack of closer agreements to the imperfection of the theoretical assumptions made in his derivation.

The phenomenon of superconductivity (a drop to extremely low resistance in the immediate neighborhood of the absolute zero) is of especial interest. De Haas, at the University of Leyden, who published much on this subject during the year, found that certain alloys, having constituents that were not superconducting, were themselves superconducting. Kapitza (*Proc. Roy. Soc.* **123**, 342, 1929) and Bartlett (*Nature* **123**, 869, 1929) also have discussed superconductivity.

Kapitza (*Proc. Phys. Soc. Lond.* **123**, 292, 1929) and Meissner and Scheffers (*Phys. Zeit.* **22**, 826, 1929) have studied the changes in electrical conductivity in strong magnetic fields. Bloch (*Zeit. f. Phys.* **53**, 216, 1929) has applied the quantum mechanics to this general problem; his conclusions are criticised by Frank (*Zeit. f. Phys.* **60**, 682, 1930). Auwers (*Naturwiss.* **45**, 867, 1929) has also treated the problem theoretically.

With regard to the conductivity of crystals, Smekal (*Zeit. f. Phys. Chem.* 3B, 162, 1929) brought forward more evidence in favor of his point of view that ionic conduction takes place at the boundaries of rifts in the crystal and that electronic conduction occurs inside the crystal. His theory has been hotly contested by Jost, many papers being published in the *Zeitschrift für Physik* and in the *Zeitschrift für Physikalische Chemie*. A list of titles is found in Jost's latest rejoinder in the latter journal for March, 1930.

Thin films have been technically applied as high resistances (*Perucca*, C. R. **189**, 527, 1929 and *Ann. d. Phys.* **4**, 252, 1930; and Kruger, *Zeit. Tech. Phys.* **10**, 495, 1929), and also as fuses (*Jl. Sci. Inst.*, **6**, 102, 1929). Ingersoll and Hanawalt (*Phys. Rev.* **34**, 972, 1929) investigated the conductivity of evaporated and sputtered nickel films. They found in the sputtered films a large gas content, which was liberated at 300 to 400 deg. cent., at which temperature the films became magnetic and better conducting. The gas content of the evaporated films was less. Braunbek (*Zeit. f. Phys.* **59**, 191, Jan. 2, 1930) applied some old results of Volmer

4. Methuen, London, 1930.

and Estermann and found that the specific resistance of a mercury layer condensing on a glass surface decreases with the amount on the surface very rapidly at first, and then more slowly, to a constant value.

Schottky and Deutschmann (*Phys. Zeit.* **30**, 839, 1929) studied the potential distribution in a copper oxide rectifier.

Herzfeld (*Phys. Rev.* **34**, 791, 1929) has published an article on the influence of surface conditions and space-charge on the conductivity of poor conductors, which may repay study.

### Photoelectricity

Photoelectricity received a marked impetus during the year through the growing importance of the applications of the photoelectric cell. Among the major fields of applications may be mentioned the talking moving pictures, color television, and two-way television, the latter two achieved during 1929 and 1930 respectively; and television broadcasting which is being quite extensively developed.

Very material increases in the sensitivities of photoelectric cells have been brought about by the formation of composite surfaces, or compounds of the photosensitive alkali metals previously employed, on the cathodes of the cells. More sensitive cells of this nature (such as those obtained with sodium and potassium on the cathode) were used in daylight television and in the wire television developments referred to above; they were reported on by Olpin (*Phys. Rev.* **33**, 1081, 1929). Cells utilizing caesium as the alkali metal have been produced by Koller (*Phys. Rev.* **33**, 1082, 1929, and *J. O. S. A.* **19**, 135, 1929) and by Zworykin and Wilson (*J. O. S. A.* **19**, 81, 1929). The type described by Koller (Cs O) seems to respond more strongly to light at the extreme long wavelength limit of the visible spectrum than does any other cell at present known. Campbell and Ritchie have written a valuable book, "Photoelectric Cells,"[5] dealing at length with their construction and operation.

Passing from the technical to the scientific side of the subject, it is certainly necessary to note the study of the long wavelength limit of thin alkali metal films, made by Ives and Olpin (*Phys. Rev.* **34**, 117, 1929). This limit depends on the thickness of the film; and the highest wavelength that it reaches, as the thickness of the film is varied, was found by these authors to coincide with the first line of the principal spectrum series of the free atom, corresponding to the resonance potential. Suhrmann and Thiessing (*Zeit. f. Phys.* **55**, 701, 1929), Campbell (*Phys. Zeit.* **30**, 537, 1929), and Fleischer and Teichmann (*Zeit. f. Phys.* **61**, 227, 1930) also studied these thin films, being interested especially in potassium adsorbed on platinum. Lawrence and Linford gave a paper before the American Physical Society, April 25, 1930, on the influence of intense electric fields on the photoelectric behavior of such films.

5. Isaac Putnam and Sons.

### Thermionics

The past year has witnessed no outstanding developments in that branch of electrophysics which deals with the emission of positively and negatively charged particles from heated bodies.

Many years ago Richardson developed a fundamental relation between the saturation electric current due to the emission in question and the absolute temperature. This law in its mathematical expression was $i = A\,T^2\,e^{-b/T}$, where $A$ and $b$ were thought to be material constants independent of $T$. There has been in the intervening years much discussion and argument as to just what values $A$ and $b$ should or do have, especially for electron emission. During the past year, Fowler (*Proc. Roy. Soc.* **A 122**, 36, 1929) considered the value of $A$ for electron emission from the standpoint of the new statistics; and Zwikker (*Phys. Zeit.* **30**, 578, 1929) tried to establish a linear relation between log $A$ and $b$ for surfaces of a metal with differing degrees of contamination.

Wahlin (*Phys. Rev.* **35**, 653, March 15, 1930) and Smith (*Phys. Rev.* **35**, 381, February 15, 1930) have both continued work on the emission of positive ions from hot metallic filaments.

The efficiency of an electron emitter, such as the filament in a vacuum tube, may be rated in milliamperes of electrons furnished per watt of heating energy. It has been found that, over a range of temperatures, thin films of so-called "active" metals are more efficient thermionically than metals in bulk. Filaments based on this result are used in practically all vacuum tubes as the source of electrons, and are for that reason the subject of much study. Thus the thermionic and other properties of thorium films on tungsten were investigated by Andrews (*Phys. Rev.* **33**, 454, 1929), by Reynolds (*Phys. Rev.* **35**, 158, January 15, 1930) and by Brattain (*Am. Phys. Soc.*, April, 1930). The Richardson constants of thin film cathodes formed by distillation were obtained by Espe (*Zeit. f. Tech. Phys.* **10**, 489, 1929). Becker (*Phys. Rev.* **34**, 1323, 1929) published the results of an extensive series of experiments on Wehnelt (Ba O, Sr O) oxide coated filaments; he found that the high activity is due to a thin film of metallic barium or strontium on the surface of the oxides, and that this metallic barium or strontium was produced by electrolysis of the oxides. Riemann and Murgoci (*Phil. Mag.* **9**, 440, March, 1930) found a parallelism between the variations, during the life of each oxide-coated cathode, of the electrical conductivity and of the thermionic emission. On the technical side a new core (Konel) for this latter type of filament has been introduced by the Westinghouse Company; and there were articles on the development of such oxide-coated filaments by Hodgson, Harley and

Pratt (*Jl. I. E. E.* **67**, 762, 1929) and by McNabb (*J. O. S. A.* **19**, 33, 1929).

The statistical variation in thermionic emission leads to minute erratic changes in the currents obtained from devices employing the emission. These minute changes are known under the name "shot effect." Williams and Huxford have recently studied the shot effect for positive ions. Williams and others attribute a portion of the fluctuations in electron space current from Wehnelt cathodes at low potentials, such fluctuations being larger than those for metallic emitters, to the presence of positive ions. Smith has also studied the modification of the shot effect for electrons by positive ions.

### Auto-Electronic Discharge

The "pulling out" of the electrons by high fields is a source of great worry to the designers of high voltage vacuum tubes, and probably enters into most high voltage discharge phenomena. A number of papers have been published during the past year on the subject. Bridgman's note in the *Physical Review*, Vol. 34, 1929, p. 1411, is an interesting analysis of the phenomenon. Houston (*Phys. Rev.* **33**, 361, 1929) applied the methods of wave mechanics to the problem of the dependence of the effect on temperature. Millikan and Lauritsen investigated the same subject (*Phys. Rev.* **33**, 598, 1929), finding the electron-emission to be independent of temperature up to 1100 deg. K. De Bruyne was of the opinion (*Phys. Rev.* **35**, 172, Jan. 15, 1930) that no temperature variation at all had been proven as yet. He also considered the effect of contaminating layers of caesium and of nitrogen on tungsten (*Proc. Camb. Phil. Soc.* **25**, 347, 1929), and Gosling, Fowler, and Stern were others who studied this case. (*Proc. Roy. Soc.* 1929 and *Proc. Camb. Phil. Soc.* **25**, 454, 1929).

### Vacuum Tubes

There is a number of different angles from which one may view a vacuum tube. It may be considered merely as a piece of apparatus, an instrument which performs certain functions; it may be looked upon as an addition to (and sometimes a considerable complication of) an existing electrical circuit; or the various physical phenomena involved in its design, manufacture, and operation may be studied. It is probably from the last mentioned standpoint that the justification for including the subject in "electrophysics" would originate. Little apology is needed, however, because of the widespread interest in vacuum tubes and their applications, and the intimate relationship to previous topics discussed and the one to follow.

The latter part of 1928 and the whole of 1929 proved a noteworthy period in the development of the type of apparatus commonly known under the generic term of "vacuum tubes." Foremost in importance was probably the development of hot cathode tubes containing gases at pressures of 0.001 mm. to several cm. The presence of this amount of gas is so much the predominant feature in the action of the tube that this division of the subject may best be discussed under "Gas Discharges" (see below).

In the case of true vacuum tubes, considering the smaller ones first, developments have been along the line of multi-grid tubes. The pentode or three-grid tube in both the space-charge screen grid and the screen grid plate shielding grid circuits, has received attention, and a space-charge grid tube with the space-charge grid co-planar with the control grid has been developed. This latter tube has low plate resistance, combined with a high undistorted output, and appears to be a very important development (Pidgeon and McNally, *Proc. I. R. E.* **18**, 266, Feb. 1930). The field of small vacuum tubes as a whole was marked by increasing stringency in the requirements of the circuits in which they were used.

Large power tubes which deliver as much as 100 kw. have been made and operated in broadcasting sets. A double-ended power tube for short waves, 15 meters, is being used in the transatlantic radio service.

Tuve, Breit, and Hafstad have succeeded in constructing a vacuum device consisting of a number of electrodes in cascade which withstood 1,400,000 volts between extreme terminals (*Phys. Rev.* **35**, 66, January 1, 1930).

Among the papers published on vacuum tube designs and circuits were:

1. "Effect of End Losses on the Characteristic of Filaments of Tungsten and Other Materials," Langmuir, McLane and Blodgett, *Phys. Rev.* **35**, 478, March 1, 1930.
2. "Calculation of the Characteristics and Design of Triodes," Kusunose, *Proc. I. R. E.* **17**, 1706, 1929.
3. "Microphonic Improvements in Vacuum Tubes," Rockwood and Ferris, *Proc. I. R. E.* **17**, 1621, 1929.
4. "Noise in Vacuum Tubes and the Attached Circuits," Llewellyn, *Proc. I. R. E.* **18**, 243, February, 1930.
5. "Output Power Obtained from Vacuum Tubes of Different Types," Pidgeon and McNally, *Proc. I. R. E.* **18**, 266, February, 1930.
6. "Circuit Analysis Applied to the Screen Grid Tube," Nelson, *Proc. I. R. E.* **17**, 320, 1929.
7. "Mathematical Theory of the Four-Electrode Tube," Brainard, *Proc. I. R. E.* **17**, 1006, 1929.
8. "Equivalent Circuits of a Triode," Chaffee, *Proc. I. R. E.* **17**, 1633, 1929.
9. "Modulators from a Physical Viewpoint," Peterson and Llewellyn, *Proc. I. R. E.* **18**, 38, January, 1930.

A new journal, *Electronics*, published by McGraw-Hill, was started in April, 1930, to take care of this subject and of thermionics and photoelectricity.

### Gas Discharges

The understanding of the physical characteristics of gaseous conduction has been advanced by a number of theoretical and experimental researches during the year.

J. J. Thomson (*Phil. Mag.* **8**, 393, 1929) has worked out new formulas for the cathode fall of potential, length of dark space, and current density in the electric discharge through gases. He has shown that radiation, as well as collision, plays an important part in discharge phenomena. Brown and E. E. Thomson have found that the potential gradient in the cathode dark space is very nearly uniform.

The effect of positive and negative space charges in the gas and at the electrodes has been made more clear by work done by Langmuir. Langmuir and Tonks (*Phys. Rev.* **34**, 876, 1929) have discovered and studied a very high frequency oscillation in the electron atmosphere of an ionized gas, called by them "plasma" oscillation. This oscillation is responsible for the abnormally high electron velocities observed by Langmuir in such a gas.

The total ionization produced by an electron has been measured again by Kulenkampff and by Eisl. The latter, claiming the highest accuracy yet attained, finds for the average amount of energy lost by an electron per ion produced in air the value $32.2 \pm 0.5$ electron volts.

The mechanism of recombination of ions and electrons has been discussed in the light of present day knowledge by Loeb and by Seeliger. One of the most interesting discoveries of the year was made by Bergen Davis and A. H. Barnes (*Phys. Rev.* **35**, 217, Feb. 1, 1930) who find that electrons and $\alpha$-particles combine only when the electrons have one of certain definite velocities with respect to the $\alpha$-particle. These results, which have attracted wide attention, are still under debate.

The study of the Ramsauer effect, the abnormally small apparent area of certain molecules to slow electrons, has been continued by Brüche, Kollath, Holtsmark, Jones, Ramsauer and others.

By means of a Langmuir probe Nottingham (*Jl. Frank. Inst.* **207**, 299, 1929) has measured the potential distribution in a copper arc, with interesting results; while Mackeown has considered arcs theoretically on the basis of certain simplifying assumptions.

The ignition and form of spark in a large number of combustible gas mixtures has been studied by Tereda and collaborators (*Sci. Papers*, Inst. of Phys. and Chem. Res., Tokyo). The activation of nitrogen by electric discharge has received a good deal of attention, and a number of papers is devoted to the synthesis of compounds by cathode rays or by the glow discharge. Brewer and Westhaven (*Jl. Phys. Chem.* **33**, 883, 1929), for instance, found that the synthesis of ammonia is initiated by the positive ions in the discharge.

The importance of metastable atoms in affecting sparking potentials in noble gases has been brought out (Penning, *Zeit. f. Phys.*, 1929). Electrons are freed from electrodes by the impacts of metastable atoms and thus strongly influence currents to electrodes in ionized gases (Uyterhoven, *Phys. Rev.*, Ratner, *Proc. Nat. Acad.*, Oliphant, *Proc. Roy. Soc.*, 1929).

The manner of extinction of alternating current arcs is being actively studied. The efficacy of the oil breakers is said to be due to the generation of gas from the oil and the rapid mixing with the arc (Slepian, A. I. E. E. TRANS. **49**, 421, 1930). Improved utilization of oil as a deionizing means has been achieved (Baker and Wilcox, A. I. E. E. TRANS. **49**, 431, 1930). Gas blasts have been effectively used as deionizing means in high voltage circuit interrupters (Biermann, *E. T. Z.*, 1930).

The discharges started by high voltage surges have been the subject of considerable work such as that of Lee, Rogowski, McEachron and Goodwin, Lissner, and Berger. Both Rogowski and Beams have found that the time lag in such discharges is extremely short, so short that according to von Hippel and Franck (*Zeit. f. Phys.*, 1929) the Townsend theory of the initial glow discharge cannot apply in these cases. Paavola, under not very different conditions, finds good agreement with the story of Townsend. Lawrence and Dunningham (*Phys. Rev.*, 1930) believe that early development of very high temperatures, with possible thermal ionization, is also indicated.

In the case of lightning discharges, a considerable mass of data must be accumulated over a period of time before we shall have conclusive proof of the voltage range of induced surges and of those due to the main or auxiliary branches of direct strokes.

While much development has been reported in the applications of gaseous conduction, only a few which present outstanding novelty and promise will be mentioned.

The importance of gaseous tubes with hot cathodes is increasing rapidly. Thus the hot cathode mercury vapor tube described by Hull, (A. I. E. E. TRANS. **47**, 798, 1928) is rapidly displacing the kenotron in practise due to superior performance and lower cost. Gaseous tubes in which the starting of the current is controlled by a grid are finding almost countless applications in control work of all types. The thyratron, developed by Hull, and the grid glow tube, developed by Knowles, are of this type.

A higher-power arc rectifier has been developed by Toulon, in which the arc takes place in air at atmospheric pressure. The arc is initiated each cycle by a timed spark, and the device is called the pilot-spark rectifier.

A daylight lamp in which part of the light comes from the arc between a mercury surface and a hot tungsten filament has been described by Strickland.

## PROPAGATION OF ELECTRIC WAVES

Continued progress has been made during the past year in the study of the propagation of short waves. Long time echo signals having delays up to 4 minutes 20 seconds have been reported by Hals, and a number of other observers have found echoes with time lags up to 30 seconds. Observations by Galle and Talon during

the solar eclipse of May 9 (reported in *C. R.*, Jan. 6, 1930) were carried out at a wavelength of 25 m., several other investigators have used wavelengths of the order of 30 m. A low group velocity as the cause of long time echoes has been considered by a number of authors; thus Breit has shown that if the refractive index of the Kennelly-Heaviside layer decreases exponentially with height it is possible that this effect would be produced (*Proc. I. R. E.* **17**, 1508, 1929). In this explanation, absorption is tentatively ignored, an assumption which many workers regard as unjustifiable. Pederson believes that echoes having a greater delay than ten seconds cannot be due to waves propagated entirely within the earth's atmosphere, and concludes that echoes with delays up to one minute are probably due to propagation along or reflections from "Störmer bands" of electrons within the magnetic field of the earth, while echoes with greater delay must be due to bands of ions located so far away as to be beyond the influence of the earth's magnetic field (*Proc. I. R. E.* **17**, 1750, 1929).

Renewed interest has been shown in theoretical and experimental investigations of the surface wave (ground wave), particularly that which is set up near short-wave transmitting antennas. Considerable attention has also been given to the "optical" properties of the earth for wavelengths in the radio spectrum.

American and European investigators have collected many data which throw light on the propagation of short waves, such as diurnal variations in layer height, effect of magnetic storms, and short-time echo signals over both long and short distances of transmission. An interferometer method of measuring slight changes in the optical path of waves reflected by the ionized region in the upper atmosphere has been devised by Hafstad and Tuve (*Proc. I. R. E.* **17**, 1786, 1929).

Magnetic storms are accompanied by severe disturbances in short wave transmission. It has been found that at such times the height of the Kennelly-Heaviside layer is materially increased. This has been attributed to unusual solar activity at such times. Several investigations to determine the correlation in greater detail are under way.

Abroad, particularly in Germany, there has been great activity in connection with very short waves from a few centimeters to ten meters in length. Methods of generating and modulating relatively large amounts of power in this range had been devised and the propagation properties of the waves studied. It is found that these waves follow substantially an optical path between transmitter and receiver, that the attenuation in space is very low, but that the ground wave is absorbed with extreme rapidity. The sky wave is unaffected by fog, rain, sunlight, or darkness.

In addition to the large amount of experimental work on short wave propagation, progress has been made in the study of the ionized regions above the earth from the point of view of the physics of the upper atmosphere. Notable in this connection is the work of Hulburt and others in the Naval Research Laboratories.

### Electromagnetic Theory; Electric and Magnetic Fields

A thoroughgoing discussion of the electromagnetic theory is found in "The Electromagnetic Field" by Mason and Weaver. Leigh Page says, "It constitutes unquestionably the foremost critical study of electromagnetic theory in the English language."

Heisenberg and Pauli (*Zeit. f. Phys.* **56**, 1, 1929) and Oppenheimer (*Phys. Rev.* **35**, 461, March 1, 1930) are continuing their researches on remodeling the fundamental theory. Kaplan and Murnaghan also published an article, quite mathematical in nature, "On the Fundamental Constitutive Equations in Electromagnetic Theory" in the *Physical Review* for April 1, 1930.

Passing to a much less abstract phase of the subject, namely, to waves on wires, there is an interesting treatment of propagation along wires from this standpoint by Aguillon in *Annales des P. T. T.* Vol. 17, 1928, p. 846, and Vol. 18, 1929, p. 89. Karapetoff discussed a *Graphical Theory of Traveling Waves between Parallel Conductors* in the Jl. of the A. I. E. E. for February, 1929. Ohashi (*E. N. T.* **6**, 1, 1929) considered the "Disturbing Effect of Traveling Waves and the Mutual Influence of Telegraph Lines," taking the lines to be both inductively and capacitatively coupled.

The experimental study of traveling wave phenomena on transmission lines has been advanced by the use of truck mounted cathode ray oscillographs and portable impulse generators, rated at 1,000,000 volts. Much work done along this line was reported in several papers at the Midwinter Convention.

Closely allied to the paper by Ohashi mentioned above is a large number treating disturbances in one electric line due to another—or to waves from a distance. Among these may be mentioned:

1. "Electrostatic Influence of a Power Line on a Telephone Circuit," Picault, *Annales des P. T. T.* **18**, 885, 1929.
2. "Disturbances Induced in a Communication Circuit by Traction Currents," Rüdenberg, *Jl. Teleg.* **53**, 145, 169, 1929.
3. "Electromagnetische Störungen," Schindelhauer, *E. N. T.* **6**, 231, 1929.
4. "Mutual Inductance Measurements on Conductors with Earth Return," Klewe, *E. N. T.* **6**, 467, 1929.
5. "Analysis of Irregular Motions with Applications to the Energy Frequency Spectrum of Static and of Telegraph Signals," Kenrick, *Phil. Mag.* **7**, 176, 1929.
6. "Power Circuit and Inductive Interference with Telephone and Telegraph Systems," Huth, *Trans. S. Af. I. E. E.* **20**, 115, 1929.
7. "Unbalance of Telephone Lines and Circuits Subject to Inductive Disturbances," Roehmann, *T. F. T.* **18**, 18, 1929.
8. "Mutual Impedance between Adjacent An-

tennas," Englund and Crawford, *Proc. I. R. E.* Aug., 1929.

9. "Magnetic Disturbances and Long Distance Reception," Kennelly, *Electronics*, April, 1930.

10. "Uber die induktive Beeinflussung von Schwachstromleitungen durch Starkströme," Schiller, *Arch. f. Elekt.* **23**, 217, 1929.

11. "Reciprocal Theorems in Radio Communication," Carson, *Proc. I. R. E.* **10**, 952, 1929, and an extensive commentary on the subject by Ballantine in the same issue.

Some papers which touch the power engineer probably as closely as the transmission engineer are:

1. "Distribution of Electric and Magnetic Fields," Hague, *Elec.* **102**, 185 and 315, 1929.

2. *Flux Linkages and Electromagnetic Induction in Closed Circuits*, Bewley, JL. OF THE A. I. E. E. **48**, 216, 1929.

3. *Forces on Magnetically Shielded Conductors*, Morecroft and Turner, JL. OF THE A. I. E. E. **48**, 25, 1929.

There should also be included here the series of papers which is probably familiar to many A. I. E. E. members, namely, that comprising the symposium on *Shielding in Electrical Measurements* held at the A. I. E. E. Summer Convention in 1929.

## MISCELLANEOUS

The year has seen notable advances in piezo-electric oscillators. Marrison (*Proc. I. R. E.* **17**, 1103, 1929) has developed a constant frequency oscillator of this nature that will maintain its frequency constant to within one part in $10^7$ over considerable time intervals. The peculiarities of parallel cut quartz crystals, such as non-oscillating thicknesses, doublet resonant frequency, etc., have been explained on a rational basis, and quartz crystals with a zero-temperature coefficient for frequency have been obtained by using special proportions Lack (*Proc. I. R. E.* **17**, 1123, 1929).

The subject of direct current amplifiers and their application to various types of measurement has been a live one during the past year. There have been papers by Brentano (*Zeit. f. Phys.* **54**, 571, 1929), Eglin (*J. O. S. A.* **18**, 393, 1929), Carwile and Scott (*Phil. Mag.* **34**, 161, 1929), Razek and Mulder (*J. O. S. A.* **18**, 460, 1929 and **19**, 390, 1929), and Rasmussen (*Ann. d. Phys.* **2**, 357, 1929).

The application of mathematical methods to electrical engineering, especially to electrical circuits, was of interest to many. The American Mathematical Society conducted a symposium on "Differential Equations of Engineering" in December. At this meeting the question of establishing a journal of applied mathematics was discussed. Two important books dealing with circuits were "Operational Circuit Analysis" by Bush, and "Heaviside's Operational Calculus as Applied to Engineering and Physics" by Berg. Some other followers of Heaviside, with the subjects of their articles, may be noted:

1. "Heaviside's Fractional Differentiation," Sumpner, *Phys. Soc. Proc.* **41**, 404, 1929.

2. "Extension of Heaviside's Operational Calculus for Invariable Systems," Van der Pol, *Phil. Mag.* **7**, 1153, 1929.

3. "A Generalization of Heaviside's Expansion Theorem," Pennell, *Bell System Technical Journal*, **8**, 482, 1929.

4. "Operator Solution of Linear Differential Equations," Van der Pol, *Phil. Mag.* **8**, 861, 1929.

5. "Differential Equations as a Foundation for Electric Circuit Theory," Fry, *Am. Math. Monthly* **36**, 499, 1929.

6. "Operational Methods in Wire Transmission Theory," Josephs, *P. O. E. E. Jl.* **23**, 60, April, 1930.

Physics as a whole has been extending its sphere of influence into the biological sciences. In this extension, many studies are being made, on subjects such as the electrical currents developed by nerves and the electrical characteristics of cell surfaces, which may be classed under the domain of the applications of electrophysics—perhaps one might say under electrobiology. Such investigations are hopeful indications of an advance in knowledge of physical processes in this division of the sciences.

Values of the general physical constants have been published by Birge in the *Physical Review Supplement*, July, 1929. Volumes V and VI of *International Critical Tables* were also published in the past year. Volume VI contains much of interest to the electrophysicist, the table of contents including electronics and gas conduction, dielectric properties, electrical conductivity, pyro- and piezo-electricity, thermo-electricity, electrolytic electromotive forces, and magnetism.

In case the electrical engineer wishes to pursue studies in a particular field in present day physics or wishes to renew his knowledge of some branch of the science, he will find helpful summaries of the theoretical and experimental conclusions to date in a series of articles entitled "Some Contemporary Advances in Physics" by K. K. Darrow, published in the *Bell System Technical Journal*, and also in the numbers of the *Reviews of Modern Physics*. The latter periodical was started (under the name of the *Physical Review Supplement*) during the past year for the purpose of providing general surveys for those who were not specialists in the subjects discussed.

For drawing up the above summary, information has been furnished by members of the Electrophysics Committee, and in addition contributions of material have been received from Messrs. R. M. Bozorth, K. K. Darrow, J. M. Eglin, J. B. Johnson, and J. C. Schelleng. The chairman is especially indebted to Dr. J. M. Eglin for assistance in compiling the report.

# General Power Applications

## ANNUAL REPORT OF COMMITTEE ON GENERAL POWER APPLICATIONS*

*To the Board of Directors:*

Your Committee on General Power Applications has continued the method of keeping in touch with developments and suggestions for papers as outlined in the report last year.

Considerable progress has been made along these lines. Sixteen committee members have supplied twelve résumés of developments in fields with which they are intimately connected, and thirteen suggestions for papers have been submitted from which your committee hopes to be able to develop several for presentation at Institute meetings during the coming year.

Your committee believes that a continued development of the existing method and material will produce gratifying results.

Fig. 1—Two 8500-Hp. A-c. Motors Driving the Twin Screws of *SS. Pennsylvania*

Attention is called to the fact that no attempt has been made in the report to cover the entire industrial field. The efforts of the committee have been confined to certain outstanding industries in which it is believed developments reflect a general picture of the advance during the year.

### Marine Equipment

*Steam-Electric.* The year 1929 was marked by exceptional activity in the application of turbine-electric drive to large liners of our merchant marine service. There was finished or under construction at the close of the year equipment totaling 114,600-shaft-hp. capacity for six ships, aggregating over 56,000 gross ton. Progress was also made in the application of this type propulsion to smaller vessels such as coast-guard cutters, towboats, and private yachts, making a total for 17 installations for the year of 157,260 shaft-hp. This indicates an increase of 40,660 shaft-hp. or approximately 0.35 per cent over 1928.

The *SS. Pennsylvania*, commissioned during the past year, is the third vessel of this type put into service by the Panama Pacific Line of the International Mercantile Marine, and, together with the *SS. Virginia* and *SS. California*, completes, in tonnage, the largest single fleet of all-electric craft in commercial service. The new ship is very similar to the two preceding vessels, having a power plant consisting of two 6600-kw. 2880-rev.-per-min. a-c. turbine generators and twin

Fig. 2—The *Seneca Sun*, A 320-Hp. Diesel-Electric Tanker Operating in the New York State Barge Canal

screws driven at 120 rev. per min. by 8500-hp. 4000-volt direct-connected motors. (Fig. 1).

Toward the close of the year, the Dollar Steamship Line announced that two ships in round-the-world service will be provided with turbine-electric drive. The driving motors will develop a total of 26,500 shaft-hp., which, from point of size and power, will make them the largest commercial vessels of this type in the United States.

The installation of turbine-electric drive was completed on the private yacht *Viking*, marking the first installation of this kind. The two driving motors are rated at 1300 shaft-hp., each with a speed of 160 rev. per min. Equipment is now under construction for a larger yacht, *The Corsair*, which will have two driving motors of 3000 shaft-hp.

A European adaptation of the turbine-electric drive is interesting to note. The exhaust from the reciprocating engines is sent through the low pressure turbine to a condenser. The alternator driven by this low-pressure turbine supplies power to a motor mounted

*Committee on General Power Applications:

J. F. Gaskill, Chairman,

| | | |
|---|---|---|
| D. H. Braymer, | E. W. Henderson, | H. W. Price, |
| C. W. Drake, | P. C. Jones, | N. R. Stansel, |
| C. W. Falls, | A. M. McCutcheon, | E. C. Stone, |
| C. D. Gray, | N. L. Mortensen, | W. H. Timble, |
| C. F. Harding, | D. M. Petty, | M. R. Woodward. |

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on the engine shaft and in some instances, supplies auxiliary power to the ship. This method of utilizing the engine exhaust has been found to increase the power nearly 25 per cent without any further increase in fuel.

*Diesel-Electric.* The year saw still wider application of Diesel-electric drive for vessels of all types. Although the total of 3595 shaft hp. is less than the total in 1928, still the number of such ships so equipped was substantially the same. Vessels with this drive include freighters, tankers, ocean tugs, river towboats, ferries and several special boats for government use. The Diesel-electric drive seems especially favored for vessels operating in sheltered waters as the majority of installations were on boats operating on our rivers or lakes.

Fig. 3—Paddle Arrangement of Caterpillar Tractor Tugboat

Each set of paddles is driven by a 80-hp. motor

The Sun Oil Company commissioned two new tankers for operation on the Great Lakes, New York Barge Canal and the open Atlantic, which are powered by Diesel engines and d-c. generators and motors. Oil engines, free from fire, are especially advantageous for tankers, while electric drive gives the flexibility so desirable in maneuvering in rivers and canals. One of these tankers, the *Seneca Sun*, is shown in Fig. 2.

The government adopted Diesel-electric drive for two survey boats, the *Liston* of the Engineer Corps and the *Hydrographer* of the Coast and Geodetic Survey. The *Liston* will develop a shaft-hp. of 350, while the *Hydrographer* has an installation capable of 650 shaft-hp. The United States Engineer Corps commissioned also two stern-wheel towboats of 150 shaft-hp. Each, for use on the Mississippi and its tributaries.

A unique application of Diesel-electric drive is shown in Fig. 3. This boat, which can operate in two feet of water, has two 100 hp. Diesel engine generator sets and two 80-hp. driving motors. Each set of caterpillar paddles has a motor so that the direction of the tug can be changed by varying the speed of the paddles. The boat, when pushing a string of barges, as in Fig. 4, acts as the rudder for the tow. This method of propulsion is especially fitted for shallow, crooked rivers and possibly may supplant the familiar paddle-wheel that has been native to these rivers for the past century.

Fig. 4—Caterpillar Tractor Tugboat Acts as the Rudder to the Tow

## Electric Railways[1]

Although it is understood that electrification of steam railways and traffic problems are more thoroughly covered by other committees of the Institute, several specific applications of new power devices and methods to electric railways may be briefly cited to advantage.

The influence of gasoline motor bus competition and the demand for higher speeds, greater rates of acceleration, lighter weight and less noise in operation have resulted in electric railway cars with light-weight high-speed motors, equipped with large ratio-gear reduction and differentials, the latter being similar to those of the automobile. Aluminum parts, and even whole car trucks and bodies of aluminum alloy, are being tried out.

The weight of the motor-control resistor has been reduced 75 per cent by the use of non-corrosive resistance strip ribbon, wound on edge, upon insulating tubes mounted on steel bolts in a light structural steel frame. The temperature coefficient is practically constant and local heating is eliminated by means of large radiating areas.

The excessive noise of operation, after careful noise amplified voltages have been determined from test, has been greatly reduced by means of annular iron and lead inserts in car wheels, the use of rubber annular cushions between spider and rims of such wheels and the use of non-resonant type gear construction.

1. Contributed by C. F. Harding.

A new type of control is shown in Fig. 5. During the year, 100 cars with this control were placed in service on the Chicago surface lines. In this car the electro-pneumatic control and air brakes are foot operated, while the magnetic track brakes are operated by hand. This development increases the practicability of the one-man cars.

That the gasoline-electric cars increased in popularity with the large railroad systems for operation on small branch lines is shown by the fact that a total of 63 such units were placed in service by large railroads during

Fig. 5—Foot Control and Auxiliary Control Handles in Light Weight Car

1929. The general tendency in this equipment is toward an increase in size and total capacity in horsepower installed.

The Diesel-electric cars are newcomers in this field, four being built and put in operation during the year. Tests to date show a surprisingly low cost of fuel per mile with a reliability equal to their predecessor, the gasoline-electric cars.

The "three-power locomotive," arranged to operate from storage batteries, oil engine or third rail, is increasingly popular in the freight yards due to the unusual versatility of its power plant.

Although the substation equipment for the new Philadelphia subway included the largest 60-cycle, compound-wound, inter-pole type synchronous converters ever built, the starting circuits of which included star-delta switching on the high-voltage side of the transformers, the competitor of such converters, the mercury arc rectifier, is apparently increasing in favor and, in many installations, is showing marked economy of operation over the synchronous converter. Net annual returns as high as 25 per cent have been reported upon new investments in rectifiers, and sustained minimum efficiencies well above 90 per cent have been secured with such apparatus upon 25 per cent load factor applications. Capacity purchased has been doubled during the year and is now well over 125,000 kw. of rating. The use of load shifting and load-limiting resistors located out-of-doors in the feeder circuits has assisted greatly in maintaining continuous service. The extensive introduction of rectifiers upon our electrified steam railroads was attributed to the natural advantage which a unit with no moving parts has over one with rotating parts with wearable and friction surfaces, high efficiency with fluctuating loads, absence of noise and vibration, low maintenance expense and the elimination of extensive ventilation facilities. Fig. 6 illustrates one of these rectifiers in the substation of a western railroad.

Steam railroad electrification has received a forceful impetus during the year. The Pennsylvania Railroad, with its 21,500-kv-a. frequency-changer sets equipped with quick-response excitation, plans for the 3000-volt motor car operation on the Lackawanna Railroad, the extension of the well-proved economies of the Great Northern electrification involving unique motor-generator type locomotives hauling 700-ton trailing load on a 2.2 per cent grade, the Cleveland Union Terminal with a 17-mi. electrified right-of-way now nearing completion, and its 22 new electric locomotives each

Fig. 6—500-Kw., 1500-Volt Mercury Arc Rectifier in Railroad Substation

having six twin-gear, 3000-volt, d-c. driving motors, 2900-hp. total capacity,—to say nothing of the extensive Mexican, British, and Austro-Swiss electrification developments—well emphasize the popularity, economy, and variety of electrical applications to heavy railway service.

The acceptance of radio communication between engine cab and caboose of a long freight train was evidenced by the number of installations during the year. In actual operation, advice and direction by radio have proved to be of great value in preventing accidents and saving of time.

### Steel Mill Industry

The year 1929 was marked by intense activity in the iron and steel industry. Operating rates were exceptionally high and new records for steel ingot production were established. Electricity contributed a considerable part in maintaining this activity, since it is only through the flexible and easily controlled operation of the mills that such production is possible.

Accompanying this increase in production is the increase in the number of new electrical mill drives that were installed or ordered. During the year, over 325,000 hp. in main-roll drives, each 300-hp. or over, were sold. This makes a total capacity on main-roll drives of over two million and a half horsepower.

As in previous years, d-c. drives exceeded a-c. drives in number and capacity, amounting to approximately 70 per cent of the total horsepower. Especially notable increased number of reversing mill drives contracted for was the during the year. Synchronous motors continued extensively applied to constant-speed drives, while to be induction motors were used principally where fly-wheel effect was necessary. All new plants installed 60-cycle equipment while many of the older plants continued with the previously established 25-cycle standard. Several instances were noted where 60-cycle replaced the old 25-cycle machines.

Due to the rapid expansion in this industry during the year many interesting and unique applications of electric drive were made—far too many to be even briefly mentioned in a report of this size. Several specific installations have been selected and will be described, as they indicate the general trend of the progress being made in this industry.

Previous to this year blooming mills have had the upper and lower rolls driven by a single motor through a pinion stand. The new 54-in. blooming mill of the Illinois Steel Company omits the pinion stand, and the upper and lower rolls will be separately driven by two 5000-hp. reversing motors. These motors are capable of a combined emergency torque capacity of 3,940,000 lb-ft., which makes this mill the most powerful of any yet installed.

The 52-in. universal intermediate mill will be driven by a 6000-hp. main and a 2000-hp. auxiliary roll reversing motor. These motors receive power from a synchronous motor-generator set consisting of two 3000-kw. 700-volt d-c. generators, a three-phase 25-cycle 8500-hp. synchronous motor and a direct-connected exciter. This is twice the size of any previous installation using the synchronous motor-generator set instead of the customary fly-wheel and induction motor set.

The most sensational installation of synchronous motors for steel mill drive is in a billet mill and sheet bar mill of the Columbia Steel Company, Pittsburg, California. Two motors were installed in this plant, one of them is shown in Fig. 7. They are rated at 5000 hp., 82 rev. per min., 2300 volts and have a diameter of 25 ft., making them the world's largest diameter synchronous motors.

A wide strip mill installation of the Illinois Steel Company is of particular interest as it uses d-c., adjustable-speed motor drives on the roughing stand. This is the first continuous wide strip mill to depart from the previous practise of using alternating current for this drive. The drive uses 12 motors totaling more than 20,000 hp. They are equipped with generator voltage control, thus eliminating the use of starting resistors and contactors.

An unusual application of reversing mill motors is being made in the new plant of the A. M. Byers Company, Ambridge, Pa. A 1200-hp. reversing motor will drive the main 750-ton ram of a large ingot press which will compress wrought iron sponge balls into a rectangular ingot form preparatory to rolling in a blooming mill. An auxiliary 200-ton ram, used for shaping the ends, will be driven by a 325-hp. reversing motor.

Fig. 7—A 5000-Hp. Synchronous Motor of 25-Ft. Diameter

Another example of departure from previous practise is in a new six-stand, 30-in. continuous mill which will be driven by three synchronous motors rated 2500, 3000, and 3500 hp. respectively. Heretofore continuous mills have been driven by a single motor, direct-connected or geared to a lay shaft from which the stands were driven through beveled gears. In this particular case, the three motors tie in through their synchronous speed making it equivalent to the former gearing between stands.

The first universal slabbing mill to utilize separate electric motors on the horizontal and vertical rolls was installed during the year. The horizontal rolls are driven by a 7000-hp., 50/100-rev. per min. motor and the vertical rolls by a 1650-hp., 112.5/270-rev. per min. motor. Control is so arranged that acceleration, retardation, and reversing are simultaneous and in exact speed ratio. Another outstanding characteristic of this installation is that power is supplied to the

motors from three 2400-kw. generators with their armature connected in parallel. This is believed to be the first installation to successfully utilize three generators in parallel to supply power for a reversing drive. Incidentally, the 7000-hp. reversing motor is one of the largest built during the year. Fig. 8 shows a motor of this size installed at the Youngstown Sheet and Tube Company.

Squirrel-cage motors with special stator and rotor design have been substituted satisfactorily for d-c. motors in the operation of pack furnaces. This application is new for squirrel-cage motors as very frequent starting and stopping is involved, sometimes amounting to over 150 starts per hour.

With new design for the control of the conveyer and doors on these pack furnaces it has been possible to eliminate some labor attendance. The operator of the rolling mill receiving the packs from the furnace controls the discharge of the packs by means of a foot switch while conveyer travel is automatically controlled

Fig. 8—A 7000-Hp. D-c. Reversing Mill Installed at the Youngstown Sheet and Tube Company

by limit switches. Operation of the doors by means of a-c. motor drive decreases the heat loss and the amount of excessive air admitted to the furnace. The entire layout is very ingenious and tends toward better working conditions as well as better quality in furnace output.

Although it is not classed under the steel industry there is an installation of a new copper mill worthy of mention, since it represents a radical departure from usual practise. The finishing stands of a continuous mill for rolling copper rods are driven by seven adjustable-speed, d-c. motors, totaling 3000 hp. This mill will deliver two strands of copper rod simultaneously, at a maximum speed of 3500 ft. per min.

### Paper Industry[2]

An improvement in the drive of paper super-calenders was obtained by a variable-voltage drive for each calender. Current is supplied to the d-c. motor from a generator driven by an a-c. motor, either synchronous or induction type. To this motor-generator set is added an exciter where no direct current is available for excitation. The fields of the generator and of the calender motor are separately excited.

Speed control of the calender motor is obtained by varying the field of the generator, thus applying variable voltages to the motor armature. The motor speed

Fig. 9—Two Calenders at the Rhinelander Paper Co. with Separate Motors and Variable-Voltage Control

being proportional to the voltage impressed on the armature, it is possible to obtain a speed range of from 50 ft. per min. to 1000 ft. per min.

In stopping, which is accomplished almost instantly, the fields of the generator are reversed to a value sufficient to give a small reversed voltage. To prevent reversal, a voltage relay causes the generator field to be

Fig. 10—Motor-Generator Set to Supply Direct Current to Calender Motor Shown in Fig. 9

opened as the voltage across the motor armature approaches zero. If reversing is desired, this can readily be obtained by reversing the generator field.

Fig. 9 shows two calenders at the plant of the Rhinelander Paper Co., and Fig. 10 indicates the motor-generator set for this application consisting of synchronous motor driving two d-c. generators, one for each of the calender motors.

2. Contributed by E. W. Henderson.

One of the greatest advances in years has been the application of individual motors to the rolls of surface winders. This application not only simplified the mechanical drive but made it possible to wind rolls of paper more evenly so that they were more acceptable to the printer. Waste per roll of paper was very materially reduced by this application. The control of each roll, individually and of the slitter, was obtained electrically. A very definite indication of winding tension was secured by the use of ammeters in each motor circuit.

Fig. 11 shows an application of individual motors to a Moore and White winder.

### Cement Industry[3]

In a large part of the cement industry the past year has been a period of curtailed production. Although the increase in consumption was about normal, the greater productive capacity due to the construction

Fig. 11—A Moore and White Winder with Individual Motors for Each Set of Rolls

of new plants and improvements in old plants exceeded that growth.

While this curtailment of production has induced unusual efforts to improve operating methods, other factors influencing this situation were certain changes in the standard specifications for cement, which led many plants to modify their manufacturing procedure to permit a product that would conform to the new standards. Such changes have been accompanied by extended electrification of old mills and refinements in the electrical applications in new mills.

There has developed a marked interest on the part of central stations, in the cement mill loads and the possibility of securing mutual benefit to both the central station and the cement industry by the utilization of off-peak power. New rates have been established and others proposed which make it attractive for cement mills to adjust their operating schedules so as to increase greatly the power consumption during the off-peak hours, correspondingly curtailing the consumption during the periods of heavy load on the central stations. While the benefits that can be derived from the rates so far promulgated have not usually been sufficient to warrant the installation of additional machinery to permit taking advantage of the low cost of such off-peak power, this factor has been given consideration in designing new plants and some existing plants have been able to benefit by minor modifications in processing methods. This appears to offer a very important field for future reduction in power costs for the cement industry, as suitable adjustment of capacities for grinding equipment and storage bins will permit large blocks of power to be diverted from on-peak to off-peak periods. A collateral benefit of such changes is to be noted in the possible reduction of labor costs where one or more entire shifts can be eliminated from the operating schedule.

There has also developed during the period under consideration a trend on the part of the central stations to its benefit from tie-ins with isolated plants operating on steam produced by waste heat from cement kilns. There is a number of cement mills now connected to central stations under contracts covering interchange of power, which permits these mills to dispose of surplus power during those portions of the day that steam production from waste heat exceeds power demands, and allows the use of central station power when required in emergency. At the rates now usually offered by central stations for such surplus power, the available quantity must be considerable to warrant the installation of a substation which is ordinarily needed. It seems probable that when a more generous return is offered for this surplus power, based not only on the busbar cost to the central station, but also on the improvement in conditions which may be expected from the connection of numerous and widely scattered power sources to a large distribution system, there will undoubtedly be more cement plants which will take advantage of this interchange arrangement. The cement mills may also be justified in charging off a part of the substation and connection costs against the benefits of the emergency service, and to improvements in waste heat plant operation due to steadier load conditions. Such interchange contracts also may be made more attractive by higher allowance for the surplus power furnished during the central station peak-load hours. The mills may then curtail load during such hours, and carry the additional load on the waste heat plant during the night off-peak period when the normal mill load would also be lighter due to the shutdown of quarries and other part time operations.

The confidence of the cement industry in the possibility of profitably disposing of its excess power may be indicated by the installation during the past year of a 10,000-kw., 100 per cent power factor, 3600-rev. per min. turbo generator which will operate from a waste

3. Contributed by M. R. Woodward.

heat power plant. This is, we believe, the largest turbine operating from a cement mill waste heat plant, and the advent of units of this size with their superior economy may be looked upon as significant of probable future developments.

This apparent development of a more sympathetic attitude toward the cement mill problem on the part of those who have power to sell, offers most hopeful prospects for the future, as the load which the mill can offer is normally most attractive to the central station from the standpoint of load factor, power factor and diversity.

In the quarries and mines, the use of electrically operated well drills for primary drilling, and electric shovels for handling quarry product, is fairly well standardized. There are instances where advantage has been taken of improved shovel performance due to the use of Ward Leonard control, and there appears to be a movement towards higher voltage distribution for quarry operations. Portable cables for connecting electrically operated equipment to distribution lines are now quite generally protected with jackets of automobile tire rubber, and more attention is being given to the grounding of such quarry equipment along the lines of recent developments in connection with the grounding of portable apparatus.

In handling material to and from the stone and coal storage, it is worthy to note that there has been completed at least one grab bucket traveling crane installation having motors throughout equipped with anti-friction bearings and complete automatic master switch control and electric braking systems interlocked to permit high operating speeds with minimum danger of over-travel. These refinements have been justified by the very severe duty imposed on such cranes in this industry due to the practically continuous service of twenty-four hours a day, seven days a week.

In the field of fine grinding the large motors used have been generally of the synchronous type with a marked tendency toward units developing sufficient inherent starting torque to eliminate the use of clutches, but the clutch and brake band motor have generally held their own on applications involving the starting of the heavy eccentric loads found in ball type grinding mills. On centrifugal type grinding equipment which present a balanced starting condition, there have been applications of the usual type of salient pole directly connected self-starting synchronous motors with excitation at 125 volts and normal field arrangement. With such motors the starting current is quite high and so in this field there has been some further extension in the use of a special synchronous motor which obtains the desirable high starting torque with low starting current by means of a wound secondary starting winding and external resistance control. This year for the first time, up to 250 volts have been used in the fields by means of a simple centrifugal, automatic field splitting switch built integral with the motor. Both the above applications have eliminated the use of clutches at a point where with synchronous motors their use had previously been required.

For the above applications the speeds have usually been quite low, ranging from 180 to 450 rev. per min. as the application required, but we have noted one case where eccentric tube mill loads are being started without clutches by high-speed salient-pole synchronous motors connected through gear reduction units.

In connection with kiln drives a marked inclination has developed toward closer speed regulation than is inherent in the slip-ring motors frequently used in the past for this service. This has led to the application of d-c. motors and motor-generator sets in a number of instances, but the requirement has also been very satisfactorily met by the application of the commutator type a-c. motor with speed control through the use of automatic brush shifting and a special speed regulating winding. This type of motor has not only made available practically perfect speed regulation under varying loads but has also permitted almost infinite speed adjustment over a range of about 3 to 1, as well as providing for creeping speeds. With this special motor, the efficiency and power factor also are superior to those of the slip-ring motor, and compare most favorably with the combination of d-c. motors and motor-generator sets previously such motors have been used extensively in the textile and oil industries, but their application to the cement kiln drives is of recent development with results that indicate the possibility of their more extensive use not only for kiln drives but for other applications in cement mills as well.

The effort to improve operating economies has led also to the installation of improved types of coal feeders, and has developed the necessity for much closer speed adjustment on d-c. motors driving these feeders. Closer speed regulation, which also has come to be considered an essential for this application, may lead engineers in the future to turn to the use of commutator brush-shifting a-c. motor for such applications, as such motors seem to have speed regulation characteristics superior to those available in the shunt-wound d-c. motors ordinarily used.

The synchronizing of raw material feeders with kiln speeds continues to claim close consideration and has led to the installation of Selsyn control for this purpose. Last year we reported the use of interconnected but separately excited shunt-wound d-c. motors, and this year has brought the development of mechanical interlocking of the field rheostats to provide the synchronizing of kiln and feeder motors where direct current is used for both drives.

The interlocking of various machines, and the material-conveying equipment is receiving closer attention both with the view of providing greater safety and also preventing delays from flooding elevator pits, conveyers, etc. Where such interlocks are not installed, lamp signals are commonly used, controlled by hatch-

way limit switches to indicate visually by flashing lamps the operation or stopping of elevators and conveyers.

### Rubber Industry[4]

The first three-quarters of 1929, like the entire year before, was a period of expansion rather than one of incorporation of new developments and applications. New plants have been built and existing plants enlarged. Power consumption has increased, and in general, the energies of the engineering staff have been of necessity largely confined to the exigencies of growth.

One of the outstanding trends of new power applications has been the more extensive use of conveyers necessitating a modification of layouts to permit a straight line flow of normal production. The conveyer load, almost negligible a decade ago, is constantly becoming a more considerable part of the total.

For heavy drives, such as mill, refiner, and wash lines, low-speed synchronous motors continue to grow in popularity and usefulness. Although evidences of such use are not yet common, there is little doubt that the synchronous motor will find wider employment in the future for the lighter drives, since its effectiveness in maintaining high power factor on individual feeders cannot be overlooked.

One rubber manufacturer installed the geared drive

Fig. 12—Combination Motor and Gear Drive on Rubber Mill

shown in Fig. 12 instead of the customary low-speed synchronous motor. This drive consists of a high-speed synchronous motor and roller bearing helical gear built as a unit. It is interesting to note that the efficiency was increased 3.5 per cent higher than the slow speed motor and it also develops 40 per cent more starting torque with the same kv-a. inrush.

D-c. drives, at least in this industry, show no signs of decreasing. The wider use of conveyers, already mentioned, and refinements of processes, make speed control constantly more necessary, and in spite of the development of various adjustable speed motors of the a-c. type, direct current still has many attractive features for this purpose.

Automatic control is being more extensively used, and probably has not yet reached its peak. One particularly fertile field is the synchronizing of calender trains. The application of close synchronization to a series of

Fig. 13—This Electric Shovel has a Scoop Capacity of 15 to 20 Cu. Yd. and Weighs 1800 Ton

motors seems, in the rubber industry, to have lagged behind the progress made in comparable drives in the paper industry. This is undoubtedly due to the less stringent requirements; however, a need for better methods undoubtedly exists.

The financial crisis in the last quarter of the year has not seriously disturbed the rubber industry which is looking ahead to a year of perhaps not quite such intensive production in the early part, but a none the less prosperous twelvemonth.

### Mining

Several power applications in the mining industry during the past year indicated that the progressive trend of this industry noted during 1928 is still continuing. Although two of the following applications are not new developments, they are representative of the trend because of their size either large or small.

In 1928 we reported on the use of electric shovels of 12 cu. yd. capacity in strip mines. The past year saw still further increases in the size of these shovels, so that there are now in service shovels of 15 to 20 cu. yd. capacity and weighing 1800 ton. The mammoth size of one electric shovel is clearly shown in Fig. 13.

Direct current is supplied to the various motors by an installation of one 1700-kv-a. synchronous motor driving three generators with a total output of 1660 kw. The total installed electrical hp. including all the auxiliary apparatus and transformers is nearly 4500. Despite the size of this shovel, it will make a complete digging cycle in 47 sec.

In contrast to the size of the foregoing equipment is

4. Contributed by P. C. Jones.

the new mine locomotive, Fig. 14, for operation in extremely thin coal seams which is the lowest in height of any mining engine of this weight ever built. This 6-ton locomotive is 24⅞ in. in height, which includes the trolley, and is rated at 56 hp. It runs at a speed of four miles per hour and is equipped, as a modern street car is, with series-parallel control and dynamic braking. There are two of these now operating in a mine near Huntington, W. Va.

Another development in connection with mine locomotives is the manufacture of the first practical gearless

Fig. 14—Gathering Locomotive in Service at Utilities Elkhorn Corp. Mine.

Over-all height, less than 26 in.

cable reel equipment. This reel is driven direct by the armature shaft and thus revolves at the same speed as the motor armature. Roller bearings are used at both ends of the shafts, the top one being tapered.

The Consolidated Copper Mines, Kimberly, Nevada, installed a mine hoist so equipped that control can be effected from either of two mine levels or from the surface. The hoist is operated by a 900-hp., d-c. motor, with a modification of the variable-voltage system. From the time a button is pressed starting the hoist, no human governance is required as the stops and dumping are all under automatic control. (Fig. 15).

One of the largest hoist motors in the world was installed during the year. Its motor is rated at 3200 hp. 600 volts, and it will raise a skip 3000 ft. per min., from a shaft 3000 ft. deep.

A hoist application worthy of note is in the new water supply system of the City of New York. The equipment includes 16 hoists, each driven by a 250-hp. 500-rev. per min. d-c. motor, and each motor having a 350-hp. synchronous motor-generator set for its supply of energy. Control is of the semi-automatic type.

### Oil Industry[5]

*Pipe Line Pumping.* Electric power is being used more extensively for main line pumping, especially where Public Utility Companies can supply the power without great additional expense for transmission lines, substations, etc., and consequently are able to offer a low rate for electric power.

A paper on *Electrification of Oil Pipe Lines in the Southwest*, by D. H. Levy, was read at the Dallas Regional Meeting May 1929, and printed on page 995 in the A. I. E. E. Quarterly Trans. July 1929. This paper contains comparative cost data on electric pipe line pumping by centrifugal and reciprocating pumps.

*Well Drilling.* There seems to be an increasing demand for electric rotary drilling rigs. Magnetic control is now being used quite extensively on the larger motor equipment, but manual control is standard on the smaller and more common sizes. As the control equipment is mounted or assembled as a unit, it can be easily moved from one well to the next. The control equipment for the mud pumps is also assembled in the same manner.

The size of drilling motors has gradually increased from the 75-hp. motor of a few years ago so that now the use of 125- and 150-hp. motors is common, and several 200-hp. equipments have been operated this year. One manufacturer has a 300-hp. motor in operation. These larger motors are required on account of the increased depth of wells; several have been drilled to over 7000 ft., and a few have reached 8000 ft. in depth. The oil well equipment companies are making designs for much greater depths which may call in the near future for motors as large as 400 or 500 hp. The motors driving the mud pumps have naturally followed the increase in size of the drilling motors.

A new development this year that is interesting is the use of electricity to heat up the heavy lubricant known as "crater compound" so that it will flow in cold weather for applying to the rotary drill bits.

Fig. 15—This Automatic Mine Hoist can be Controlled from Either of Two Levels or from the Surface

*Pumping and Pulling.* To meet the demands of heavier pumping service a larger two-speed motor has been developed so that now a 35/75-hp. motor at 600/1200 rev. per min. is available in both open and protected types. Control equipment for these motors, as for other sizes, is mounted together on a single frame work so it can be easily transported to the well and installed with a minimum of field service.

*Open and Protected Control Equipment.* The electrical manufacturers are now able to supply gas pro-

5. Contributed by C. D. Gray.

tected control equipments for use in all departments of the oil industry. Open equipments are extensively used where the risk of explosion is small and where the expense of protected equipment would be prohibitive, but there seems to be a growing tendency toward gas protected apparatus in which partial protection is given.

There is an increasing demand for explosion-proof housings on the collector rings of slip-ring variable-speed motors which are made strong enough to resist an internal explosion and are designed to prevent the exit of hot gas that might ignite the exterior gas.

A recent development in gas protected apparatus is the housing of the drum controllers used with variable speed motor equipment. In these controllers the drum axis is mounted vertically and the contacts are made

Fig. 16—Self-Propelled Automatic Arc Welder for Welding Floors, Tanks, Ship Decks, Etc.

very sturdy and enclosed in a heavy steel case which is strong enough to resist internal explosion, and so designed that the temperature of any gases forced out from such explosion is reduced so much that an external explosion is prevented.

## Electric Welding[6]

The superior and more economic designs brought about by the recognition of welding as a basic manufacturing process rather than as a substitute for riveting indicate an increasingly effective utilization of the essential advantages of this art. Another outstanding sign of progress is the legal recognition of welding in building construction, as exemplified by the new law in Pennsylvania allowing welding in the construction of buildings in first class cities, and the adoption by 71 cities throughout the country of building codes authorizing this type of building construction.

An interesting example of the use of electric arc welding is the recent extension to the powerhouse of the Haddon Hall and Chalfonte Hotels of Atlantic City, where it was imperative that the work should be done quickly and quietly, without disturbing the guests in the hotels or the residents in their vicinity. This power house has a height of 134 ft. and is one of the tallest welded steel building frames in the world. The Hotel Homstead, Hot Springs, Va., is probably the highest welded steel building so far completed, having eleven stories with an over-all height of 150 ft. Another example of welded steel structure is a footbridge 846 ft. long and containing 105 tons of steel, over the Delaware and Hudson Railroad tracks in Schenectady, N. Y.

The announcement by the American Institute of Steel Construction in November, of a new type of arc welded steel floor promises to reduce the weight of buildings to such an extent that an increase of 25 per cent or more in height may be realized without increasing the weight on foundations. The new flooring utilizes steel plates and structural steel beams. The total cost of a floor constructed of 3-in. I beams and 3/16-in. plates, covered on the top with cork tile and fireproofed on the under side, is estimated by the Institute at a little over $1.00 per sq. ft., which is less than the cost of a good carpet. This "battle deck" floor is applicable to residences, multiple-story buildings and bridges, and will save from 20 to 60 lb. per sq. ft. of floor in dead weight. Fig. 16 illustrates the type of equipment used in this work.

Several thousand miles of long pipe lines have been constructed during the year 1929 by the arc welding method. Notable examples are as follows: A 714-mi. line from Port Arthur to El Paso, Texas, which carries oil at a pressure of 800 lb. per sq. in.; 425 mi. of 12-in. pipe from Cushing, Okla., to Chicago, Ill.; and a 205-mi. pipe line running from Jal, New Mexico, to El Paso, Texas, 16 in. in diameter, to carry gas for the El Paso Utilities Company.

The new vehicular tunnel under the Detroit River between Detroit and Windsor, Canada, was built on dry land in sections which were placed in position on the bottom of the river and caulked around the full circumference of the shell by the arc welding process.

The manufacturers of electric apparatus are increasingly using arc welded machine structures to replace castings. The stator for a 160,000-kw., turbo generator has recently been constructed of arc welded steel. On another page is illustrated, (Fig. 8) a 7000-hp. d-c. motor of welded construction.

It is interesting to note that 90 per cent of American made airplanes are now of welded steel construction.

The resistance welding process has been advanced and is being used for welding boilers of both the water-tube and fire-tube types. Great savings are realized when arc welding is used for repairing such machine

6. Contributed by W. H. Timbie and E. C. Stone.

parts as locomotive draw bars, broken housings, gear teeth and railroad tracks.

An outstanding example of welding making seemingly impossible repairs possible was noted in St. Joseph, Mo. A 285-ft. stack fractured 190 ft. from the base. Arc welding repaired the break which otherwise would have necessitated rebuilding the entire stack. The first complete arc welded ship, a 2500-barrel oil tanker, was recently launched at Charleston, S. C. This boat, which is 120 ft. long with a 10-ft. draft, required but nine workmen for its construction.

### Industrial Heating[7]

*Three-Phase Arc Furnaces.* The trend this year, continued from 1928, in the use of the three-phase arc furnace for melting steel was toward larger transformers for a given physical size of furnace. However, there is no common method of rating arc furnaces so there is no way of expressing this trend, such, for example, as kv-a. per ton holding capacity of the furnace. The largest arc furnace in the steel industry has a nominal holding capacity of 80 ton and is equipped with two sets of electrodes, each set being supplied by a 10,000-kv-a. transformer. This is 250 kv-a. per ton. This furnace, installed during the latter part of 1928, has shown during this year a distinct gain in the economy of steel melting by the use of large units. A furnace now being installed for melting steel has a nominal holding capacity of 25 ton. A transformer rated 10,000 kv-a. was supplied for this furnace. This is 400 kv-a. per ton.

There is a tendency to increase the furnace voltage for steel melting furnaces. The upper limit at present is around 250 volts.

The use of multiple voltages for steel melting furnaces has increased. The general trend is towards three operating voltages for furnaces 1000 kv-a. and above.

There was a marked increase in the recognition of the importance of alloy steels during the year. This led to a revival of interest in the induction furnace for the production of this class of steel. A six-ton core type induction furnace was placed in service for remelting alloy steel scrap. This furnace is rated 800 kw., 0.40 power factor, 8.5 cycles, 220 volts, is single-phase and is supplied by a 2000-kv-a. frequency-changer set. The pouring capacity is approximately 30 ton per day of 24 hr. This is the third furnace of this type and size installed in the United States.

The coreless induction furnace made marked progress in the alloy steel industry. The standard frequency for that service is 960 cycles. The largest installation of the year consists of four furnaces which are supplied by two 300-kw. single-phase 800-volt generators, one driven by an induction motor and one by a steam turbine.

Widely different and many new applications of electric heat for heat-treatment processes were made. Some of particular interest are as follows:

Two new sizes of wire enameling ovens have been brought out that enable a wire speed considerably higher than that previously received. These ovens handle wire sizes from 18 mil to 3 mil. Each oven bakes five separately enameled coats to 16 wires. The resulting product conforms with the most rigid electrical specifications.

In the annealing of fine copper wire the discoloration due to moisture has been overcome by the use of a mixed gas atmosphere in closed steel retorts. The furnace is of the lift type and will handle 6000 lb. of work per 24 hr. day in retorts 2½ ft. in diameter by 3 ft. deep with an economy of 15 to 25 lb. per kw-hr.

One large plant is installing four large furnaces with equipment for controlling the cooling rate. Two of these are rectangular pit furnaces with a connected load of 1100 kw. capable of annealing (temperature 1500 deg. fahr.) in one charge, 50 ton of alloy steel bar stock in 25 ft. lengths. The heating and cooling cycle is completed in 24 hr.

A double-chamber car bottom furnace, each chamber rated 675 kw., is used for annealing bar stock. These furnaces are equipped for accelerated cooling, employing the same method as the pit furnaces, above which is a closed forced air circulation system that prevents the air from coming in contact with the work.

Adjustable timing devices are used to regulate an entirely automatic continuous furnace for normalizing or quenching (1500 to 1650 deg. fahr.) 6000 lb. per hr. of bar stock 23 ft. long. This furnace has a connected load of 1000 kw.

A differential drive is to be used for a flat top continuous conveyor furnace now nearing completion. A production of 600 lb. per hr. is automatically discharged through a chute in the rear. This is similar to the new standard mesh belt conveyor furnace as shown in Fig. 17, which handles 300 lb. per hr. of small steel parts to 1600 deg. fahr.

For annealing the new short-cycle malleable iron, three-elevator type furnaces are used, producing 100 ton per week. The cycle has been shortened to 24 to 30 hours. This new process reduces the inventory, eliminates boxes and packing.

A new type of continuous recuperative furnace has been introduced to the vitreous enameling industry which, due to elevating the firing chamber, has a natural effective heat seal. Recent improvement has reduced the standby losses by the introduction of a lift type refractory tile barrier between the firing and preheating chambers. This furnace shows a gross economy of 14 to 16 lb. per kw-hr. when firing steel at 1450 deg. fahr. to 1700 deg. fahr.

An important design change has been made in the large 70 ft. long, copper, hydrogen brazing furnaces for refrigerator evaporators. The greater portion of the alloy car supporting the work is now in a separate,

7. Contributed by N. R. Stansel.

enclosed chamber (except for a narrow slot) beneath the heating chamber. This has resulted in better economy, longer life of car and permits the use of a less expensive alloy for the car. There is now in use a smaller furnace of the same type which, with a connected load of 100 kw., automatically brazes 120 pieces per hr. The operator has only to place the work on the cars that carry 14 pieces, at 7-minute intervals, into the furnace.

A new pit type furnace with a simplified control equipment has been introduced for heat treating aluminum alloys, Fig. 18. This furnace is equipped with high heat and low heat switches which give a high power input for quick heating and low power, low gradient input so essential for the holding periods. Improvements in the cover design have reduced the losses to an absolute minimum.

Fig. 17—45-Kw. Two-Circuit Mesh Belt Conveyer Furnace

Two new glass annealing lehrs have been developed for the continuous annealing of sheet glass at about 100 deg. fahr. The larger of these is 13½ ft. wide and 800 ft. long. Heating units totaling 1600 kw. are installed in the first 400 ft.

The cast-in immersion units, which have been successfully applied to heating stereotype metal with as much as 360 kw. in one melting pot, are now being applied to a cable press pot 3 ft. 2 in. in diameter and 4½ ft. deep. This pot, with a connected load of 210 kw., will be capable of melting 18,000 lb. of lead per hr.

Figs. 19 and 20 show a bell type furnace which uses gas to prevent scaling of the charge. In this particular type furnace the base remains on the floor and the bell shaped top may be removed. In this way one furnace can keep several bases busy, saving in equipment investment, material handling and heat required per charge.

The increasing use of furnaces with a controlled atmosphere has created a demand for equipment to economically produce gases suitable for this work. Development work is now being done to produce a mixed gas of hydrogen and nitrogen from ammonia. Another method is to "crack" city gas and make it suitable by breaking up the methans and causing it to unite with steam, giving a resulting mixture of carbon monoxide, carbon dioxide, hydrogen and nitrogen. A furnace for this work is in operation with a connected load of 65 kw. which delivers 1000 cu. ft. of mixed gas per hour for use in brazing furnaces. Approximately 2 cu. ft. of mixed or cracked gas are obtained from 1 cu. ft. of city gas.

## Electrical Control[8]

Gang control, the control by an individual at a distance of a group of electrical drives, has received much attention during the past year. Twelve motors of similar operating characteristics, design and duty cycles, may now be started by means of only two sets of control equipment. With this new interlocking control, applicable to any one of the twelve motors as frequently as is necessary for starting this particular long-hour service, it is possible to eliminate nearly all of the cost of nine complete control equipments previously considered necessary for such an installation. This system provides a method whereby either of two autotransformer starting equipments may be selectively connected to any one of twelve motors for starting purposes. This unit interlock control is entirely self-contained and is so mounted that each control section can be easily removed from the control benchboard for

Fig. 18—84-Kw. Pit Type Electric Furnace for Heat Treating Aluminum Alloy Castings

8. Contributed by C. F. Harding and N. L. Mortensen.

inspection and maintenance or for replacement with a spare unit. Selector switches and relays of the type used in telephone exchanges have been adapted to this service, the entire interlock control operating from a 48-volt storage battery.

Elevator control has also been perfected to such an extent that uniform rates of acceleration up to speeds of 800 or 900 ft. per min. and correspondingly comfortable

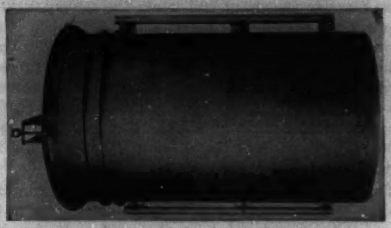

Fig. 19—The Top of This Furnace Can be Readily Moved from Base to Base

retardation to standstill at a predetermined floor level, may be made automatically with entirely enclosed passenger elevator cars. It is claimed that the high speeds are not objectionable to passengers if the walls of the shaft cannot be seen and if the acceleration and retardation are uniform.

Elevator control switches operated under the advantages of direct current are now possible from an a-c. supply by the introduction of a recently developed copper-oxide rectifier unit. This adaptation should prove popular because of its low space factor, low cost and sturdy construction. Similarly, the d-c. brake can

Fig. 20—The Base of This Furnace Remains Fixed, the Removable Hood Fitting Down Over the Charge

be used with a-c. drive of hoisting machinery with the intermediate rectifier unit.

Another interesting application of the copper-oxide rectifier was made to the control of polarity in building up the voltage on synchronous converters. A double-wave rectifier supplied a separate source of direct current. A blocking rectifier in the converter field circuit makes it possible properly to bias the excitation during the starting period by utilizing the positive half of the wave and stopping the negative half. The double-wave rectifier is connected in parallel with the converter armature so that it is only necessary to open the separate source of excitation and short circuit the blocking rectifier when synchronous speed is reached. No transfer equipment is, therefore, necessary. In some of the smaller installations even the brush raising mechanism has been eliminated.

The "fuseless fuse box," or small circuit breaker for domestic appliance and panel-board use, to take the place of fuses, is as simple as a light switch, cannot be "held in" upon injurious overloads, is safe, moisture and shock proof, and should meet with generous usage in the multi-motored home, office, and factory.

The deion principle, which was first applied to relatively high-voltage, heavy-current circuit breakers, is now available for industrial control breakers in 440- to 600-volt motor circuits, thereby providing greater

Fig. 21—Ordinary Arc Chute on a Switch

interrupting capacity in small enclosures. The application of this principle produces rapid deionization of the arc path after the factors producing ionization have become inactive at the cyclic zero of the current wave. The magnetic blow-out coil is thus eliminated. A comparison between the flame emitted from an ordinary breaker and a deion breaker when opening the same load is shown in Figs. 21 and 22. Tests have been reported upon a deion contactor rated for a 40 hp., 440-600-volt circuit in which currents as high as 2500-amperes were successfully interrupted at 48 per cent power factor.

A unique oil type hydraulic operating unit to take the place of large a-c. or d-c. magnets and solenoids, or even air cylinders, where quiet and smooth mechanical thrust is desired throughout a definite distance, consists of a motor-driven oil centrifugal impeller pump located within the movable piston itself. The moving impeller is driven from a stationary motor by means of a spline shaft. In the normal position the piston is at the bottom of the cylinder, which is approximately two-

thirds full of oil. When energized, the motor drives the impeller, thereby creating a pressure between the bottom of the piston and the bottom of the cylinder. This pressure tends to move the piston upward throughout the full length of the cylinder.

Metal-clad switchgear continues to merit further application and successful operation, although its details are far from standardized as yet. Fillers of hard asphaltum compound, petrolatum or vaseline and thin insulating oil, each with its advantages for certain classes of service, are being thoroughly tried out. Care should be exercised in defining and developing standards to distinguish between metal-clad switchgear, with its complete insulation of all parts and resultant space reduction, and the contrasting conventional truck type switchgear.

In connection with motor operation of large valves in steam power plants and in the chemical industry, the

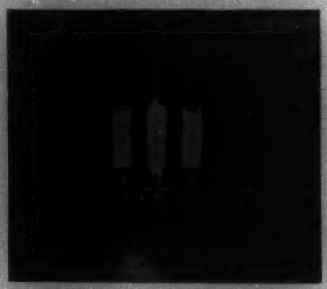

Fig. 22—Arc on Deion Switch When Opening Same Load as Switch in Fig. 21

trend toward extremely high pressures, up to 3000 lb. per sq. in., and relatively high temperatures, has imposed unusual requirements as to positive and accurate seating of the valves. Strains and resultant deformation may result from the pressures and from expansion and contraction of parts due to temperature changes. Also dissimilar metals are used, such as monel stems and chrome steel valve bodies which have unlike temperature coefficients of expansion. Therefore, the standard motor control with a mechanical limit set for an accurate number of turns of the yoke nut would not, under certain conditions, close the valve tight, while under other conditions it might seat the valve before this mechanical limit was reached and thus damage the valve seat.

A torque limit device known as a "valve-tight-seating relay" was developed to meet these varying conditions. This relay is used in connection with the valve control and assures a seating of a valve at a definite, predetermined seat pressure, or a fixed torque on the motor.

The "tight-seating relay" operates on the lock-out principle, or rather, the lock-in principle. The pivoted armature of the relay is held in by a calibrated spring and a shunt magnet. A series magnet on the opposite side of the pivot tends to pull the relay armature out. The pull of the shunt coil is in excess of that required to hold the relay in on the high current inrush of starting the motor. The mechanical limit of the valve operating mechanism is connected to the shunt coil. This limit is set to open the shunt coil while the valve is still an appreciable distance from the seat. As the valve approaches the seat, only the spring on the relay tends to hold the contacts closed. The valve seating pressure then builds up and increases the current passing through the motor and the series coil until this current reaches the predetermined value which then snaps the relay open and disconnects the driving latch, allowing the motor to drift on free of the valve mechanism.

This "tight-seating relay" system is unique in that the full torque of the motor is available clear up to the actual tight seated point on the valve. It also does away with the necessity of accurate setting of the mechanical limit.

A new design known as the duplex magnetic clutch has been developed. This type of clutch is for particular application to hard service.

In the duplex design the magnet members have no relative rotation. They are fastened together and rotate as a unit. The armature member is carried on a spring plate which is bolted at the inside to a projection from the field member. The magnet members carry flanges extending outward on which are mounted the metal friction members which clamp the lining faces. Provision is made for adjusting the distance between the metal friction faces and also for setting the lining carrier to provide positive clearance when the clutch is disengaged.

This design increases the lining area and the driving force for a given diameter, and reduces the possible damage which may result from improper maintenance. When the magnet members make contact as the lining wears, the clutch loses all driving force and obliges the maintenance crew to readjust. In that condition, the magnet members cannot score each other since they have no relative rotation.

Several devices for the control of motors are worthy of note. Fig. 23 illustrates a field relay for synchronous motors with definite time element and lockout coil. The lockout coil prevents the timing mechanism from operating until the motor has accelerated to approximately 95 per cent of synchronous speed when the voltage decreases, permitting the lockout coil to release the timing mechanism.

A new line of starters was developed for ¾-to 3-hp. d-c. motors. This definite-time starter, Fig. 24, is smaller and more compact than previous designs, although the three points of acceleration is an increase.

Definite time acceleration is adjustable over a range of from two to eight seconds.

### Textile Industry[9]

During 1929 there were at least two outstanding developments in applying electrical equipment to textile machinery.

The more important development was the application

Fig. 23—Field Relay for Synchronous Motor with Definite-Time Element and Lockout Coil

of a-c. variable speed motors to spinning machines, printing and finishing machinery, and full-fashioned hosiery knitting machines. Until recently this type of equipment has been driven with various degrees of success by d-c. adjustable-speed motors, by wound rotor-induction motors, multi-speed squirrel-cage motor or constant-single speed squirrel-cage motors with

Fig. 24—Definite-Time Automatic Starter for D-c. Motors

mechanical speed changing devices. With each of these drives there has been one or more undesirable features such as insufficient number of speed points, low efficiency, and inability to obtain exactly the same speed curve repeatedly without resetting the control.

Numerous applications of the a-c. adjustable-speed shunt-characteristic induction motor, Fig. 25, has demonstrated that this motor overcomes all of these disadvantages of the previous drives and permits easy but complete control of the process with improved quality and increased production. The successful and increasing use of this adjustable speed alternating current motor represents a distinct advance in the art.

Another definite development or trend has been the increasing use of "built-in" motors and individual drive with more compact control equipment, many tending toward simplification of the complete equipment and a reduction in the amount of floor space required.

The rayon spindle motor offers a notable example of the increasing use of individual drive. The trend for rayon motors has been toward higher speeds, such as

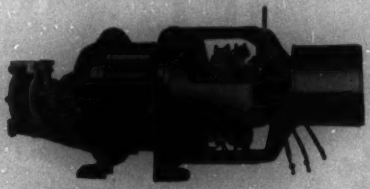

Fig. 25—3-Hp. Brush-Shifting, Adjustable-Speed, A-C. Motor

Fig. 26—Gas—Electric Delivery Truck in Door-to-Door Service

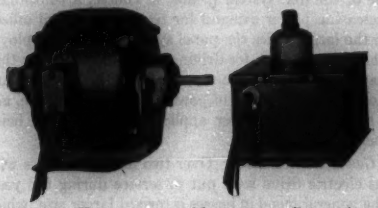

Fig. 27—1/4-Hp. Capacitor Motor with Three Speeds

8000 rev. per min. and upwards. While successful motors have been developed for even higher speeds than these, limitations in the strength of the buckets and in the process itself have somewhat retarded this trend. However, these difficulties are gradually being overcome.

The flexibility of individual drives, together with the improved quality of product, as demonstrated in rayon spinning, has caused a movement toward the use of individual spindle motors for silk and cotton machinery.

9. Contributed by C. W. Falls.

This trend will be watched with great interest by the textile industry.

During 1929, motors were built more compactly into looms and similar machines, with resulting simplicity and economy in floor space. There seems to be considerable opportunity for development in this direction.

Coincident with this movement has been the introduction of very compact combination controllers, which reduce the required space and wiring to a minimum. These control devices combine in one case the motor starter, full protective features, safety disconnecting means and fuses for short-circuit protection.

Fig. 28—The Above Motor Develops 1250 Hp. at 3600 Rev. per Min. To the Right is the Rotor of One of these Motors

## Miscellaneous Applications

*Telephones.* The continued and rapid increase in the use of the dial system means, of course, a continually increasing power demand for telephone central offices. In the larger cities the panel system is being employed which uses motors for driving the switches rather than magnets. The telephone central office is thus more and more becoming a user of power of some magnitude, and a larger field of power applications is steadily being opened.

*Gas-Electric Busses.* Over two hundred busses with gas electric drive were put in service during the year. The general trend in busses is toward larger size, which greatly favors gasoline-electric drive as it is superior to mechanical drive in large units.

Development of a pleasure car with this type drive was undertaken during the year. Five cars were so equipped and tests indicate that the smooth acceleration and easy handling obtained with electric drive will make this application a commercial success when equipment is fully developed.

Gasoline-electric drive has already been applied to small delivery trucks for door-to-door service. Fig. 26 shows one of the 100 Thorne delivery trucks put in service during the past year.

An unusual application of this drive was made by the U. S. Signal Corps. Three 1½-ton trucks with paneled bodies were equipped with motor-generator sets and switchboards. Two of the trucks supply current at 2000 volts to the radio transmitter and the other supplies 12-volt current for battery charging.

*Capacitor Motors.* Although the operation of repulsion motor has been satisfactory on fans, blowers and unit heaters, the need of an even more quiet motor which would not cause radio interference was apparent. Accordingly, the adjustable varying speed capacitor motor was developed for smaller ratings see Fig. 27. The capacitor is so connected in series with one phase of the two-phase stator that it will transform some of the input to make the motor operate like a polyphase induction motor. The other phase of the stator is connected to the speed adjustment switch which has four positions; high, medium, low and off. This causes the motor to operate at 90, 75, and 65 per cent of synchronous speed when loaded to rated capacity.

*High-Speed Motors.* In order to raise the feedwater to a pressure of nearly 1600 lb. in the Deepwater station, New Jersey, eight 1250-hp. induction motors driving five stage centrifugal pumps were installed. These motors develop a speed of 3600 rev. per min., the limit for 60-cycle motors. A feature of the motors is the size of the rotors which have a diameter of about 15 in., which compares favorably with the size of the rotor in a 900-rev. per min., 100-hp. motor. Fig. 28 illustrates these motors.

The committee is indebted to the following firms, institutions and publications with which committeemen are connected or whose cooperation and publications we have made use of in compiling this report:

American Brown Boveri Company.
Bethlehem Steel Company.
Bell Telephone Laboratories.
Braymer Equipment Company.
Cutler Hammer Manufacturing Company.
Duquesne Light Company.
Electric Power Equipment Company.
General Electric Company.
Lehigh Portland Cement Company.
Massachusetts Institute of Technology.
National Council of American Shipbuilders.
Philadelphia Electric Company.
Purdue University.
Reliance Electric & Engineering Company.
University of Toronto.
Westinghouse Electric & Manufacturing Company.
J. G. White Engineering Corporation.
Iron and Steel Engineer Magazine.
Electrical World Magazine.
Machine Design Magazine.

# Instruments and Measurements

## ANNUAL REPORT OF COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

*To the Board of Directors:*

The Committee on Instruments and Measurements reports activities for the past year as follows:

1. Measurement of Core Losses in Terms of Sine-Wave Core Losses.
2. Method of Measuring Distortion Factor.
3. Dielectric Power Loss and Power Factor Measurements.
4. High-Frequency Measurements.
5. Definitions Relating to Telemetering.
6. Measurement of Starting Currents in Fractional Horse-power Motors.
7. Standard for Recording Instruments.
8. Revision of Standard No. 14, Instrument Transformers.
9. Convention of Phase Angle in Instrument Potential Transformers.
10. Standard on the Technique of Temperature Measurement.
11. Reactive Power.
12. Papers.
13. Conclusion.

### Measurement of Core Losses in Terms of Sine-Wave Core Losses

Last year, the Committee outlined three suitable methods for correcting results of core loss measurement to a sine-wave basis when made with a distorted wave of applied voltage, and for such correction recommended preference for methods utilizing average voltage. (See Annual Report, Committee on Instruments and Measurements, A. I. E. E. TRANS., Vol. 48, Oct. 1929, p. 1386).

Following this recommended preference, the Committee has recommended that a method based on the measurement of average voltage be used for correcting core loss results to a sine-wave basis when made with a distorted wave of applied voltage. This action has been regularly transmitted to the transformer subcommittee of the Committee on Electrical Machinery, and to the Standards Committee.

### Method of Measuring Distortion Factor

Last year the Committee defined "distortion factor" of a voltage wave and suggested several methods of measurement. Of these, the use of the Belfils Bridge seemed to be the most promising, though it was recognized that further study and development of the apparatus was necessary. (See Annual Report, Committee on Instruments and Measurements, A. I. E. E. Quarterly TRANS., Oct. 1929, Vol. 48, p. 1386.)

This year, the Committee reports that a Belfils Bridge has been built and is being used for further study of distortion factor in electrical rotating machinery.

A "dynamometer method" for measuring distortion factor has been suggested, but upon investigation it was found that this method belonged in previous Classification D covering "harmonic analyzers."

### Dielectric Power Loss and Power Factor Measurements

During the past year, there has been relatively little advance made in the development of new apparatus or new methods for the determination of dielectric loss and power factor. The various people interested in these measurements have concentrated on making their apparatus more workable, the changes made in technique and apparatus being of a very minor nature.

One interesting application is that of the phase defect compensation method to the three-phase measurement of dielectric power loss and power factor.

Work is being continued on the development of high-capacitance standards for use in checking equipments designed for measurement on full reels of cable. Work on these standards is under way at the present time and it is hoped to develop a capacitor having a capacitance of 0.1 $\mu$f. for use on voltages as high as 45 kv. It is hoped that the capacitor will have a power factor of approximately 0.0025, and will be unaffected by temperature or other operating conditions.

### High-Frequency Measurements

The subcommittee has prepared a partial list of measurement papers appearing in 1929. This is given in Appendix A of this report.

### Definitions Relating to Telemetering

The subcommittee on remote metering has prepared definitions of terms relating to telemetering which by Committee action are given here for comments, which are solicited and should be sent to the secretary of the committee, H. C. Koenig:

*Telemeter*: Measuring, transmitting and receiving apparatus for indicating, recording or integrating at a distance by electrical means the value of a quantity.

*Telemetering*: The indicating, recording or integrating of a quantity at a distance by electrical translating means.

*COMMITTEE ON INSTRUMENTS AND MEASUREMENTS:

Everett S. Lee, Chairman,
H. C. Koenig, Secretary,
E. J. Rutan, Vice-Chairman,

| | | |
|---|---|---|
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| A. L. Cook, | I. F. Kinnard, | R. W. Sorensen, |
| E. D. Doyle, | A. E. Knowlton, | H. M. Turner. |

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*



30-134

*Voltage (Type) Telemeter*: A telemeter which depends on the variation of a voltage as the translating means.

*Current (Type) Telemeter*: A telemeter which depends on the variation of a current as the translating means.

*Frequency (Type) Telemeter*: A telemeter which depends on the variation of a frequency as the translating means.

*Impulse (Type) Telemeter*: A telemeter which depends on electrical impulses as the translating means.

*Duplicate Position (Type) Telemeter*: A telemeter which depends on duplicating at the receiving end changes in angular relation or impedance of the translating means.

*Direct-Acting (Type) Telemeter*: A telemeter in which the translating means (voltage, current, frequency, etc.) increases in value with increase in the measured quantity.

*Inverse-Acting (Type) Telemeter*: A telemeter in which the translating means (voltage, current, frequency, etc.) decreases in value with increase in the measured quantity.

Note: In the above definitions the word "type" has been included in order to make clear the characteristic being defined. It is hoped that, after these definitions have more common application, the word "type" may be dropped and the terms used understood.

It is suggested that a telemeter which measures
Current be called a teleammeter.
Voltage be called a televoltmeter.
Watts be called a telewattmeter.

## Measurement of Starting Currents in Fractional Horsepower Motors

A subcommittee has prepared the following report relative to measurement of starting currents in fractional horsepower motors.

"In 1925 one of the large middle western power companies undertook an independent investigation into the operating characteristics of fractional-horsepower motors. This investigation was started because of the numerous service calls due to flicker in lamps caused by the starting of small motors operated from the same lighting circuit.

"A paper on this subject was read at the 1925 annual meeting of the Association of Edison Illuminating Companies. Shortly thereafter a joint committee was formed which included representatives from the Association of Edison Illuminating Companies, National Electric Light Association, National Electrical Manufacturer's Association, the American Washing Machine Manufacturers' Association and various individual manufacturers of small motors and of motor-driven domestic electrical equipment. This committee held several meetings in 1927, 1928 and 1929, resulting in the setting up of specifications for performance of fractional-horsepower motors. These specifications are in use and are readily applied in all particulars except the limitation upon starting current.

"In the specifications of the joint committee and also in other specifications issued by various engineering societies, starting current has been defined as the reading obtained on a well-damped ammeter. Efforts to determine compliance with the specifications of the joint committee brought about discussions as to the methods of measuring such starting currents. It was suggested at the meeting of the Instruments and Measurements Committee held on November 29, 1929, that the question of measuring starting currents could very well be considered by a subcommittee. A subcommittee was appointed to investigate the question, and report to the main committee.

"The starting current taken by a fractional-horsepower, single-phase motor persists for a relatively small number of cycles.

"In the case of repulsion-induction motors, the maximum current drawn in the first cycle falls rapidly in successive cycles, is suddenly increased momentarily by the action of the short-circuiting device on the rotor, and then quickly reduces to the normal running current.

"In the case of split-phase motors, the initial input may persist for from 6 to 15 or 20 cycles, and is then rapidly reduced to the normal running current.

"The ideal instrument for the measurement of starting currents would, of course, be the oscillograph. There is no question that the oscillograph represents the true conditions in the motor circuit during the starting period. Because of its expense and bulkiness, however, the oscillograph does not readily lend itself to the measurements of starting currents in the field.

"On the other hand, readings of an ammeter must be interpreted in terms of damping and inertia of moving parts, personal equations, and the magnitude and duration of the starting current as actually recorded by the oscillograph.

"In other words, we have at least five variables to be considered in setting up any standard method for measurement of starting currents for small motors.

1. Meter damping.
2. Inertia of moving elements of meter.
3. Initial amplitude of starting current.
4. Duration of starting currents.
5. Personal equation.

"The nearest approach to the oscillograph in an a-c. instrument would be one which is critically damped and has such a short period (by reducing the moment of inertia or increasing the restoring torque) that its pointer would follow exactly the changes current. Such an instrument must have a period of the order of 0.01 second or less, which naturally places it outside the class of ordinary a-c. ammeters.

"The action of a current of short duration on the ordinary a-c. instrument has a ballistic effect, but unfortunately this effect is not proportional to the current or its square, but depends upon $\int i^2 \, d\,t$, which shows

that the same indication would result for widely differing currents provided they had correspondingly different durations. This effect is further complicated by the fact that the electromagnetic constant of the instrument varies greatly throughout its scale, so that the ballistic effect depends in addition upon the duration of the current relative to the responsiveness of the movable system, which differs among instruments of various manufacturers and even among instruments of the same manufacturer.

"It seems evident therefore that the simple indication of any of the ordinary a-c. ammeters cannot be used as a measure of current for short durations, such as motor starting currents.

"Since the origin of this investigation was concerned with the flicker effect upon lamps, it seemed logical to study motor starting currents in relations to the physiological perception of flicker. Recent studies have tended to show that the physiological effect of flicker produced in the starting of motors was approximately proportional to the locked-shaft current.

"In view of the above facts the committee recommends the use of an ammeter equipped with an adjustable backstop, by means of which the pointer can be initially set at any place upon the scale. By making several trials, a point can be found from which the pointer moves but very slightly upon the starting of the motor. This point has been found to be the maximum current drawn by the motor in starting. In other words, it is approximately equivalent to the locked-shaft current. This meter therefore, permits the measurement of locked-shaft current without the attendant difficulties due to heating.

"The committee has not attempted to devise a new instrument for the purpose of measuring starting currents, for the instrument referred to has already been used for this and other work and can be made by any of the instrument manufacturers."

### Standard for Recording Instruments

A tentative draft of Standard for Recording Instruments has been prepared, using Instrument Standards No. 33 as a basis and making necessary modifications and additions. The latest copy of this tenative draft is now being circulated to members of the subcommittee on recording instruments, and to other instrument manufacturers who are not represented on the Committee.

### Revision of Standard No. 14—Instrument Transformers

A subcommittee has been appointed to revise Standard No. 14. Mr. E. J. Rutan is Chairman of this subcommittee.

### Convention of Phase Angle in Instrument Potential Transformers

Present A. I. E. E. Standard No. 14, Par. 59 provides that for instrument potential transformers, the phase angle is conveniently considered as negative when the reversed secondary voltage vector leads the primary voltage vector. This convention, however, has not been universally followed. To harmonize procedure, the Committee has recommended to the Standards Committee that the rule be changed to provide that the phase angle be considered as positive when the reversed secondary voltage vector leads the primary voltage vector.

### Standard on the Technique of Temperature Measurements

The Committee hopes to complete the work on this Standard during the coming year.

### Reactive Power

The Committee is studying the question of the measurement of reactive power.

### Papers

A total of twelve papers was reviewed during the year, eight of which were presented, as follows:

*Measurement of Electrical Machine Characteristics*

*A Recording Torque Indicator that Automatically Records the Torsional Effect of Motors during Acceleration*, G. R. Anderson, A. I. E. E. Quarterly Trans., Vol. 49, p. 333, January 1930.

*Determination of Generator Speed and Retardation during Loss Measurements*, O. E. Charlton and W. D. Ketchum, Northeastern District Meeting, Springfield, Mass., May 1930.

*Measurement of Temperature*

*A Self-Compensating Temperature Indicator*, I. F. Kinnard and H. T. Faus, A. I. E. E. Journal, Vol. 49, p. 343, May 1930.

*Measurement of Light*

*An Ultra Violet Light Meter*, Dr. H. C. Rentschler, A. I. E. E. Quarterly Trans., Vol. 49, p. 546, April 1930.

*Oscillographs*

*Design and Application of a Cathode Ray Oscillograph with Norinder Relay*, O. Ackermann, A. I. E. E. Journal, Vol. 49, p. 285, April 1930.

*A New Portable Oscillograph*, C. M. Hathaway, North Eastern District Meeting, Springfield, Mass., May 1930.

*Network Analyzer*

*The M. I. T. Network Analyzer*, H. L. Hazen, O. R. Schurig, M. F. Gardner, North Eastern District Meeting, Springfield, Mass., May 1930.

*Air Capacitors*

*Phase Difference in an Air Capacitor*, W. B. Kouwenhoven and C. L. Lemmon, North Eastern District Meeting, Springfield, Mass., May 1930.

### Conclusion

The interest of the members of the Committee on Instruments and Measurements has been maintained in its activities during the past year, resulting in definite action on several subjects. The study now being given to present projects should result in further definite action next year.

## APPENDIX A

A partial list of papers on high-frequency measurements appearing in 1929.


AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS QUARTERLY TRANSACTIONS, APRIL 1929, VOL. 48

*Ionisation Studies in Paper-Insulated Cables*, C. L. Dawes, H. H. Reichard, P. H. Humphries, p. 382.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS QUARTERLY TRANSACTIONS, JULY 1929, VOL. 48

*Electrical Instruments Used in the Measurement of Flow*, W. H. Pratt, p. 737.

*Telemetering*, Linder, Stewart, Rex and Fitzgerald, p. 766.

*A Precision Regulator for Alternating Voltage*, Stoller and Power, p. 808.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS QUARTERLY TRANSACTIONS, OCTOBER 1929, VOL. 48

*Shielding and Guarding in Electrical Apparatus Used in Measurements—General Principles*, H. L. Curtis, p. 1263.

*Some Problems in Dielectric Loss Measurements*, C. L. Dawes, P. L. Hoover, and R. H. Reichard, p. 1271.

*Shielding in High-Frequency Measurements*, J. G. Ferguson, p. 1286.

*Guarding and Shielding for Dielectric Loss; Measurements on Short Lengths of High-Tension Power Cable*, E. H. Salter, p. 1294.

*Precautions Against Stray Magnetic Fields in Measurements with Large Alternating Currents*, F. B. Silsbee, p. 1301.

*Magnetic Shielding (Shielding of Magnetic Instruments from Steady Stray Fields)*, S. L. Gokhale, p. 1307.

*Electrical Wave Analyzers for Power and Telephone Systems*, McCurdy and Blythe, p. 1167.

Report of Committee on Instruments and Measurements, p. 1385.

*Institute of Radio Engineers Proceedings, Vol. 17, 1929*

"A Direct Reading R. F. Meter," R. E. Hitchcock, Jan., p. 24.

"An Extension of Method of Measuring L. & C., Harris, March, p. 516.

"Use of Electron-Tube Peak Voltmeter for the Measurement of Modulation," Joliffe, April, p. 660.

"Measurement of Height of Heaviside Layer," Kenrick and Jen, April, p. 711.

"Measurement of the Frequencies of Distant Radio Transmitting Stations," Pession and Gorio, April, p. 734.

"A Direct Reading Frequency Bridge Based on Hay's Bridge Circuit," Loury and Bayly, May, p. 834.

"Vacuum Tube Voltmeter Design," May, p. 864.

"Measurement of Direct Interelectrode Capacitance of Vacuum Tubes," Loughren and Parker, June, p. 957.

"Measurement of Directional Distribution of Static," Harper, July, p. 1214.

"Routine Measurement of Frequency of Broadcasting Stations," Bogardus and Manning, July, p. 1225.

"Electromagnetic Monochoid for Measurement of A. F.," Harries, Aug., p. 1316.

"Static and Motional Impedance of Magnetostriction Resonator," Lange and Myers, Oct., p. 1687.

"Inductance as Affected by Initial Magnetic State, Air Gap, and Superposed Current," Turner, Oct., p. 1822.

"Measurement of Frequency," Jimbo, Nov., p. 2011.

"Frequency Measurements Based on a Single Frequency," Hall, Feb., p. 273.

*Bell System Technical Journal, Vol. VIII, 1929*

"Articulation Testing Methods," H. Fletcher and J. C. Stemberg, p. 806.

"Braun Tube Hysteresigraph," J. B. Johnston, p. 286.

"High Precision Standard of Frequency," Marrison, p. 493.

"Shielding in High Frequency Measurements," Ferguson, p. 560.

"Observations on Modes of Vibration and Temperature Coefficients of Quartz Crystal Plates," Lack, p. 515.

"Loud Speaker Measurements," Bostwick, p. 135.

"Speech Power and Its Measurement," Sivian, p. 646.

"Physical Properties and Methods of Test of Some Sheet Non-Ferrous Metals," Townsend and Straw, p. 749.

"Test for Polarization of Electron Waves by Reflection," Davisson and Gerner, p. 466.

*Journal of the Franklin Institute, Vol. 207, 1929*

"Measurement of Sound Absorption Coefficients," Sabine, p. 341.

"A Mechanical Method of Measuring Sound Pressure," Eisenhour and Tyzzer, Vol. 208, p. 397.

*Physical Review, Vol. 34, 1929*

"Determination of Charge of Positive Irons from Measurements of Shot Effect," Williams and Huxford, Vol. 33, p. 773.

"Contact Potential Measurement with Absorbed Films," Langmuir and Kingdon, p. 129.

"Measurement of Ionization Potential in Mercury Vapor," Bleackney, p. 157.

"New Method of Measuring Dielectric Constant of Conducting Liquids," Aston, p. 300.

"Measurement of Discontinuous Change in Magnetization," Bozorth, p. 772.

"Dielectric Loss at High Frequency," Owen, p. 1035.

"Static Balance Electrometer for Measuring Dielectric Constants of Electroytes," Carman, Young and Smith, p. 1040.

"Variation of Dielectric Constant with Frequency," Johnston and Williams, p. 1483.

*Institution of Electrical Engineers, Vol. 67, 1929*

"Contact Effects Between Electrodes and Dielectrics," (E. R. A. Report).

"Precautions in the Use of Standard Instruments," Lawes, p. 541.

"Effect of Added Impurities on the Breakdown Voltage of Insulating Oils," (E. R. A. Report), p. 750.

"Recent Developments in Electricity Meters," Carr, p. 859.

"Electromagnetic Testing for Mechanical Flaws on Steel Wire Ropes," Wall, p. 899.

"Portable Radio Intensity Measuring Apparatus," Hollingworth and Marsmith, p. 1033.

"A Measurement of the Sound Pressure on an Obstacle," West, p. 1137.

"A Precise Electrometer Method for Voltage Transformer Testing," Spisbury, p. 1143.

"The Testing of Porcelain Insulators," Goodlit, p. 1177.

"Directions for the Study of Mecamte," (E. R. A. Report), p. 1243.

"Precision Permeability Measurements on Straight Bars and Strips in the Region of High Permeability," Webb and Ford, p. 1302.

*Experimental Wireless and the Wireless Engineer, Vol. VI, 1929*

"Notes on the Calibration, Permanence and Overall Accuracy of Series-Gap Precision Variable Air Condensers," Griffiths, p. 23, p. 77.

"Measurement of Grid-Anode Capacity of Tetrodes," Bligh, p. 299.

"The Problem of Grid Turn-Over Capacity," Reed, p. 310.

"A Portable Radio Intensity Measuring Apparatus for High Frequency," p. 316.

"Measurement of Wave Length of Broadcasting Stations," Braillard and Divoire, p. 412.

"Frequency Departure of Thermionic Oscillators from the LC Value," Pack, p. 472.

"Potential Difference and E. M. F.," Brederman, p. 481.

"Potential Difference and E. M. F.," (Comment on), Wilmotte, p. 551.

"Notes on Standard Inductances for Wavemeters and other R. F. Purposes," Griffiths, p. 543.

"Comparison of Power Factors of Condensers," Wilmotte, p. 656.

"A Sensitive Valve Voltmeter Without 'Backing Off'," Von Ardenne, p. 669.

*Revue General de L'Electricite, Vol. 25, 1929*

"Measurement of 'Residual' Voltage by Resonant Bridge," Belfils, p. 523, (Previous articles on same subject), Vol. 17, p. 32 and Vol. 18, p. 844.

"The Measurement of High Frequency by Means of Piezo-Electric Oscillators," Decaux, p. 322.

"The Calibration of Tuning Forks Used to Measure High Frequency," Decaux, p. 283.

"Contribution to Mathematical Theory of the Measurement of Inductance," Cobras, Vol. 26, pp. 939.

"Measurement of Very High Potentials by Means of a Spark-Gap in Air," A. Segall, Vol. 26, 1929, p. 716.

"Note on Measurement of Capacity Unbalance in Telephone Cables," Dimand, Vol. 26, p. 105.

*Miscellaneous*

"An Ampere-meter for Measuring Currents of Very High Frequency," Moullin, *Proc. Roy. Soc.*, Nov. 1928, p. 41.

"A Sensitive V. T. Voltmeter (Heterodyne)," *J. O. S. A.*, Dec. 1928, p. 440.

"Note on the Application of the Whiddington Ultra Micrometer," J. S. I., (London), March 1929, p. 81.

"Measurement of R. and L. of Iron Cored Coils Carrying Direct Current," Hartshorn, *J. S. I.* (London), April 1929, p. 113.

"A Method of Determining the Equivalent Resistance of Air Condensers at High Frequencies," Sutton, *Proc. Roy. Soc.*, Feb. 15, 1929, p. 126.

"A. V. T. Impedance Bridge," Stone, *J. O. S. A.*, Nov. 1929, p. 326.

"Characteristics of Audio-Frequency Transformers," Turner, *Proc.* Radio Club of America, Sept. 1929.

"Characteristics of Audio-Frequency Transformers," Turner, *Radio Broadcast*, Nov. 1929.

"On the Modes of Vibration of a Quartz Crystal," Harding and White, *Phil. Magazine*, London, Aug. 1929.

# Applications to Iron and Steel Production

## ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION*

*To the Board of Directors:*

The unprecedented activity in the iron and steel industry, which resulted in record production of steel during 1929, is also indicated by the number of rolling mill electric drives purchased and installed.

Last year it was pointed out that synchronous motors for driving constant speed mills were increasing in number every year and this has been especially noticeable during the past year. Synchronous motors are desirable in any kind of constant speed mill application where the peak load conditions are not of sufficient size to interfere with the capacity of the power plant. One of the largest single installations of synchronous motors so far is that at the national works of the National Tube Company at McKeesport, Pa., where six large synchronous motors will be used for driving two seamless tube mills.

Hand-to-mouth buying by users of rolled steel products is one of the factors responsible for single mills being required to roll during one day small tonnages of a considerable variety of products. To meet this condition, the mills must be extremely flexible and this flexibility is most readily obtained by using individual adjustable-speed motor drive for all or many of the roll stands. An interesting example of this is a 15-stand, 10-inch merchant mill at the Indiana Harbor Plant of the Inland Steel Company which will be driven by 13 adjustable-speed d-c. motors, totaling 4900 hp.

The past year saw the application of the first twin motor drive to a blooming mill. The development of this idea has been carried on for some time and was probably an outgrowth of the idea of the individual stand drive which has been carried on for the past several years, on various types of billet, strip and skelp mills. The advantage of this type of drive is readily appreciated inasmuch as it eliminates the pinion stand with its losses and maintenance and at the same time permits a variation in roll diameter thus eliminating matching of rolls and permitting flexibility in the mill operation.

There is a continual demand from the steel plant operators to reduce delays and maintenance costs, and great strides have been made in the application of magnetic control in various motor drives.

There has also been further development in the automatic screw-down, which the year 1929 saw applied to plate mills and structural mills.

Development in the application of voltage control has continued to show the following advantages: less maintenance, ease of operation, faster manipulation of the screw-down, and simplicity of control. All of these factors are of vital importance and result materially in improved efficiency and increased production of the mills.

The control for reversing mill motors has been improved. This improvement includes the advantages gained on voltage control as applied to screw-downs, and simplified voltage control of reversing mill drive by controlling the fields of individual exciters for the motor and generator fields of a reversing mill drive. This has greatly reduced the maintenance on the field control equipment for reversing mills and has permitted simpler and more sturdy apparatus for field control. It has practically eliminated the high inductive arc on the field control panel contactors when a mill motor is accelerated and decelerated.

During the past year the installation of photoelectric cells for use as flag switches has incresed. In addition, the successful operation of the photoelectric cell has created other uses, such as direct and recording temperature indicators to replace the present pyrometer counters for sheets, tubes, billets and ingots, fire prevention, etc. The field for this little device is spreading rapidly and the demand for photo-electric cells in the steel mills in the next few years will be greatly increased. The design of this apparatus lends itself to practically any application where it is desired to automatize a mechanical operation or adjust an operating condition to obtain increased production.

Extended research and experiment are being made in the economical use of fuel in steel mills. The electrically operated recording calorimeters and electrically operated gas meters are being used to control the combustion automatically and more economically.

The use of electric welding has developed enormously in the steel mills. Particularly of note is the development in the electric welding of steel tubes.

A new mill which eliminates all hand and mechanical puddling, has been completed at Pittsburg for the manufacture of wrought iron. This plant is electrically equipped throughout and is the most modern mill in the world electrically operated for the manufacture of wrought iron. The method of operation consists essentially of pouring molten iron over molten cinder in a ladle under suitable conditions to form a ball. This ball is then formed by a powerful motor driven

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M. M. Fowler, Chairman,

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| F. B. Crosby, | A. G. Pierce, | Wilfred Sykes, |
| A. C. Cummins, | F. O. Schnure, | T. S. Towle, |
| S. L. Henderson, | W. B. Shirk, | J. D. Wright. |

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.*



30-136

press into a bloom which in turn is rolled down in the electrically operated blooming mill to muck bar or billets preparatory to being sent to the skelp mills.

Up to this time the limiting feature in the wrought iron industry has been the economical inability to produce wrought iron on a quantity basis. As a result, the principal use of wrought iron has been confined to the manufacture of pipe. With the development of this new method of making wrought iron on an economical quantity basis there will undoubtedly be markets opened to it where previously it was unable to compete.

The growth of blast furnace production is being greatly assisted by the automatic operation of skip hoists, the application of stock line recorders, pyrometers and other features that tend to give the furnace operators more information regarding their operation.

# Production and Application of Light

## REPORT OF THE COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT*

*To the Board of Directors:*

### Production of Light

*Statistics on Incandescent Lamp Sales.*[1] The sale of large tungsten filament lamps (as distinguished from the miniature types) totaled 344,000,000 during 1929, an increase of 8.7 per cent over the previous year's sales. The fact that the production of large tungsten filament lamps alone is running well over a million lamps per working day will give some impression of the extent to which our modern life has become dependent upon this source of artificial illumination.

For these lamps the average watts per lamp in 1929 ran 60.7 as compared with 51.5 in 1919, and the average lumens per watt were 13.1 as compared with 10.5 ten years previously.

In the 100-130-volt range half of the incandescent lamps sold (49.5 per cent) were of 115 volts, 39.4 per cent were of 120 volts, 6.5 per cent were of 110 volts, and 3.4 per cent were of 125 volts, these four voltages accounting for 98.8 per cent of the total. Lamps for 220-260 volt service totaled in quantity 3.3 per cent of that supplied for the lower standard voltage range. These facts should be of special interest to electrical engineers as indicative of the trend of voltage standardization.

The Service Voltage Standardization Committee of the Apparatus Committee of the National Electric Light Association recommended some years ago as standard practise the selection of such a service line voltage as will supply the proper average voltage to 115-volt lamps, with recognized departures in the case of 110-volt systems and existing 120-volt systems. As there is commonly at least two or three volts drop in the interior wiring the voltage delivered at the customers' service switch should be correspondingly higher in order to supply an average voltage at the socket corresponding to the standard voltage of lamp selected for use.

*Sources of Ultra-Violet Radiation.* Within the past year there has been a marked advance in the production and home use of ultra-violet for artificial sunshine. The American public has shown a great interest in this development.

In a paper, *Simulating Sunlight—A New Era of Artificial Lighting*, presented at the Winter Convention, Dr. M. Luckiesh described a new tungsten-mercury arc lamp made in a bulb of special glass which transmits the short wave radiation desired. This lamp has been developed to provide a simple source of artificial sunlight having the same general form as that of an incandescent lamp. The lamp operates on low voltage, and must be used with a transformer designed with a special shape of drooping characteristic curve. A tungsten filament is placed in parallel with the arc. The filament lights first, and almost instantly some of the mercury in a small globule free in the bulb becomes vaporized and the mercury arc is formed between the tungsten electrodes. The initial starting voltage applied to the filament then drops to the normal operating value.

The carbon arc lamp has during the past year been developed to a high degree of efficiency for the reproduction of sunlight in the home. The use of cerium-cored carbons, for example, with a carefully designed chromium-plated reflector, enables it to give a close reproduction of natural sunlight throughout the ultra-violet, visible and infra-red zones. Filters of special glass can be used to cut out the very short ultra-violet radiation and transmit only that part found in natural sunshine. A limited burning period provides an important safety feature.

*Other Lamp Developments.* The use of larger screens in the projection of motion pictures and the probability of the perfection, in the near future, of methods for stereoscopic projection, have created a demand for a source of light of greater brilliancy than any now in use. This demand has been met by the development of a super high-intensity projector carbon. Operated at a current of 225 to 250 amperes, this carbon arc possesses an intrinsic brilliancy 50 per cent greater than the sun at zenith.

The use of gaseous conductor lamps has continued to increase during the year, and developments in the field of the hot-cathode neon lamp and in a type of lamp which produces in a single tube a light which appears subjectively white are reported in progress.

### Utilization of Light

*Color Lighting.* Important developments have been

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Mr. H. S. Broadbent, Secretary,

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| Prof. J. W. Barker, | Mr. L. A. Hawkins, | Mr. P. S. Millar, |
| Mr. W. T. Blackwell, | Prof. H. H. Higbie, | Prof. W. T. Ryan, |
| Prof. J. M. Bryant, | Mr. W. C. Kalb, | Mr. B. E. Shackelford, |
| Mr. W. T. Dempsey, | Prof. C. L. Kinsloe, | Mr. C. J. Stahl, |
| Mr. E. E. Dorting, | Mr. R. D. Malley, | Mr. G. H. Stickney. |

1. The Lamp Committee of the National Electric Light Association presents each year to that association a report in which the statistics relating to incandescent lamp production are analyzed in detail, and in which important developments in the production and application of light are reviewed. It is impossible to deal with this subject without covering much of the same ground. However, the statistics presented and the features of the past year's progress commented upon in this report are believed to be of particular interest to the electrical engineering profession. Those who wish more detailed statistics, as well as those who are concerned with the commercial and engineering problems of lighting, will find valuable the reports of various committees of the National Electric Light Association and the Illuminating Engineering Society.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

made during the year with regard to the production of color-lighting effects in conjunction with which several systems for controlling the voltage of large blocks of power supplied to incandescent lamps have been employed. In this field the Selsyn-Thyratron Control system, used in the Chicago Opera House, and the system installed at the Barcelona Exposition (as described by Mr. C. J. Stahl in an Illumination Item in the A. I. E. E. JL., December, 1929, p. 918) may be mentioned particularly. A device known as the "Lumitone" has also been developed to provide for manual or automatic control of color lighting circuits. These systems of control have placed at the disposal of the illuminating engineers more efficient and effective tools with which to work and will help further to popularize color lighting.

In this connection a simple yet effective application of controlled color lighting has made its appearance in the form of the Colorama, first used in the Ballroom of the St. George Hotel in Brooklyn.[2] The room is finished in flat white, and the money that would otherwise have been spent for the usual sort of wall and ceiling decoration has been put into an elaborate system of concealed color lighting by which patterns of colored light in never-ending variety are thrown on walls and ceilings. Another form of interior color lighting has been used effectively in the Sherman Hotel, Chicago.

*Modernistic Note in Lighting.* Modernistic lighting, referred to in the report last year, has continued to grow rapidly in favor, particularly in lobbies, entrances for office buildings, and commercial establishments visited by the public. The movement is being reflected somewhat in residential lighting equipment.

*Lighting for Aviation.* This subject was dealt with at length in last year's report. The incandescent lamp is used extensively in this field where the ease with which it lends itself to remote control and to operation by inexperienced personnel are important factors. The number of lighted airports has jumped from about 75 to over 300 during 1929. There has been a considerable improvement in the design of field lighting equipment as well as an extension in the application of light in actual aerial navigation.

An important contribution to the solution of the problem of night illumination of airports has been made through the use of a carbon arc searchlight equipped with a lens throwing a flat beam of wide horizontal distribution. This "pancake" of light provides good ground illumination over a radius of more than 5000 ft. The point source of light permits the use of a shadow band or path, which can be controlled from the operating tower, to protect the eyes of the aviator from glare while landing.

A method of tapping high-tension transmission lines for small amounts of power has been developed which is of interest in marking them with light in the vicinity of air ways and airports. In this system, capacitors made up somewhat similar in form and appearance to ordinary type high-tension insulators, are used. A series of these capacitors, their number depending upon the voltage of the line, is supported from the tower and the terminal on the lowest capacitor is connected to the line, while the terminal at the top is connected in series with the lighting unit to ground.

*Silent Carbon Arc.* The perfection of a method for silencing the carbon arc by filtering out the commutator ripple has placed it in a position where it can be used in the production of sound motion pictures, from which field it had been temporarily barred. A high capacity electrolytic condenser is connected from a point between the auxiliary and series field windings to the opposite terminal of the d-c. generator. Oscillograph tests show that the commutator ripple and consequent arc noise are effectively eliminated by this means.

*Other Applications.* A possible application of underwater lighting, described in the annual report last year, may be found in outlining seaplane base landing areas with light. The lighting of football fields and race tracks is becoming increasingly popular and is now fairly well standardized, increasing the recreational opportunities afforded to the public. The popularity of such night sports is indicated by the increased attendance as compared with that at similar contests held during the day; night attendance has been reported to run from two to ten times the usual day figure. Baseball is now being added to the list of night-lighted sports.

## Present Saturation in Lighting

A subject of basic interest to the electrical industry was dealt with at a meeting of the New York Section of the A. I. E. E.[3] under the title of *How Much Light*. The results of a careful study made by an informal committee organized at the instance of the New York Section, "to set up an approximate estimate of the present percentage saturation of the United States in artificial light," were presented. It was estimated that the present annual consumption of 20 billion kw-hr. for lighting would have to be increased to approximately 151 billion to provide the level of illumination of probable greatest economic advantage. The present saturation in artificial light as compared with the desirable value, based solely on eye considerations, was estimated to be about 3 per cent. The room for growth in the field of electric lighting, in spite of all the progress that has been made in the last quarter century, is still very great. Physical limitations, particularly in the distribution of energy, must be removed or overcome

2. See "Decorating with Light," *The American Architect*, Feb. 1930, p. 26; "Decorative Color Lighting," by A. T. North, *Architectural Forum*, Feb. 1930, p. 288.

3. See A.I.E.E. JL., Vol. 49, January 1930, p. 70. The report was submitted to the meeting by Frank W. Smith, Chairman of the Lamp Committee of the N. E. L. A., Arthur E. Allen, Vice-President, Westinghouse Lamp Co. and Dr. E. E. Free, Consulting Engineer.

before the electric lighting field can develop as freely and rapidly as it should, and this is a problem of particular interest to the electrical engineer.

### Operating Voltage in Relation to Lighting

*Voltage Conditions on Lighting Circuits.* The past year has seen a general and rather surprised awakening, on the part of the electrical industry engaged in furnishing electrical energy and equipment for lighting, to the fact that the ever-increasing demands for electric light and electric service have in many cases thrown such heavy loads on existing circuits that the voltage delivered at the point of utilization during the hours of greatest use is considerably below the presumed nominal value for which the devices have been designed to operate. When the voltage at the socket is less than this normal value the customer spends less for energy to operate the lamps and for lamp renewals, but he gets so much less light in return for his reduced expenditure that the unit cost is increased and, of course, the illumination he receives from each unit is also diminished, as one per cent reduction in voltage reduces the light output about 3.4 per cent.

The problem of delivering electrical energy at the proper voltage to the point of utilization is worthy of the electrical engineer's most careful study. He should first of all have a clear comprehension of the effect of voltage variations on the wattage consumption, light output, operating cost and unit cost of light production with incandescent lamps as this is essential to the proper treatment of the problem of the economic production of light. It is rather difficult to visualize the relations of the several elements involved in this problem, especially when the effect of wiring losses and fixed charges on the wiring are taken into account (as they should be). On this account an animated form of voltage demonstration chart has been devised as a means of presenting these data.

The subject has been discussed at length from the point of view of the central station in the 1930 report of the N. E. L. A. Lamp Committee, in which the results of an extended survey of socket voltages are given.

*The Mean-Voltage Meter.* A device for measuring average voltage, described in an Illumination Item in the A. I. E. E. Jl., May, 1929, p. 397, has been redesigned and is now produced in a more compact form. One element is virtually a watt-hour meter with two potential coils instead of a voltage and current coil so that it registers volts squared times hours in place of watt hours. The other element is a telechron which gives the time reading so that the average voltage (root mean square) can be easily obtained. It is designed for use on 60-cycle current, 100-130 volts. This device, plugged in at the lamp socket, records only when the lamp is in operation so that it shows the average voltage delivered to the lamp during the time it was in operation. It should find extensive use in making surveys for the purpose of correcting the undervoltage operation of lamps and other electrical devices. Where recording meters are used for obtaining average socket voltage they should also be plugged in at the lamp terminal so as to register only when the lamp is burning. Voltage at other time does not affect the lamp.

### Interior Wiring

*Installation Standards.* The problem of maintaining the proper average voltage at the socket also involves the question of the voltage drop in the wiring on the customer's premises. In last year's report reference was made to the preparation of a set of model specification paragraphs dealing with the adequacy of wiring. The Commercial and Industrial Lighting Committee of the N. E. L. A., with the collaboration of other branches of the industry and with other authorities interested in this subject, has prepared and recently issued a minimum specification for the adequate wiring of lighting circuits in commercial and public structures. Every electrical engineer who is brought into contact with the design or operation of lighting installations should be familiar with these specifications.

In this connection the wiring of the Chrysler Building described in two articles, "Wiring the World's Tallest Building," by David M. Goe, and "Chrysler Building Feeder Design," by L. Mackler, both appearing in *Electrical Contracting*, March, 1930, is well worth careful study because it represents advanced practise and refinement in design. Primary current is carried at 13,800 volts to the basement, the 30th, 60th and 72nd floors where secondary switch boards are located. The first article considers the average individual occupant in relation to his electrical requirements, floor area basis for circuiting, flexibility, facts rather than assumptions, adequacy, standardized feeder lengths, and provisions for the future. The second article describes in detail the calculations and recheck made to insure adequacy and adherence to voltage drop requirements. All this is very important from the standpoint of the application of light for it is not uncommon to find lamps operating at a voltage five or more volts below their labeled values in commercial buildings and probably rather more than this in industrial plants (extreme cases running as low as 80 per cent have been found). This undervoltage burning diminishes the light output more than it does the operating cost and results in inefficient and unsatisfactory lighting service.

### Miscellaneous

Photoelectric cells are finding use in conjunction with the control of lighting installations. Electric signs, ordinarily operated by time clock alone, can have the photoelectric cell control added so that the sign will be lighted during exceptionally dark periods of the day during which it would ordinarily be unlighted. Many other applications will in all probability be found as the equipment is further developed.

A new system of interchanging lighting information

among lighting engineers through the medium of data sheets describing outstanding installations has been inaugurated by the I. E. S. Committee on Lighting Service.

The accepted specifications for motor vehicle headlights have been revised by the I. E. S. Committee to include the dual-beam type of equipment, a revision of the tail-light specification is practically complete, and a new signal light specification has been drawn up.

The celebration in this country of Light's Golden Jubilee officially opened with elaborate lighting effects and special ceremonies, at the time of the National Electric Light Association Convention in Atlantic City last June. Wide-spread interest and enthusiasm lead up to the grand climax at Mr. Ford's dinner on October 21st, at which Mr. Edison completed a model of his early lamp in his old laboratory reconstructed by Mr. Ford at Dearborn.

The proceedings of the meeting of the International Commission on Illumination held in September, 1928, have been issued during the past year. The U. S. National Committee of the I. C. I. has been actively interested in the preparations which are being made for the meeting to be held next year in England. It has been especially concerned with the subject of lighting in air navigation, the movement for a better international understanding with regard to standards of light, and the dissemination of information regarding the Jubilee of Electric Light, celebrated last year in many countries.

In practically every field of service electric light is continuing to expand in usefulness, but for the most part, as pointed out above, the developments during the past year have not been of a striking nature. Only by looking back over a period of several years can the fact that steady but slow progress is being made in this field or that one be determined. Even though, in this report, no specific comment to such progress in many important fields has been made, the fact that it is being made should not be forgotten.

# Application to Marine Work

## REPORT OF COMMITTEE ON APPLICATION TO MARINE WORK*

*To the Board of Directors:*

This Committee's chief activities during the present term have been devoted to an extensive review and revision of Standards No. 45. Having been advised that the stock on hand was practically exhausted, the committee had its choice of reissuing Standards No. 45 in its present form, or of revising the same to incorporate the latest developments and expansion in the marine practise. In view of the fact that Standards No. 45 is now nationally recognized by naval architects, marine engineers, shipbuilders, and ship owners, as the American Standard governing electrical installations on shipboard, and owing to many desired revisions and additions, the committee decided to review all sections of the rules and bring them up to date.

The task of revision was accomplished completely during the present term and the committee has turned over the revised rules to its Subcommittee on Editing. All sections were carefully reviewed by the working subcommittees and the main committee, and have received the required approval. It is expected that the Subcommittee on Editing will complete its work and submit the revised rules to the A. I. E. E. Standards Committee in the early fall of this year, or before.

New sections have been added on brakes, water-tight doors, electric clutches, and the radio direction finder. The section on gyroscopic stabilizers has been expanded to cover practise which is now considered standard.

Where desirable, the subcommittees consulted outside authorities on their subjects. At the committee's request, the Institute of Radio Engineers appointed representatives to cooperate with the subcommittee handling radio.

Our efforts were continued with the Steamboat Inspection Service to obtain classification and rating for electrical operating engineers on shipboard. A few conferences were held with representatives of that organization and some progress of an educational nature was made.

The chief activities in the marine field to which electricity has contributed its share are:

1. Four additional U. S. Coast-Guard cutters having electric propulsive equipment, are now being constructed.
2. Two 26,500-ship-hp., twin-screw turbine-electric liners for the Dollar Steamship Lines, Inc. are now under construction.
3. One 12,600-ship-hp. twin-screw turbine-electric liner was placed in service for the Grace Line.
4. One 6000-ship-hp. twin-screw turbine-electric yacht was placed in service.
5. One 2600-ship-hp. turbine-electric yacht was placed in service.
6. Two 7200-ship-hp., twin-screw turbine-electric drive lake car-ferries were placed in service.
7. Two 2000-ship-hp. tunnel-screw turbine-electric drive, river tow boats, are under contruction.
8. Several small craft now have Diesel-electric drive.

The Jones-White Act is having a decided influence on shipbuilding and several contracts are pending, some of which will use turbine-electric drive. The use of electrical auxiliaries has become standard practise for practically all ships of reasonable size.

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*COMMITTEE ON APPLICATIONS TO MARINE WORK:

W. E. Thau, Chairman,
R. A. Beekman, Vice-Chairman,
J. L. Wilson, Secretary,

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|---|---|---|
| Edgar C. Alger, | H. L. Hibbard, | Edgar P. Slack, |
| H. C. Coleman, | A. Kennedy, Jr., | H. M. Southgate, |
| E. M. Glasgow, | J. B. Lunsford, | A. E. Waller, |
| H. F. Harvey, Jr., | E. B. Merrian, | Oscar A. Wilde, |
| C. J. Henschel, | I. H. Osborne, | R. L. Witham, |
| Wm. Hetherington, Jr., | G. A. Pierce, | W. N. Zippler. |
| | W. H. Reed, | |

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*



30-137

# Applications to Mining Work

## ANNUAL REPORT OF THE COMMITTEE ON APPLICATIONS TO MINING WORK*

*To the Board of Directors:*

In the report made one year ago mention was made of the prediction that both coal and metal mining are entering a new era of development. This has begun and indications point to a continuance of development particularly as to mechanization. We now have references made to some modern mines as being 100 per cent mechanized. Future developments will no doubt modify the scheme of application of mechanical operation in many details. Statistics indicate that an increasing percentage of coal is undercut, drilled, and loaded mechanically. This means that added generating capacity and conductors for distribution will be required. Also, inasmuch as power purchased from the utilities is increasing in use at the mines, the mechanization adds to the utility load.

### Pumps

One company[1] installed ten synchronous motor-driven mine pumps from 300 to 600 hp.

### Motor Generator Sets

With increasing mechanization more power at the face is required. This has been accomplished in many cases by sets near the face. These are usually controlled by automatic switchboards, which have been simplified by the majority of manufacturers.

Some installations of portable substations have been made.[2] These are adaptable to installations where conditions of loading change rapidly.

Some installations of mercury arc rectifiers have been made, rated 300 kw. at 275 volts.[3]

### Shovels

The largest shovel made to date was placed in operation this past year.[4] It has a 15-yd. dipper on 120-ft. boom, weighing 1800 tons with an aggregate of some 5500 hp. in equipment, consisting of 700-kv-a. synchronous motor on multiple mg. set and main hoist operated by two 450-hp. motors, with a number of smaller motors, all handled by Ward Leonard control.

Smaller electric shovels from two to eight yard capacity are rapidly displacing steam shovels in the metal mines, 22 having been purchased by one company since January 1929.

In connection with electric shovels, as well as with other portable equipment, the trailing cables are important. The art of field vulcanizing is being perfected rapidly to take care of break-downs.

### Slushers

Motor-driven double-drum slushers generally driven by a 15-hp., three-phase, 440-volt motor, have become a part of the metal miner's equipment.

### Mining Machines

Track-mounted cutting machines have found a general use in mechanized coal mines. With such a machine about twice the work per day can be performed as is possible with the shortwall type of mining machine.

### Loading Machines

In coal mining there has been some increase in the use of pit-car loaders, where low ceiling and bad roof prevail. However, where conditions permit, the full mechanical loaders have gained in favor. Statistics are not complete, but indications are that some 500 or more units of this type are now in service. There have been many experimental loaders tried out, and there are more now in the process of design and manufacture. The principal problem is one of a mechanical nature, though nearly all designs involve the use of electric drive.

### Welding

The mines have been using both electric and gas welding to an increasing advantage. This has been applied to repair work more than to construction work.

### Safety Work

The Bureau of Mines has continued to expand its field of work.[5] In 1929 there were 19 approvals, 760 extensions granted and 31 manufacturers holding approvals on "Permissible" motor driven equipment.

The Industrial Commission of Utah has passed Resolution No. 950, providing that nothing except "Permissible" equipment may be used in gaseous mines after Jan. 1, 1932. This will necessitate a considerable amount of new equipment.

One company has displaced electric motors for jigging conveyors at the face and is now using air engines. Another has installed air motors on arc wall cutting machines, instead of electric motors. In both instances this was for safety.

Agitation continues for better lighting. In the metal mines this has been met to some extent by installing 440-volt/110-volt dry type transformers and portable lamps at or near a-c. motor-driven slushers.

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*COMMITTEE ON APPLICATIONS TO MINING WORK:

Carl Lee, Chairman,

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|---|---|---|
| A. R. Anderson, | E. J. Gealy, | D. E. Renshaw, |
| Graham Bright, | L. C. Ilsley, | W. F. Schwedes, |
| John H. Edwards, | J. E. Kearns, | F. L. Stone, |
| Frank E. Fisher, | W. H. Lesser, | J. F. Wiggert. |
| | S. O. Miller, | |

1. Susquehanna Collieries Co.
2. Butler Consolidated Coal Co. Furnished by G. E. Co.
3. Glen Alden Coal Co. Equipment by G. E. Co.
4. United Electric Coal Co. Equipment by G. E. Co. and Marion.

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

5. See Bureau of Mines Circulars 6997 and 7061.

Many explosions have been started by temporary stoppage of air circulation. This year there has been developed a co-related system of relays, signals,[6] etc., which can be applied to mine ventilation doors, air currents and electrical circuits to perform several functions such as operating a signal, making a graphic record, sounding an alarm, shutting off inside power, etc. This system applied to a gaseous mine would be of material value in avoiding explosion hazards.

6. See *Coal Age*, Feb. 1930, p. 89.

# Power Generation

## ANNUAL REPORT OF COMMITTEE ON POWER GENERATION*

*To the Board of Directors:*

The major work of this committee during the past year devolved upon its subcommittee on interconnection, composed of F. C. Hanker, Chairman, and affiliates, several of whom were selected outside of committee personnel to secure broad contact with current problems in the subject and to serve as liaison members on associated engineering committees handling related subjects. Recognition of the technical import of interconnection was initially made by the Power Generation Committee in a symposium of papers presented at the mid-winter convention in 1928, when the subject was treated chiefly from a regional aspect. Experience throughout 1928 and 1929 focused attention upon several problems of the mechanics of operating interconnections, and the subcommittee appointed in 1929 was enabled to obtain for a symposium at the January, 1930, Convention papers on two operating topics which have been investigated with definite results. The other three papers sponsored for the Winter Convention by the subcommittee were just as pertinent, but covered rather the principles of successful service to separate and contiguous load areas in typical metropolitan districts by relating the fundamental plans upon which the electric systems in Chicago, Detroit, and Philadelphia have been developed. These three papers, together with companion papers describing the method of power supply recently adopted in New York City which had been presented under the auspices of the Power Transmission and Distribution Committee at the 1929 Summer Convention, form an excellent compilation of the status of interconnection of power generation sources in large city electric systems. The papers included in the 1930 Interconnection Symposium were:

*Controlling Power Flow with Phase-Shifting Equipment.* by W. J. Lyman.

*Operating Characteristics of Turbine Governors,* by T. E. Purcell and A. P. Hayward.

*System Connections and Interconnections, Chicago District,* by George M. Armbrust and Titus G. LeClair.

*The Fundamental Plan of Power Supply of The Detroit Edison Company,* by S. M. Dean.

*Fundamental Plan of Power Supply in the Philadelphia Area,* by Raymond Bailey.

To accomplish the most thorough treatment of the subject of Interconnection, a joint interconnection subcommittee has been proposed by H. R. Woodrow, Chairman of the Power Transmission and Distribution Committee, to be composed of representatives of the committees on Power Generation, Power Transmission and Distribution, and Protective Devices. The purpose of this joint committee would be to keep the three major committees advised of all studies and developments pertaining to the subject, and to facilitate the handling of Institute activities with regard to the many interrelated phases of the interconnection problem. Mr. F. C. Hanker has been designated chairman of this joint subcommittee with the expectation of selecting such associates from the three principal committees as may be in position to assist in the prosecution of this work.

The committee has not undertaken for this year's report a resumé of the status of power generation similar to that prepared last year. The committees in the past four years have concluded for several reasons that a continuous and coherent history of power generation development can be written most advantageously at biennial intervals. The present Committee, while cognizant of the wide scope of its subject, believes that the introduction of new ideas in power plant design, construction, and operation, are principally matters of ensuing development over a period of two to three years rather than of immediate and complete innovations. An attempt to portray yearly significant progress would therefore result in duplication if the committee subject were to be covered thoroughly, or else the yearly resumés would consist of disjointed monographs as might appeal at the time to the individual committee. It is recommended, in consequence, that unity of outline and continuity of discussion be established between successive résumés and that this can best be accomplished by allowing sufficient perspective between reports of a historical nature on the subject of Power Generation.

Pertaining to the frequently recurring question of the general character of survey reports on the subject of power generation, the Committee is indebted to Mr. J. B. Crane who has made a statistical study of the membership common to both the A. I. E. E. and the A. S. M. E. national societies. It was found that in 1928 only 4.6 per cent of the membership of the A. I. E. E. were members of the A. S. M. E., while likewise only 4.7 per cent of the A. S. M. E. membership

*COMMITTEE ON POWER GENERATION:

F. A. Allner, Chairman,
J. R. Baker, Secretary,

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| J. W. Andree, | A. H. Hull, | E. L. Moreland, |
| H. W. Brooks, | G. A. Jessop, | I. E. Moultrop, |
| J. B. Crane, | J. H. Lawrence, | F. A. Scheffler. |
| N. E. Funk, | W. S. Lee, | A. E. Silver, |
| W. S. Gorsuch, | F. T. Leilich, | W. F. Sims, |
| F. C. Hanker, | H. W. Leitch, | A. R. Smith, |
| C. F. Hirshfeld, | E. B. Meyer, | E. C. Stone, |
| F. H. Hollister, | | R. W. Stovel. |

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.*

were enrolled in the A. I. E. E. In view of these facts the Committee believes there is unquestionable justification in striving for completeness and representative detail in summary reports of the historical development of power generation, irrespective of contemporary surveys which may be prepared by other societies. It is evident that the A. I. E. E. membership would be inadequately served were this Committee to circumscribe its report to avoid likely duplication of progress reports of A. S. M. E. committees treating similar topics.

Subcommittees on the Rehabilitation of Hydro Plants, and on Electric Power Generation Practises in Industrial Plants, were continued from the previous year, as well as Committee effort to keep in contact with the development of European power plant practise. The economic and engineering aspects of the rehabilitation of steam-electric power plants were admirably discussed in a paper by Mr. C. F. Hirshfeld at the 1929 Summer Convention, and it is the sense of the Committee that a companion treatment of the problems incident to the revamping of hydro developments is indicated by the increasing volume of such work that is now technically possible, and in many instances, economically feasible. Data regarding European high-pressure boiler types included in last year's report, and a paper obtained this year on European hydro practise, have seemed both pertinent and valuable, and the Committee therefore believes that this source of information can be profitably investigated by future committees.

The subcommittee on Electric Power Generation Practises in Industrial Plants, consisting of Messrs. F. A. Scheffler, Chairman, H. W. Brooks, and A. R. Smith, and affiliates from the A. S. M. E., Messrs. Fred M. Gibson, and William F. Ryan, endeavored to get in touch with representative industrial plant engineers for the purpose of discovering the problems of electric power generation peculiar to industrial installations and of learning how the activities of the Power Generation Committee could be of greater benefit in the industries. Accordingly notices inviting correspondence with the subcommittee were placed in the A. I. E. E. JOURNAL, A. S. M. E. *News*, *Power*, *Electrical World*, and *Power Plant Engineering*. In addition, letters were written to various engineers in the coke, steel, paper, automobile, textile, rubber, and soda ash industries for the same purpose. The ensuing correspondence developed suggestions for Institute topics fully appreciated by the subcommittee, but which after review have seemed to the subcommittee to consist almost entirely of topics more related to the work of other technical committees of the A. I. E. E. and of trade and commercial organizations in the various industries, than they are to that of the Power Generation Committee. The subcommittee consequently believes there is no apparent feeling among industrial plant engineers that the services of the Power Generation Committee are not available to them for the presentation of Institute papers on relevant subjects; and in conclusion the subcommittee recommends that it be discontinued after acknowledging the suggestions of its correspondents and offering to facilitate the presentation of such papers as may be prepared, either under its own auspices or through the several Institute technical committees to which the subject matter of the subcommittee's investigation has been transmitted.

The balance of the work of the committee has been undertaken with the idea of securing for Institute persentation papers on the subject of power generation describing recent and salient aspects of power plant design in Europe as well as in this country. The committee is recommending, therefore, as illustrative for this purpose, papers regarding

1. The East River Generating Station of the New York Edison Company.
2. A new system of speed control for a-c. motors.
3. Hydro power practise in Central Europe.
4. Hydraulic and electric possibilities of high-speed adjustable-blade waterwheels for low-head developments.

The first paper named describes a metropolitan power plant in which generators, boilers, and frequency converters of notable size and novel design have recently been installed. The second paper is of interest because the new system of speed control was developed for the regulation of a-c. motor driven auxiliaries in power plants. The paper on European hydro practise is a good exposition of the method of design adopted by European engineers who have had recourse to extensive preliminary model testing of entire hydro developments as well as of component parts. The fourth paper treats of the economic advantages to be derived from the high-speed propeller turbine of the manually and automatically adjustable blade type, through the increased part-gate efficiency, greater reduced-head capacity, and decreased electrical costs, that are possible. The paper foreshadows a wider adoption in this country of the Kaplan turbine that has been successfully applied to low-head installations in Europe.

# Power Transmission and Distribution

## ANNUAL REPORT OF COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

*To the Board of Directors:*

The Committee on Power Transmission and Distribution has found its problem sufficiently broad to justify the division of the work into several classes. A subcommittee has been appointed to cover the scope of the problems falling within each class and this year it has been possible to get each one of these problems more carefully defined and the work started in a definite direction.

In practically every phase of the work the subcommittees find their activities closely related to the activities of other committees of the Institute or similar committees in other organizations. Particular attention has been given to the coordination of this work with the work of the other committees in order that unnecessary duplication may be avoided and that none of the important phases will be left out of consideration.

The classifications as handled by the several subcommittees this year are as follows:

A subcommittee, of which Mr. C. T. Sinclair is chairman, has reviewed the problems of the distribution of electrical energy in cities and rural communities.

Mr. Philip Sporn has continued the very active work of chairman of the subcommittee on lightning and insulators.

A subcommittee, of which Mr. R. N. Conwell is chairman, has recently been appointed to review the problems of steel transmission towers and conductors.

The study of the question of interconnection and stability factors has been continued under the leadership of Mr. R. D. Evans as chairman.

The work of the subcommittee on cable development has been very active under the leadership of Mr. T. F. Peterson.

The research work on impregnated paper insulated cables has been continued in the joint subcommittee of the N. E. L. A. Underground Systems Committee, A. E. I. C. Committee on High Tension Cable, and the Committee on Power Transmission and Distribution of the A. I. E. E., with Mr. D. W. Roper, serving as chairman of this joint activity.

Mr. F. M. Farmer has coordinated the activity of the bodies on standardization within the field of power transmission and distribution.

The problem of interconnection and stability factors has engaged several subcommittees in extensive study, and steps have been taken to coordinate this work by the appointment of a joint subcommittee reporting to the Protective Devices Committee, Power Generation Committee, and the Committee on Power Transmission and Distribution of the A. I. E. E., and carrying on its activity in close cooperation with the Power Systems Engineering Committee of the N. E. L. A. Although it is impossible at this time to predict the activities for the coming year, it is thought by all three of the A. I. E. E. committees that this joint subcommittee should be appointed to correlate the work and analyze the problems in this important field.

### Distribution

The development of the a-c. low-voltage network has altered the methods of distributing electricity in locations having a large load density. Where tall buildings exist, the problem of distributing the electrical energy throughout the building has reached the proportions of street distribution which has resulted in the introduction of vertical networks within the building.

The rural communities distribution problem has brought forth some interesting solutions to insure reliable service and at the same time keep the cost within the permissible limits.

### Lightning and Insulators

Additional instruments have become available during the past year in studying lightning. These are the lightning stroke recorder which measures the current in a lightning stroke, and the field intensity recorder which records the electrostatic field (kv. per ft.) under the cloud. With these instruments have been recorded currents reported in the order of from 50,000 to 175,000 amperes in a lightning stroke, and field gradients as high as 85 kv. per ft. on an insulated antenna. Field gradients on transmission lines as high as 52-kv. per ft. of height have also been recorded by surge recorders.

The cathode-ray oscillograph, during the past year, has yielded some 150 field records of actual lightning voltage wave shapes on transmission lines. Analysis of these records show a maximum crest voltage of 1260 kv. wave fronts in the order of one to over 80 microseconds, and a total length, until the wave falls to zero, of as high as 150 microseconds. These data comprise a large increase of this type of information over the two records of natural lightning secured in the previous year. Lightning voltages up to 15.2 times normal line voltage to neutral have been recorded; and switching surges as high as 5.5 times normal were observed.

Additional data on the attenuation of both natural and artificial lightning have been obtained which further confirm past data and theory, showing the rapid

*COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION:

H. R. Woodrow, Chairman,
P. H. Chase, Vice-Chairman,
T. A. Worcester, Secretary,

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|---|---|---|
| R. E. Argersinger, | R. D. Evans, | D. W. Roper, |
| R. W. Atkinson, | F. M. Farmer, | A. E. Silver, |
| E. T. J. Brandon, | J. H. Foote, | C. T. Sinclair, |
| A. B. Campbell, | K. A. Hawley, | L. G. Smith, |
| R. N. Conwell, | D. C. Jackson, Jr., | Philip Sporn, |
| O. G. C. Dahl, | A. H. Lawton, | H. C. Sutton, |
| H. C. Dean, | L. L. Perry, | Percy H. Thomas, |
| E. W. Dillard, | T. F. Peterson, | H. S. Warren, |
| L. L. Elden, | G. E. Quinan, | R. J. C. Wood. |

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.*

decrease in the crest value of lightning waves in excess of corona voltage as they travel away from their point of origin. The lightning generator has been used extensively in the field the past year, three such installations being in use for a large part of the lightning season.

A study of lightning attenuation has also been carried on to determine the effect of steepness of wave front and polarity, of ground wire size and resistance, and also the effect of counterpoises. Field studies have also been started to show the behavior of traveling waves at the juncture of cables and open wire lines.

Extensive work has been done in the field measuring the surge impedance of actual lines, and determining the effect of tower footing resistances under lightning conditions.

*Line Design from the Lightning Point of View.* The benefits derived from the use of substantially installed ground wires on steel tower lines are now generally accepted. In some cases more than one ground wire has been employed; but the location of additional ground wires is still an open question due to the lack of definite knowledge, at the present time, as to whether the direct or induced lightning stroke is more important to protect against on high-voltage lines.

The insulation of wood pole lines from the lightning aspect has been receiving attention, and there are now in service several such lines using wood crossarm braces, insulated guy wires, and pole ground gaps, in an attempt to raise the lightning flashover of the line and at the same time minimize the possibility of pole and crossarm splitting. The fused grading shield is another design feature which has been given further study in service the past year. In one case the tower footing resistance of a 56 mile, 132 kv. steel tower line has been materially lowered by auxiliary ground rods in an attempt to improve the lightning performance of the line. Similar work is also being done on another high-voltage 33-mile line at the present time. Over-insulation of steel tower lines, materially higher than past practise, is not making much headway although one important line has been designed for extra line insulation should this be found desirable.*

*Presentation of Data and Results.* During the year the Committee has sponsored, wholly or in part, groups of papers at three A. I. E. E. conventions, namely, the Winter Convention in February 1930, where eight papers were presented in the lightning group, the Springfield Convention in May, 1930, where five papers were presented at the transmission session, and the Toronto Convention in June, 1930, where seven papers were presented on rationalization of transmission system insulation strength. Practically all of these papers deal with this most important subject of lightning, its effect on the transmission system, and protective measures to bring it under control.

*Another method of lowering the tower footing resistance has been tried on a 220-kv. line. This consists of connecting the tower base to buried cable which in turn extends some distance away from the tower.

Some valuable data have been obtained which have not yet been analyzed and assimilated. It is the intention of the committee, however, not only to cooperate in every way possible to have these data as well as future information made available to the electrical field for immediate use, but also to encourage the undertaking of new investigations where needed and to have the results of these investigations made available to the Institute Membership.

*1930 Lightning Investigations.* Field investigations of lightning is being carried forward on an increased scale. The instruments available and being used include:

1. Klydonographs and surge recorders.
2. Cathode ray oscillographs.
3. Lightning generators.
4. Lightning stroke recorders.
5. Surge indicators.
6. Field gradient recorders.

The work planned includes a wide field of investigation in which are studies on:

1. Lightning voltage magnitude.
2. Wave shape of natural lightning.
3. Attenuation and change of wave shape of lightning.
4. Effect of tower footing resistance.
5. Effect of counterpoises.
6. Determination of cloud field gradients.
7. Lightning voltage behavior at terminals of open wire line and cable.
8. Current in lightning strokes.
9. Importance of direct and induced strokes.
10. Records of insulator flashovers caused by lightning.
11. General investigation on distribution systems.

*Insulator Situation.* The present situation in the insulator field indicates a feeling among manufacturers that most of the troubles experienced in the past have been overcome. A summary of their attitude shows that:

1. Porous porcelain, under present manufacturing conditions, should seldom if ever be encountered.
2. Raw materials from selected sources and careful factory inspection have greatly improved the product.
3. Present controlled factory processes of mixing, forming, and firing the porcelain have resulted in a uniform product.
4. Porcelain as made today is practically free from aging.
5. Insulators may deteriorate due to the method of hardware attachment and stress distribution within the porcelain but this problem, it is felt, is being worked out satisfactorily.
6. The expected life of suspension insulators should be practically equal to that of the line or towers.
7. The use of high strength units appears to be making considerable headway.

The manufacturers, with their close attention to the various steps and processes in the manufacture of porcelain, and to the design and assembly of hardware, and with their knowledge of the actual results obtained on their product in the field, seem to have reason for feeling satisfied with conditions as they are. On the other hand, a piece of equipment subject to as many variables as is a completely assembled porcelain insulator, with each variable offering possibilities for deleteriously affecting the product, particularly after a lapse of time, is not a product on which vigilance can be relaxed at any time. It is believed that accelerated life tests and accurate loss measurements on porcelain insulators offer a means for determining in advance the probable performance and life of modern insulators, and of variations of them. Again, it is believed that it is possible to incorporate refinements in the control of temperatures and of humidity involved in the various steps of the insulator manufacture that will further decrease the variability in the product and increase the possibility of longer life. To these problems the Committee expects to give serious consideration during the coming year.

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## Steel Transmission Towers and Conductors

The numerous unsolved problems in connection with the design of steel transmission towers and conductors indicate the desirability of lending aid and encouragement to research and development work, which work must be coordinated with that carried on by other associations and development bodies. Progress can be made in the matter of simplification and standardization and this again requires the cooperative efforts with other associations and standardizing bodies.

In particular, the following problems are under review at the present time and these will be brought before the Institute as soon as the studies have indicated a clearer presentation of the problems or their solution.

1. Definition of terms and the elimination of ambiguous expressions in specifications.
2. Study of clearances required between towers and conductors due to the electrical and mechanical conditions imposed upon the line.
3. Study of protective coatings.
4. Study of the electrical and mechanical features of ground wires in cooperation with the Subcommittee on Lightning and Insulators.
5. Study of the effect of size or amount of steel exposed to a conductor on flashover.
6. Study of whipping, vibration, and impact of conductors including devices for the reduction or elimination of these phenomena.

## Interconnection and Stability Factors

Interconnections and the increases in the extent of power systems have raised a number of important questions. Of these, the measures necessary to insure reliability of operation are of the greatest importance. Technically, this means that the system, including interconnecting lines, must be so designed and operated that synchronism will be maintained between generating units and synchronous machines of the load. In other words, interconnected systems must possess adequate stability under normal operating conditions, and also during times of system disturbances.

An outstanding development in interconnection and stability is concerned with the application of high-speed circuit breakers and relays. Synchronous equipment, because of the inertia, cannot lose synchronism instantaneously. Consequently, the transient stability limits of a system may be materially increased by isolating the faults promptly. This is particularly true of interconnections since fast isolation of faults on either system minimizes the abnormal load thrown on the interconnection. The use of high-speed circuit breakers and relays offers very considerable promise for improving system stability.

Oil circuit breakers which have been available in the past for use on high-voltage systems, have been relatively slow in their operation, their average operating time being of the order of 20 to 40 cycles. The new high-speed breakers recently brought out are capable of isolating a fault in from 8 to 12 cycles from the instant the trip coil is energized until the arc is extinguished. Heretofore, protective relays, being of the induction type, have been relatively slow in their operation. The new high-speed relays will have a maximum operating time of one or two cycles at the most, and even less time for the relays located close to the fault.

Double-winding generators have received considerable attention in connection with metropolitan type systems for reducing the short circuit currents, and at the same time maintaining adequately high synchronizing power.

The use of quick response excitation for machines on transmission systems has become fairly well established with the exciter response rate being usually arranged for 200 to 600 volts per second. In special situations, higher response rates may be found desirable especially in connection with synchronous condenser installations.

In connection with certain major transmission projects, there has been discussion of the use and effects of damper windings. It is probable that the ideas on the use of damper windings will be clarified by papers to be presented in the near future.

The relative merits of different methods of grounding from the standpoint of system stability have been considered. Some operating companies have found it desirable to limit the severity of faults to ground at certain locations, and have grounded only a part of the transformer banks at a given location, or have introduced neutral impedance devices. In general, for major transmission systems, solidly grounding has been viewed favorably from the protection standpoint and unfavorably from the stability standpoint. The recent development of high-speed circuit breakers and relays tends to remove the latter objection, thus leaving the

2. A. I. E. E. Trans., Vol. 49, Oct. 1930.

choice of the method of grounding to be determined by consideration of protection.

System stability is a subject which has been before the industry for several years. Several of the measures which have been proposed to increase stability have actually been tried out on power systems, and new methods of operation are being put into effect. Thus, the operating data accumulating from year to year provide an increasing amount of information as a guide to the design of power systems with increased stability. A few examples in this connection will be cited. The scheme of system connections known as "synchronized at the load," has now received over a year's operating experience in New York City, and very satisfactory results in both stability and reliability of operation have been secured, the indicated margins of stability being more than adequate. In the southeastern district, one operating company has obtained increased reliability of operation by several means including synchronizing of hydro-generators and transmission lines only at load points, grounding only a part of the transformers at a station, installing quick response excitation. Observations on the performance of systems under short circuit tests on high-speed circuit breakers and relays have indicated that the shocks to the system are much reduced by high-speed isolation of faults.

During the past year, the subject of prime-mover governor control has received attention, particularly as a result of operating experience with automatic frequency control. This apparatus provides an arbitrary distribution of prime-mover input increments required by an undetermined distribution of load increments. Hence this apparatus, while of some advantage from the stability standpoint, does not insure the ideal control of the distribution of prime-mover input. This should not be serious, however, since with complete application of automatic frequency control to a system, generating units will not ordinarily carry loads below 50 or 60 per cent of rating.

The a-c. calculating devices which have been developed permit an accurate determination of current, voltage, power, and phase angle relations in an a-c. power system. These devices are an outgrowth of the d-c. calculating tables and the miniature a-c. systems which have been used in the past to represent power system networks.

The a-c. calculating device already has found a wide field of application in making system analyses; for example:

1. Normal System Studies: Determination of current distribution, power distribution, and voltage conditions in a-c. power system networks. Also, studies of voltage and power factor control.

2. System Fault Studies: Determination of magnitude and distribution of current under three-phase, single-phase, and line-to-ground fault conditions. If the faults are unsymmetrical the quantities can be determined by the use of the "symmetrical component" method.

3. System Stability Analysis: Determination of steady-state power limits, power angle curves, and studies of transient conditions by point-by-point analysis.

The interest in the analysis of power system problems on the part of engineers who deal with system planning and operation is increasing. In this connection reference may be made to a group of papers on interconnection presented at the Winter Convention under the auspices of the Power Generation Committee which include a discussion of the system connections in relation to stability. This interest was also reflected at the colloquium on power circuit analysis held at the Massachusetts Institute of Technology June 10 to 22, 1929, and at the annual fall meeting of the Great Lakes division of the N. E. L. A. held at Madison, Wis., October 23 to 26, 1929. The papers presented a general review of the situation at the time as related to the solution of power circuit problems with particular emphasis on those involving system stability.

The desirability of a standardized terminology for stability investigations is being reviewed by a group of the subcommittee with a view to submitting a report through the regular channels to the proper standardizing committee.

## Cable Development

This year's developments have been largely along lines of standardization, simplification, and reduction of rudimentary and experimental designs and methods to economic and practical feasibility. Such advances or radical departures from accepted practises as have appeared can be ascribed to the ever present urge to meet certain economic conditions or to the need for adaptation to the new installation and operation requirements which developments in other fields evoke, rather than to fundamental inherent evolution. For example, a-c. network services to tall buildings call forth vertical riser cable designs for high voltage and long suspension. Interconnection of operating companies may present unprecedented problems in submarine cable transmission. Change-over from open wire overhead construction necessitates substitution of new types of aerial and buried cable. Radio communication with planes in flight prompts studies and developments of shielded wire and cable to prevent interference, and so on.

Throughout the past year attention has been paid to what may be termed the mechanics of cable installation and operation. The fact that failures due to inherent causes constituted such a small percentage of the total, served to emphasize the importance of these aspects of cable use. Although some improvements have been made results which appear below indicate that there is still a wide enough spread between inherent and non-inherent failures to justify very close study on the part of operating companies.

*Research.* Cable and dielectric researches as described in last year's report have been continued unremittingly. Already the results of coordination are manifesting themselves in improvement in manufacture and operation. Moreover, they have in other instances opened avenues of progress in standardization, etc.

At the present time a subcommittee of the Underground Systems Committee of the N. E. L. A. is engaged in the preparation of rating tables for cables installed under varying conditions. Other groups are working up tables of thicknesses for rubber, varnished cambric and paper cable.

Although practises abroad do not allow of as high temperature of cable operation as are met with in this country, and undoubtedly cable is therefore not used so severely as it is here, the fact remains that some engineers attribute much of the trouble encountered in operation to voids developed and mechanical stresses set up as a result of the tendency of copper conductors to open when longitudinal thermal expansion is constrained. Special conductors and tensioning devices have been designed to counteract these movements. Information on the results of operation will probably be available to the industry at large and will certainly be watched for with interest. In the meantime it would be well to have our local inspection forces pay particular attention to this phase of cable failures in an effort to explain those which may have fallen too readily in the unknown class.

*Inspection, Testing, and Specifications.* There have been no special developments in testing and inspection practise in connection with underground cable. Improvement in technique continues slowly, resulting in greater accuracy and more reliable results. In particular long-time, high-voltage tests are being made more carefully and greater attention is being given to the results of such tests. A standard method for measuring thermal conductance of cable is being developed at Massachusetts Institute of Technology in connection with extensive research on thermal insulation. Moderate variations in the thermal conductance of the insulation of underground cables is not in itself a very important matter but it is possible that this quantity can be used as a measure of thoroughness of impregnation. If so, the development of a simple practicable procedure for measuring it in connection with acceptance testing is desirable.

Summaries of a large amount of inspection and test data collected in connection with the inspection of over 9,000,000 feet of paper-insulated cable are reported in the annual report of the Underground Systems Committee, N. E. L. A., for the year 1929. These data show a continued downward trend in the percentage of deficient cable from over 20 per cent in 1923 to less than 3 per cent in 1929. During that period there has been a steady increase in dielectric strength from less than 300 volts per mil in 1923 to over 500 volts per mil in 1929. There have been corresponding improvements in other characteristics.

Greater effort is being made to obtain more accurately the very valuable information which is available in the service records of the companies operating underground cable systems. In particular, more detailed studies are being made of the probable causes of failures. Many data covering cable failures during 1929 are thoroughly analyzed in the report of the Underground Systems Committee referred to above. Incidentally, it may be noted that these studies confirm the improvement in quality of cable indicated by the inspection and test data. Failures due to causes inherent in the cable were, in the calendar year 1929, less than 1.5 per 100 miles of paper-insulated, underground cable rated at over 7500 volts. In 1926 this figure was nearly 3.0. The rate, including all failures for all causes, has decreased from over 9 to nearly 7 in the same period. The grand total rate of failure in 1929 for underground, paper-insulated cable systems, including joints, was a little less than 12 per 100 miles.

The status and developments during the year in respect to specifications and other standards dealing with wire and cable are referred to elsewhere in this report.

*Development in Practise.* The records for the year 1929 again bear witness to the fundamentally sound bases for designs of oil-filled 132-kv. cable. The 18 miles installed in New York and Chicago (referred to in previous reports) have now continued in operation without electrical failure for a period of two and one-half years. Several installations akin to these were made during the past year and are worthy of note at this time.

In New York a second 132-kv. oil-filled line, 12 miles in length, was installed paralleling the first one built in 1927. In Chicago approximately three additional miles of oil-filled cable were placed in service. The outstanding feature of these installations as contrasted with those previously made is that the cable was shipped impregnated and oil-filled so that the only field impregnation necessary was a short treatment of the joints. This, together with the development and use of horizontal stop-joints, effected a considerable reduction in the time required for installation. In both cases sections of approximately 1800 ft. were employed between stop-joints. In Chicago, however, about one-half of the new cable was arranged with practically all joints of the positive stop, condenser type. As a result of the use of shorter sections, smaller volumes of oil have to be handled and lower hydrostatic pressures are encountered. This allows of the introduction of a smaller hollow core and a modified sheath construction.

Of the several unique types of cable installations made or operated during the year, the following are worthy of particular note:

In Syracuse approximately 3000 ft. of three-conductor oil-filled, 33-kv. cable were placed in service.

An especially notable installation of high-voltage submarine cable was made between Deep Water, N. J. and Pigeon Point, Delaware, on the Delaware River. Eight lengths, each 4075 ft. without splices, of single-conductor, paper-insulated, leaded and armored cable, rated at 75 kv., were installed for operation at 66 kv. This is understood to be the highest voltage submarine crossing of its kind in the world and uses the longest continuous lengths of paper and leaded cable.

10,000 feet of multiple conductor buried cable installed at Birmingham, Alabama, have continued to give satisfactory service at 44 kv. during the year. The construction of the cable is unusual in that the insulated conductors are individually leaded before the three are cabled together and protected with jute and flat steel tape over-all.

The introduction of new methods of supplying tall buildings in the New York metropolitan district with power had led to the design and installation of several types of multiple conductor vertical riser cables for operation at 13.8 kv. Although rubber, varnished cambric, and composite varnished cambric and rubber have found uses in this field, other details are quite uniform. In general, the insulated conductors are shielded with copper tape and cabled without the use of a lead sheath to hold them together. Steel binder tape, jute, and round wire armor serve this purpose and the latter allows of single point support without undue strain on copper conductors or insulation.

Of late there has been a marked tendency toward the use of various types of buried cable. These have been of the conventional makeup as well as numerous variations from this in the form of non-metallic sheathed cable. Although the latter have found quite general acceptance for street and airport lighting projects, experiments are now being conducted to determine their advisability for a-c. secondary network mains. There have recently been installed 66,000 ft. of 4/0 non-magnetic buried cable to serve an area in the metropolitan district which has a moderate load density.

Shielded multiple-conductor cable for transmission continues in increasing favor throughout this country. The field which it dominates has widened and now there are many installations for use at voltages as low as 13.8 kv. The extended use of this cable has been in a measure accelerated by the fact that manufacturers have expressed their willingness to guarantee operation of the so-called type "H" cable at the same maximum temperature as single-conductor cable.

*Papers and Future Projects.* Among the many problems being considered by this and other committees engaged in similar work, are a comparison of the relative merits of aluminum and copper for transmission and distribution cable and a study of the economics of buried cable installations. The last mentioned had been begun by a subcommittee of the Underground Systems Committee of the N. E. L. A. and is now being carried on with our cooperation.

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Sameda, "Solid Dielectrics in the Industry," p. 14.

Emanueli, "Installation of High Tension Cable," p. 609.

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## Impregnated Paper Insulated Cable Research

Research work of various types continue unabated in this important field. It is being carried on under many different auspices. Some of it is of a character which justifies formal reports either periodically or at irregular intervals. The progress of other projects, for one reason or another, cannot be formally reported. All of the activities, however, are serving the purpose of research, that is, the increase in knowledge in respect to impregnated paper insulated cable. A very considerable part of the advancement in the art of underground, high-voltage power transmission is undoubtedly the tangible result of the large amount of research work that is being carried on.

The research projects directly under the sponsorship of the impregnated paper insulated cable research subcommittee have been actively continued during the year. The work at Massachusetts Institute of Technology on the rate of deterioration of impregnated paper was formally completed with the publication by the National Electric Light Association in July, 1929, of the results found for wood pulp paper (N. E. L. A. publication No. 289-87, July 1929). The findings on manila paper were published in the A. I. E. E. Journal, May, 1925, and in the annual report of the N. E. L. A. Underground Systems Committee for 1927. During the past year, the development of a standard test procedure for determining the thermal conductance of high-tension cable has been under way at M. I. T. and it is expected that a final report will be available during 1930.

The work at Johns Hopkins University under Professor Whitehead continues on the original assignment, a study of the effects of residual air and moisture in the insulation of high-tension cable. Progress reports are made from time to time in the form of papers before the Institute; the last one was presented at the Baltimore regional meeting in Baltimore, April, 1928 (A.I.E.E. Trans., Vol. 47, July 1928, p. 826. The relation between the amounts of residual air and moisture, respectively, and various electrical properties have been pretty well established for the particular materials used. The work for over a year has been devoted to obtaining the relation of these residuals and the life of the insulation under high stress. Much difficulty has been encountered in getting thoroughly satisfactory results and much time has been expended in developing the technique of preparing test samples which will yield thoroughly reliable results under long-time tests. Furthermore, a large number of test samples must be prepared and tested in order to establish the desired relation beyond question. This work will be reported by suitable publication when the final conclusions are obtained.

Professor Dawes at Harvard University has continued the study of the characteristics of ionization in the insulation in paper-insulated, high-tension cable. A third progress report on this work was presented at the Winter Convention in January of this year.

In the aggregate, a large amount of experimental research work in high-tension cable is being done by the central station companies, some of it of a fundamental character and of a very high order. These researches are being carried on both by the company staffs and at universities. Conspicuous among the utilities carrying on research work are the Brooklyn Edison Company, the Detroit Edison Company, and the Commonwealth Edison Company. The last also

joins with the other Insull companies in supporting the Utilities Research Commission, which sponsors a large number of fundamental researches at universities, and the Bureau of Standards. Several of these are on high-tension cable problems.

Among the many research projects being carried on by the utilities may be mentioned the following:

1. Production of very highly refined and treated oils and study of the electrical characteristics and stability of such oils.
2. Study of high-frequency discharges which accompany ionization in insulation and their effect.
3. Systematic study of the performance of various types of cable for 132-kv. service.
4. Elimination of sheath losses in single conductor, high-voltage cable.
5. Study of mechanical properties of cable sheaths with a view to their improvement.
6. Development of method of detecting ionization at any part of a cable.
7. Studies of the fundamental properties of dielectrics used in cable.
8. Studies of the effects of long-time application of electric stress to the cable-insulating materials under various pressure conditions,—rate and kind of gas evolved, change in electrical characteristics, etc.
9. Continuous studies of cable in service as to rate and kind of gas evolved, changes in electrical properties, etc.

Several of the cable manufacturers are carrying on fundamental researches such as:

1. Chemical effects of internal corona on paper and compounds.
2. Internal hydrostatic pressure versus life of cable.
3. Effect of internal voids at various pressures on life of cable.
4. Study of sheath corrosion.
5. Thermal conductance of insulating materials.
6. Development of a stability test for cable insulation.

A considerable amount of work of a research character is continually carried on by the Electrical Testing Laboratories on behalf of the central station companies in connection with the acceptance, inspection, and testing of cable. Extensive analyses of the summaries of a large amount of inspection and test data are made quarterly. Summaries of these studies are reported annually to the Underground Systems Committee of the N. E. L. A. and the High-Tension Cable Committee of the A. E. I. C. Continual and systematical studies are also made of failures of high-tension cable in service on the systems of a number of the larger central station companies. The results of these surveys are also reported annually to the above committees. In addition, a certain amount of experimental research work is conducted on problems of particular concern to the operating companies.

The above outline is intended to present a brief picture of the organized research work which is being carried on in this particular field. These activities, together with the fundamental researches on dielectrics under the auspices of the National Research Council and those being carried on by independent workers, justify the conclusion that continued advancement in the high-tension cable art can be anticipated.

## Standardization Activities

The following is a brief summary of the developments during the year of the organized standardization activities in the transmission and distribution field.

*A. S. A. Project C 1, Regulations for Electric Wiring and Apparatus in Relation to Fire Hazard.* The 1930 edition of the National Electrical Code was approved by A. S. A. as American Standard July 19, 1929. It was put into effect by the National Board of Fire Underwriters, January 1, 1930.

Steps are being taken towards another revision in the near future.

*A. S. A. Project C 8, Insulated Wires and Cables.* Standards for so-called "Code" insulation for rubber-insulated wire and cable, for weather-resisting coverings and for fire-resisting coverings have been completed during the year and are now before the sectional committee on Insulated Wires and Cables for consideration.

The remaining standards on the committee's program, namely, those dealing with stranding, varnished-cloth insulation, paper insulation, metallic coverings and fibrous coverings and fillers, are either nearly ready for consideration of the Section Committee on Insulated Wires and Cables or well under way.

Section No. 30 of the A. I. E. E. Standards, which deal with wire and cable, was submitted by A. I. E. E. to A. S. A. for approval. The Standards Council of A. S. A. withheld approval and referred it to the sectional committee on Insulated Wires and Cables for recommendation as to changes necessary to make it fit in the program of the sectional committee.

*A. S. A. Project C 17, Specifications for Miscellaneous Pole Line Materials.* This project, originally proposed as a rather comprehensive one, got under way in 1925. However, work being done on separate projects involved in the same general subject made it advisable for the sectional committee to hold up work until progress was well along on these individual projects (tubular poles, trolley construction, line insulators, and wood poles). These are well under way so that a definite start by the sectional committee having project C 17 in hand is expected soon.

*A. S. A. Projects C 20 and C 29, Specifications for Line Insulators.* Plans are being made to combine these two projects (one for insulators below 750 volts and the other for insulators above 750 volts) and reorganizing the work.

Specifications for insulator tests (a revision of Section No. 41 of A. I. E. E. Standards) have been prepared and approved by the sectional committee having in hand project No. C 29. They are now before the sponsors (A. I. E. E. and N. E. M. A.) for approval before submission to the Standards Council of A. S. A.

*A. S. A. Project 0 5, Specifications for Wood Poles.* Difficulty has been experienced in getting agreement among the various interests involved in this project but it is understood that, after considerable delay, progress is now being made and that standard specifications will be recommended in the near future.

*A. S. A. Project C 42, Definitions of Electrical Terms.* This project is being planned on a rather comprehensive scale. It will be, in effect, a complete glossary of terms used in the entire electrical field together with their definitions.

The sectional committee having this project in hand has been organized under the chairmanship of Dr. A. E. Kennelly and the work has been started through fourteen subcommittees, each dealing with a branch of the electrical industry. One of these, with C. H. Sanderson as chairman, deals with transmission and distribution.

*A. I. E. E. Standards for Transmission and Distribution.* The Transmission and Distribution Committee of A. I. E. E. has recommended to the Standards Committee, A. I. E. E. that complete standards be formulated for transmission and distribution.

*Specifications for Impregnated Paper Insulated Lead Covered Cable.* The so-called N. E. L. A. Specifications for this class of cable ("Suggested Specifications for Lead Covered Underground Cable Insulated with Impregnated Paper") have been withdrawn.

The fourth revision of the A. E. I. C. "Specifications for Impregnated Paper Insulated Lead Covered Cable" is under way and it is expected that the revised edition will be issued during 1930.

The progress made by the Committee this year is, in a very large measure, due to the active work of the subcommittees and credit should be passed on to the chairmen and members of these subcommittees who have given so much of their time in the study and analysis of the problems referred to them.

# Protective Devices

## ANNUAL REPORT OF COMMITTEE ON PROTECTIVE DEVICES*

*To the Board of Directors:*

Following a custom established a number of years ago, all the work coming under the jurisdiction of the Committee on Protective Devices has been divided among subcommittees, accounts of whose activities are presented as part of this report and as evidence of what has been accomplished during the year. These subcommittees, with their chairmen, are as follows:

1. Circuit Breakers, Switches and Fuses, A. M. Rossman, Sargent & Lundy, Inc., Chicago, Ill.
2. Current Limiting Reactors and Resistors, N. L. Pollard, United Engineers & Constructors, Newark, New Jersey.
3. Lightning Arresters, Herman Halperin, Commonwealth Edison Company, Chicago, Ill.
4. Relays, H. P. Sleeper, Public Service Electric & Gas Co., Newark, New Jersey.

Except for the disbanding of one subcommittee, the organization was the same as that of the preceding year. The subcommittee on Industrial Equipment and Service Protection, which functioned in 1928-1929, reported at the beginning of the year that its work was complete. This subcommittee was therefore discontinued with the understanding that features of protection affecting industrial equipment and service would be followed in a general way by the main committee.

The work of the subcommittees during the past year has followed three established lines:

1. Arranging for and following through the preparation of papers for presentation before the Institute.
2. Revision of existing, and preparation of new, standards.
3. A survey and review of research and development during the year in those things over which the committee has jurisdiction.

### Revision and Preparation of Publications and Standards

Perhaps the greatest activity has been shown in the matter of preparing a supplement to the Relay Handbook and in revising the proposed Standards on Lightning Arresters.

The Relay Handbook was published in 1926 under the sponsorship of this committee and the Electrical Apparatus Committee of the National Electric Light Association. Developments since then have been of sufficient importance to justify the publication of material necessary to bring the Handbook up to date. The spirit of cooperation between the Subcommittee on Relays and the corresponding subcommittee of The National Electric Light Association has been most gratifying, and at this time, your committee wishes to express its appreciation to that organization for the privilege of joining in this work which promises to produce such good results.

The revision of the lightning arrester standards has been a particularly difficult task, both because of the rapidity of development of this class of equipment and because of new methods of research which result in a continuous uncovering of new facts and the formation of new theories. Excellent progress has been made, however, as is indicated in the report of the subcommittee on lightning arresters, included in this report.

Progress may also be reported in the preparation of standards for fuses. It is expected that the succeeding committee can readily prepare these for presentation to the Standards Committee during the coming year.

A revision of the section of standards covering disconnecting switches is now under way and progress is reported. This revision will include knife switches in its scope.

The question of standards for fault current-limiting devices was given consideration and a recommendation covering this is made in a following subcommittee report.

### Interconnection and Stability Factors

Early in the year your committee was asked to give consideration to the formation of a joint subcommittee to study the problem of interconnection and stability factors. It was proposed that this subcommittee be made up of members selected from the committees on Power Transmission and Distribution, Power Generation, and Protective Devices. This proposal was endorsed by your Committee and it is recommended that the organization be set up early in the coming year.

### Meetings

The practise of having all the work covered by subcommittees has resulted in simplifying the work of the main committee, in that it reduces to a minimum the number of main committee meetings.

Two meetings, only, were held this year, the first for purposes of organization, and the second at the end of the year for review of the work of the subcommittees. It has been found that the smaller groups can work much more efficiently, and that the reduction in the

*COMMITTEE ON PROTECTIVE DEVICES:

E. A. Hester, Chairman,
Raymond Bailey, Vice-Chairman,
L. E. Frost, Secretary,

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|---|---|---|
| J. E. Allen, | F. C. Hanker, | A. M. Rossman, |
| L. N. Blagoveschensky, | L. F. Hickernell, | C. H. Sanderson, |
| A. C. Cummins, | J. Allen Johnson, | A. H. Schirmer, |
| H. W. Drake, | M. G. Lloyd, | H. P. Sleeper, |
| W. S. Edsall, | J. B. MacNeill, | R. M. Spurck, |
| E. E. George, | J. P. McKearin, | E. R. Stauffacher, |
| H. Halperin, | R. C. Muir, | H. R. Summerhayes. |
| | N. L. Pollard, | |

*Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.*

number of main committee meetings is a decided advantage.

It is interesting to observe that another advantage has developed from this method of handling committee work. The chairmen of the subcommittees are usually chosen from the main committee, but its members may be drawn from the general membership of the Institute. This has proved an excellent way to initiate younger members of the Institute into technical committee work, and actually creates an enthusiasm for it. Consequently, there is always available a number of members who are going through a training process, and appointment to a main committee does not find them entirely unprepared.

### Reports of Subcommittees

*On Circuit Breakers, Switches, and Fuses.** During the past year, much time and study have been devoted to research in oil circuit breaker design. A large part of this effort has been aimed at the discovery of the fundamental laws which govern the formation, control, and breaking of an electric arc under oil. These studies led to the development of the deion grid for controlling the arc in a high-voltage oil circuit breaker, probably the outstanding achievement of the year in oil circuit breaker design. The theory of the deion grid, the method of adapting it to oil circuit breakers, and test data from experiments conducted on oil circuit breakers equipped with these grids, were ably presented at the Winter Convention of the A. I. E. E. in two papers; *Extinction of a Long A-c. Arc*, by Dr. Joseph Slepian and *Use of Oil in Arc Rupturing*, by Messrs. B. P. Baker and H. M. Wilcox. The tests presented in these papers show that the addition of deion grids to an oil circuit breaker of moderate operating speed reduces the time of arcing, increases its interrupting capacity, and decreases the energy that must be dissipated during the interrupting process.

The demand for more rapid clearing of short circuits, to increase the stability limits of transmission systems, has stimulated the development of high-speed oil circuit breakers. During the year, two manufacturers of this equipment have announced designs of circuit breakers capable of interrupting circuits of voltages up to 230,000 volts in eight cycles after the trip-coil is energized. Field tests have been made, as high as 230,000 volts demonstrating the claims made by these manufacturers.

Interest in metal-clad switchgear is growing as its advantages are becoming better known. The past year has seen refinements in design and a steady increase in production. The trend is very definitely toward standardized forms which should lead to mass production methods in manufacture and substantial reductions in price. So far, operating experience with metal-clad switchgear has justified the expectations of both designing engineers and operating engineers as is evidenced by the increasing purchases of this type of switchgear by those companies which have had the greatest amount of experience with it.

One of the outstanding installations of this kind of switching equipment was made at the State Line Generating Station in Chicago. A complete description of this installation, together with a recitation of the factors influencing the choice and design, was presented by Mr. A. M. Rossman at the 1930 Winter Convention in a paper entitled *Metal-Clad Switchgear at the State Line Power Station.*

In the matter of standards, it is likely that the revision covering the section on disconnecting switches will be submitted to the Standards Committee before the expiration of the current committee year. In revising this section, a division on knife switches which has not heretofore been covered by the standards is being included.

Work is progressing on a draft of standards for fuses. This probably will not be completed this year and it is recommended that the succeeding subcommittee continue actively in all this standards work.

A number of organizations are engaged in formulating standards and definitions for circuit breakers, switches, and fuses, as well as for accessory equipment. Chief, among these are the N. E. L. A., A. S. A., N. E. M. A. and A. E. I. C. It is recommended that the succeeding subcommittee determine and classify the activities, and coordinate its work with these groups in order to avoid duplication.

*On Current-Limiting Reactors and Resistors.** The Sub-committee on Current-Limiting Reactors and Resistors has this year sponsored the preparation of papers on reactor and resistor subjects and has studied the question of revising and enlarging the standardization work relating to subjects coming under its jurisdiction. The following papers prepared under its auspices were presented at the North Eastern District Meeting, Springfield, Mass., May 7-10, 1930:

*Shunt Resistors for Reactors*, by L. V. Bewley, F. H. Kierstead, and H. L. Rorden.

*Arcing Grounds and Effect of Neutral Grounding Impedance*, by J. E. Clem.

Carrying out an assignment made at the beginning of the year, the subcommittee secured representative opinion as to the desirability of enlarging the scope of the A. I. E. E. Standards to cover, in one section, all fault current-limiting devices, such as reactors and resistors and possibly grounding transformers. It is possible that the little use made of grounding resistors may not justify the effort necessary to work them into the standards. It is recommended, however, that definite steps be taken to cover in one section the other devices mentioned, and at such time give further consideration to grounding resistors and transformers.

*A. M. Rossman, Chairman.

*N. L. Pollard, Chairman.

Several years ago, the Committee on Protective Devices made an exhaustive study of the general subject of the grounding of neutrals on power systems. This work was done under the direction of a special subcommittee and resulted in a number of excellent papers on the subject being presented before the Institute in 1922 and 1923. The study having been concluded, the subcommittee was disbanded, since which time the subject has been followed in its general aspects by the main committee.

This year, the question was raised as to whether there had been sufficient development during the past six or seven years to warrant another study of the same kind. There was enough uncertainty to cause doubt, so the Subcommittee on Current-Limiting Reactors and Resistors was asked to investigate and recommend as to whether or not the subcommittee should be reorganized.

Obviously this is a matter which will be of vital interest to other A. I. E. E. technical committees, particularly those on Power Transmission and Distribution, and Power Generation. Since it is believed that developments over the past few years have introduced new factors into the problem of grounding, it is recommended that the joint subcommittee referred to elsewhere in this report include this subject in its duties. This recommendation has been endorsed by the main committee and transmitted to the chairmen of the two other committees concerned.

*On Lightning Arresters.** In the past year, work has been done to determine the effects of lightning on transmission and distribution circuits, and to provide experimental and commercial forms of protection. Field studies of natural and artificial lightning were made by several investigators using high-grade forms of recording devices. The new developments included arresters which were installed experimentally on transmission line towers.

Much of the progress during the last year is well described in several valuable papers which have been presented before the Institute, among which the following may be mentioned:[1]

*Development of New Autovalve Arrester*, by Slepian, Tanberg, and Krause.[1]

*Thyrite, A New Material for Lightning Arresters*, by McEachron.[1]

*Cathode Ray Oscillograph Studies of Lightning on Transmission Lines*, by Cox and Beck.[2]

*Surge Characteristics of Insulators and Gaps*, by Torok.[2]

*Lightning Investigations on Lines of Public Service Electric & Gas Company*, by Conwell and Fortescue.[2]

*Lightning Voltages on Transmission Lines*, by George and Eaton.[2]

*Study of Traveling Waves on Transmission Lines with Artificial Lightning Surges*, by McEachron, Hemstreet and Rudge.[2]

*Lightning Investigation on 220-Kv. System of Pennsylvania Power and Light Company*, by Smeloff and Price.[2]

*Lightning Investigation on Ohio Power Company System*, by Sporn and Lloyd, Jr.[2]

*Lightning Investigation on Transmission Lines*, by Lewis and Foust.[2]

*Effect of Transient Voltages on Power Transformer Design*, by Palueff.[2]

Still other instructive papers on the subject can be found in the following publications:

"Lightning Arrester and Factors Affecting Its Performance and Application," by Towne, *G. E. Review*, August 1929.

"The Ideal Lightning Arrester, What is It, Can It Be Produced?" by Atherton, *Electrical Journal*, August 1929.

Several very excellent articles on lightning and protection problems have appeared in European magazines, among them,

"The Present Status of the Problem of Lightning Protection," by Matthias, *Elektrotechnische Zeitschrift*, October 1929.

"Protection of Electrical Systems against Over-Voltages" (Report of Electrical Institute of Technology College Aachen), by Flegler, *Elektrotechnische Zeitschrift*, January, 1930.

"Over-Voltages in Electrical Systems," by Berger, *Bulletin of Schweizerischer Electrotechinscher Verein*, February-March, 1930.

In all these articles many conclusions are drawn confirming findings by investigators in this country.

In the field studies on overhead transmission lines during the lightning season of 1928, only two oscillograms were obtained of natural lightning. In 1929 over two hundred such oscillograms were obtained, greatly increasing our knowledge of the magnitude and wave shape of lightning surges on transmission lines. Numerous records were obtained of artificial surges applied to overhead lines, the lines being terminated with various apparatus or connections or in series with underground cables. Since the findings of these various tests have been so thoroughly described in the articles listed above as well as summarized in various electrical journals, they need not be repeated here.

For distribution circuits, experiences of several utilities indicate that the proper use of lightning arresters reduces the number of transformer failures by 50 to 90 per cent, depending on the nature of the lightning in the given locality and the nature of the equipment. In general, it has been found that the older transformers, which are usually of the smaller sizes and have smaller clearances between leads and case and over the bushings, are more susceptible to failure due to lightning than the newer transformers. One company found that transformers from 15 to 25 years old had a rate of failure due to lightning several times the rate for trans-

*Herman Halperin, Chairman.

1. A. I. E. E. Quarterly TRANS., April and July, 1930.
2. A. I. E. E. TRANS., July, 1930.

formers made in the last five years. Three years ago this company revised its specifications for 2080- to 230/115-volt distribution transformers, improving the arrangement of the leads and increasing the flashover voltages of the leads to case and over the bushings. Over two thousand of these transformers were in service in 1929 and not one failed due to lightning.

The Commonwealth Edison Company has continued the investigations of lightning damage on its distribution system as described in previous reports. Last year a detailed study was made of transformer locations adjacent to points where transformers failed due to lightning, and the many possible factors of such adjacent points correlated in an attempt to discover the factors causing the failure to occur on the particular transformer. No new factors of importance were discovered. The previous findings were verified; that is, that old transformers and transformers with poor bushings and lead clearances are those most likely to fail. Furthermore, there appears to be a peculiar tendency for failures to occur in greater numbers than is a fair proportion at locations where the ground resistance is less than 20 ohms. Incidentally, 99 per cent of all the ground resistance in the area studied is less than 75 ohms. This tendency is not what would be expected from laboratory tests and is not in agreement with certain data obtained on some other systems. Studies are being continued.

An extensive klydonograph investigation has been made by the American Telephone and Telegraph Company on communication circuits. Some of the most interesting findings were that the capacity of the protector ground to earth is generally more important than its resistance; that practically all the potential drop in a protector circuit was between the ground rod and the earth; that conductor potentials and sheath potential are nearly equalized a short distance inside a lead-sheathed telephone cable regardless of length of outside conductor exposure; and that large differences, even opposite polarity of induced potentials, can exist in the same overhead wire within short distances.

One of the chief accomplishments of this subcommittee in the past year has been the revision of the proposed Standards for Lightning Arresters. Much time has been spent on this work and it is believed that the proposed preliminary Standards are in such good shape that in 1930 they may be adopted with only minor revisions.

Standard laboratory waves have been incorporated in these proposed standards for testing arresters. These waves have been made as severe as possible up to the limit of the laboratory testing equipment, in preference to a simulation of any particular lightning wave.

It is hoped that an active interest will be taken in these proposed standards. Probably after the experience of a few years it will become feasible to revise them and incorporate additional paragraphs, making use of such additional technical information as will no doubt become available. In view of this outlook, it seems advisable to have the advantage of the use of the proposed standards in the meantime.

It is recommended that the succeeding subcommittee actively pursue the adoption of these standards.

It is further recommended that the subcommittee, (1) study a standard test surge and the surge which should be applied in the duty cycle test; (2) investigate the value of merit of low-resistance grounds, (a, on distribution systems, and b, on transmission systems); and (3) investigate the effect of "repeated flash" in lightning stroke on arrester characteristics.

*On Relays.** The efforts of this subcommittee have been directed into three channels as follows:

1. The completion of the Standards for Relays, begun by the previous subcommittee.
2. The preparation of a supplement to the Relay Handbook.
3. The preparation of a series of papers on the subject of relays for presentation before the Institute.

The previous subcommittee completed the preparation of a set of tentative standards and presented it to the Standards Committee for consideration. Recently, Working Committee No. 48 was appointed by the Standards Committee, with Mr. George Sutherland as Chairman, and certain members of this subcommittee were appointed on the working committee to assist in the preparation of a final draft of these standards. The part played by this subcommittee consisted largely, therefore, of assistance rendered to Mr. Sutherland's committee. It is expected that a final draft of these standards will be available for distribution this year.

The most important work of the year has been the preparation of a supplement to the Relay Handbook. To carry out this work, a joint subcommittee was appointed whose members are representatives of the relay subcommittee and of the corresponding N. E. L. A. group. The present edition of the Relay Handbook was published in 1926 under the same auspices, and it was felt that the development in design and application of protective relays during the subsequent four year period has been sufficient to warrant the addition of new material to the original publication. The first consideration was to decide upon a method of adding this new material, the two obvious courses being first, to rewrite completely the Handbook and bring all chapters up-to-date, and, second, to review the present book and present the revisions and additions in the form of a supplement. It was finally decided to follow the second course, publishing a supplement to the existing book. Factors affecting this decision were as follows:

1. To rewrite the old book would require at least a year's time, including that necessary for

*H. P. Sleeper, Chairman.

publication, while a supplement could be prepared in a relatively short time.

2. The supplement can be published and sold separately for a small sum and can be added to further editions of the present handbook at no appreciable additional cost.
3. The stock of the existing handbooks is now practically exhausted and it was felt that a reprinting should not be made until such new materials as is available has been added in some form.
4. The immediate preparation of a supplement would enable the stock to be replenished in an up-to-date form, whereas at least a year would elapse before new stock could be obtained containing the new material if rewriting was attempted.

The joint subcommittee therefore proceeded with the preparation of the supplement instead of a revision. The present book was carefully reviewed, necessary corrections made, obsolescent material omitted, and the newest developments added. Fortunately, but few revisions were found to be necessary and the supplement proved to be just what the name implied, added material. Both the manufacturing and operating engineers have cooperated wholeheartedly, and it is felt that all material which will be of value has been included in the new publication. The final report of this joint subcommittee has been submitted to the main committee for approval and with recommendations for publication.

The subcommittee has been quite active in the preparation of the following papers being presented at the Summer Convention in Toronto:

*Directional Ground Relays*, by E. E. George and R. H. Bennett, Jr.

*High-Speed Relaying*, by L. N. Crichton.

*Modern Requirements for Protective Relays on Important System Interconnections*, by O. C. Traver, and L. F. Kennedy.

*Transmission System Relay Protection, Part III*, by W. W. Edson.

*Problem of Service Security in Large Transmission Systems*, by Paul Ackerman.

The last symposium on the subject of relays was held at the Pittsburgh meeting in 1923. Since then, many papers on relays have been presented in mixed sessions but no concerted effort has been made to bring the Institute records in the art up-to-date. It was felt that the present time was particularly appropriate for this by reason of the revision work being done on the Relay Handbook. An additional reason for holding a symposium at this time is that a new era in protective relay developments seems to be approaching. This is called "High-Speed Relaying" and is the subject of two of the papers scheduled for the Toronto meeting. Furthermore, during the past few years the use of ground or zero-phase sequence relaying has developed rapidly and results and possibilities both deserve more publicity. Indications are that both of these phases of protective relaying have an extensive future ahead.

The paper *Transmission System Relay Protection, Part III*, may be regarded as a sequel to two other papers which have been presented before the Institute. The first of these was written by Messrs. Woodrow, Roper, Traver, and MacGahan in June, 1919. The second, presented at Niagara Falls in June, 1922, was the work of Messrs. Hester, Traver, Conwell and Crichton. Each of these gave a concise summary of current relay practise up to the date indicated, and the paper presented this year is designed to bring the subject up-to-date for Institute records. The scope of this last paper has been broadened to some extent and includes relays and relaying for both apparatus and transmission lines.

It is not necessary in this report to attempt to summarize new developments, since the symposium presented at Toronto completely covers the subject. It would seem fitting, however, to make brief mention of the trend in the art as indicated by the latest developments. The major part of the effort expended in development work during the past year or so seems to be towards the reduction of time element or the development of so-called "high-speed relays." For the past ten years, the so-called "time element relaying" has been accepted rather generally as the solution to protection problems. However, with the advent of high-voltage interconnections, the instantaneous disconnection of system faults has assumed vital importance. Where seconds have been acceptable, a few cycles are now often the maximum which can be allowed to maintain system stability. The speed of operation of circuit breakers has been reduced materially and it is obvious that relays must follow suit. Many forms of these high-speed relays are now in commercial use, some of them being entirely new developments and some of them being evolutions of existing time element design.

It cannot be said that the use of time element relays has been, or will be, entirely superseded. They will probably always be of use in some form, and indispensable for certain applications—such as back-up protection. It is certain, however, that the benefits to be derived from the reduction of time in relay and breaker operation are of sufficient value to justify the general use of high-speed relays.

In order that the Institute may have a complete record of the development and use of these high-speed relays, it is recommended that the succeeding subcommittee follow the symposium at Toronto with papers on the application of high-speed relays and their effect on interconnection and system stability.

# Electrical Transportation

## ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL TRANSPORTATION*

*To the Board of Directors:*

In accordance with instructions, your Committee submits a brief review of the recent developments of importance in the application of electricity to transportation.

### Steam Railroad Electrification

*Pennsylvania Railroad.* The Pennsylvania Railroad is actively engaged in the construction of three sections of its electrification program. These sections are from Philadelphia to Trenton, N. J., Philadelphia to Norristown, and New Brunswick to Jersey City and Sunnyside Yard. This construction work involves 88 route miles and 370 track miles. Until the section between Trenton and New Brunswick is completed, only multiple unit passenger service will be operated electrically in addition to the present electrified service. This electrification utilizes power distribution at 11,000 volts, 25 cycles, single phase.

*Delaware, Lackawanna & Western Railroad.* This project, comprising 67.9 route miles with 160 track miles, is progressing. Power contracts have been executed with the Public Service Electric & Gas Company, the Jersey Central Power & Light Company, and the New Jersey Power & Light Company. One hundred and forty-one multiple unit motor cars, each equipped with four motors, have been ordered. The coaches now used in steam operation will be equipped for use as trailers. Each motor car will be permanently coupled to a trailer to form a unit. The substation converting apparatus is to consist entirely of mercury arc rectifiers, which are all now in process of installation. It is expected that the construction will be substantially completed by the end of 1930. This will be the first extensive installation in this country of 3000-volt d-c. power distribution applied to motor car equipment.

*Reading Railroad.* The Reading suburban electrification in the vicinity of Philadelphia is progressing according to schedule, although it has been held up somewhat by grade crossing elimination. The initial installation will consist of about 50 route miles and 110 track miles, and the equipment will be multiple unit cars, orders for which have been placed. It has been stated that a second step is contemplated upon completion of the first, between Langhorn and Bound Brook and New York and Lansdale to Bethlehem and along the Schuylkill Valley to Reading. Contract has been made for purchase of power with the Philadelphia Electric Company. This electrification is on the basis of 11,000-volt, single-phase, 25-cycle power distribution.

*Cleveland Union Terminals Company.* The construction of the two substations and six circuit breaker houses or tie stations required for this electrification project, has been completed. Twenty-two 204-ton, 3000-hp. locomotives have been delivered, and power is being supplied to the catenary system west of the terminal for the purpose of training locomotive crews. All construction work will be completed this year and the operation of trains by electric power will begin before the end of the year. The conversion of power will be by means of motor-generator apparatus and the trolley voltage will be 3000 volts direct current. Contract has been executed for purchase of power with the Cleveland Electric Illuminating Company.

*New York Central Railroad—West Side, New York City.* In connection with the electrification of the freight service on the west side of New York City, south of Sputen Duyvil, three new substations are being constructed. They will be automatic or operated by means of supervisory control. Forty-two road freight locomotives of a capacity of 2500 hp. each have been ordered for operation between Croton and the 72nd Street yard. They will weigh approximately 275,000 lb. and will be operated from 660-volt d.-c. third rail. For switching in the yards, and operation of the freight trains south of 60th Street, thirty-five combination oil-electric-battery locomotives have been ordered. The Diesel engines on these locomotives will have a capacity of 300 hp. and the battery will have a capacity of 650 ampere hours at the 6-hr. rate, at an average voltage of 464 volts. The approximate weight of these locomotives will be 257,000 lb.

*Great Northern Railroad.* It has been necessary to add new equipment on account of increased demand for service, and four additional motor-generator type locomotives, duplicates of those now handling the passenger service, are under construction. This electrification is on the basis of 11,000-volt, 25-cycle, single-phase power distribution.

*New York, New Haven & Hartford Railroad.* Authority has been received for purchase of ten new electric locomotives and thirty-three multiple-unit cars in addition to nine multiple-unit cars which have been received during the year. This electrification is 11,000 volt, 25 cycle, single phase.

*Illinois Central Railroad.* During the past year, freight tracks and yards from Monroe Street to 39th

*COMMITTEE ON ELECTRICAL TRANSPORTATION:

Sidney Withington, Chairman,

| | | |
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| A. E. Bettis, | D. C. Jackson, | A. S. Richey, |
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| E. R. Hill, | Ralph H. Rice, | Richard H. Wheeler, |
| W. K. Howe, | | G. I. Wright. |

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30-96

Street, Chicago, having a total mileage of 21.2 track miles, have been electrified as an integral part of the present electrification, which utilizes 1500-volt d-c. distribution. Freight service in these yards will be handled by four 100-ton straight electric locomotives having a one-hour rating of 1460 hp. Switching service on non-wired tracks north of this point will be handled by six 600-hp. oil-electric locomotives, this diversity of motive power being made necessary by the unfeasibility of wiring certain yard tracks north of Randolph Street. This project will enable the handling electrically of all freight service north of Roosevelt Road (with the exception of manifest trains) to be done with motive power other than steam, as is called for by city ordinance.

### Substations for Electrified Railroads

It is of interest to note that of the two above-mentioned 3000-volt d.-c. traction installations, one is on the basis of mercury arc rectifiers and the other of motor-generators. The substation design characteristics vary accordingly.

### Diesel-Electric Locomotives

Four combination oil-electric-battery locomotives, known as "three-power" units, have been ordered by the Michigan Central Railroad for use in Chicago. The New York Central Railroad has ordered two and the Chicago, Rock Island & Pacific Railway one, of the same type, for use at the La Salle Street terminal, Chicago. Thirty-five oil-electric-battery locomotives have been ordered by the New York Central Railroad in connection with the west side electrification in New York City, as above mentioned.

The Delaware, Lackawanna & Western Railroad has ordered two three-power locomotives equipped to receive power from 3000-volt, d-c. trolley. These engines in general resemble those of the New York Central Railroad.

The Illinois Central Railroad, as above stated, has in operation six 600-hp. Diesel-Electric locomotives.

The Erie Railroad has purchased one 800-hp. Diesel-electric locomotive.

Perhaps the outstanding Diesel-electric locomotive of the year is the "No. 9000" of the Canadian National Railways. The two engines of this locomotive have a total rated capacity of 2660 hp. at 800 rev.-per min.

### Rail Cars

There has been a steady increase in the demand for heavier and more powerful rail car power plants. In 1927, eight cars of over 500 hp. were produced; in 1928, fifteen; and in 1929, thirty-seven cars which weigh about 180,000 lb. Designs have been completed for two eight-cylinder gas engines of over 500 hp. In this connection, it is of interest to note that five steam rail cars of 400-500 hp. have been ordered.

### Marine Transportation

At the close of 1929 there had been completed six turbo-electric driven ships aggregating 56,000 tons, using motors totaling more than 71,000 shaft-hp. capacity. Electric propulsion has been applied for the first time to railroad car ferries, large pleasure yachts, etc. A number of Diesel-Electric craft have been produced.

### Aviation

The developments in aviation during the past year include the "altimeter," indicating the distance above the surface of the ground; the magneto compass, virtually a d-c. generator using the horizontal component of the earth's magnetic field as its field; the electric-gasoline engine temperature indicator; and an oil immersion heater for warming oil before starting motor-generators and dynamotors. Power plants of extreme lightness for radio purposes have been developed to take the place of wind-operated generators.

### Car Retarders

Retarder installations, both electric and pneumatic, for gravity freight classification yards, have been continued during the past year. One of the advances which has been made is in the use of track circuits and cab signals for the hump yard locomotives. A retarder scheme utilizing a magnetic braking circuit has been tried abroad with considerable promise of success. This will eliminate all mechanical contact with the car wheels.

### Signaling

An extension of railroad signaling of importance has been made in centralized remote control of switches and signals, to enable the despatcher to control trains directly (without train orders) by manipulating switches and signals from his office.

### Communication on Railroads

Carrier current telegraph circuits have been extended during the past year on railroads. Further tests of communication with moving trains have been made with success, although tests of radio communication between front and rear of long trains have been discontinued under orders from the Federal Radio Commission.

### Automatic Train Control

Little additional installation in the field of automatic train control has been indicated during the past year. Two systems, one the so-called "Coder Type" with continuous cab signal indication, and the other the "Intermittent" or "Track Induction Type," which merely requires acknowledgment from the engineman when passing a track inductor, are the most common types of installation. Some railroads are installing cab signals over considerable mileage without the train control features.

### Street Railways

There has been a great deal of activity in this field during the last two or three years, especially in developing high speed motors with either worm or double

reduction gear drive, wherein the motor is entirely spring supported.

The tendency is towards the use of motors of larger capacity than formerly, with lighter cars and very much higher rates of acceleration. In order to secure these higher rates of acceleration with reasonable comfort to the passengers, it has been necessary to develop new control systems with many more steps than in the old hand controllers. The tendency is toward the use of automatic multiple contact control, and a variable automatic control has been developed which may be either foot or hand operated. The rate of acceleration thus depends simply on the pressure of the foot on the pedal.

## General

Attention is called to the development of various types of apparatus which apply to transportation as well as to other forms of electric utilization, as described in the appropriate committee reports; such as turbines and other power plant facilities, circuit breakers, lightning arresters, high tension cable, substations, hydroelectric facilities, etc. Attention is especially called to quick-acting circuit breakers, both oil and air, which are especially applicable to railroad work.

# The Status of the Young Engineer

## President's Address

BY HAROLD B. SMITH

A LIFETIME'S work has been primarily with students of electrical engineering, and close connection has been enjoyed with many of them, not only immediately, but frequently for many years after graduation from college. It is natural, therefore, that it is counted a high privilege to have been brought closely into touch with their problems and their aspirations.

In this address, an attempt will be made to present some of the factors which appear to carry great weight with these young engineers in the critical years of the establishment of foundations for their future careers. There is a particular stimulus to do this at this time, because the whole problem of the status of the engineer is undergoing critical survey and it is believed that many of the problems which confront the young engineer at the very beginning of his professional experience offer a key which will be helpful to unlock problems apparently arising later in life. Much of this applies equally to young engineers other than those in electrical engineering.

Because of the comparatively few years that we have known the profession of engineering, even in its older branches, military and civil, we find comparatively few young men in college who are sons or close connections of older engineers upon whom they can depend for friendly, personal advice and guidance. Particularly is this true in electrical engineering where, while we still have with us many of that first small generation of the pioneers and even the second generation was not numerically large, we have only recently come to a generation numerically large enough to be able to cope with the multitudinous contacts and influences needed and desired by the larger generations now developing. The percentage of young men now in college and affiliated by close ties with older men of the engineering profession is much smaller than is desirable. The medical profession has some very useful and valuable policies in this connection of far reaching importance for the younger men. The profession of electrical engineering, in general, has but recently appreciated the importance of these relationships, as is evidenced by increased Branch activity and particularly by increased Branch and Section interrelationships. While this is a great help toward the solution of this problem, it is by no means the whole of it.

The young engineer of several decades ago, upon graduation found an old established order such that it was not always advisable to present his college training, abilities and aspirations too prominently. The older apprenticeship system had not wholly disappeared and the earlier English influences in this respect were still strong in this country. Many of our organizations were still feeling that they were showing much consideration when they paid their new men fresh from college as much as six to nine cents per hour their first year. This was because they could make immediate comparison with other organizations still charging the new man an apprenticeship fee the first year. The industry has itself, and without undue pressure, recognized the financial needs of the young engineer for his own development and, under wise leadership, from time to time, has advanced the rate of compensation so that the young engineer may now expect to receive a reasonable rate of compensation upon starting upon his professional work. Not only that, but very largely throughout the industry is there now a fairly well fixed range of expectation. At least there is a fairly well established minimum rate of compensation to which any well trained and dependable young man of good ability may look forward as a starting compensation upon graduation. There is, if not a definite agreement, a sufficiency of understanding that a young man who has made a good record, not necessarily among the first of his class scholastically, but on the whole a *good* record, through four years of engineering college training, may reasonably expect to receive $125.00 to $150.00 per month his first year out of college and, depending upon a variety of conditions, sometimes much more. Frequently it is not the job that pays the most money the first few months that is most advisable for the young man to accept for his first experience. There are compensating and counterbalancing factors of great variety to be considered, both by the employer and by the young engineer. It is not thought that too great a uniformity should be set up for this initial starting compensation, nor is it likely that there will be. The present general understanding serves its purpose very satisfactorily in providing a sufficient and reasonable recognition of a minimum starting rate after the completion with a good record in a four year engineering college course. It sufficiently informs the profession, the college, the industry, and the individual of reasonable limits upon which they can plan and build for the future. This is true, even if it be recognized at the beginning that modification may be brought about from time to time as changing conditions may justify.

The above is all predicated upon the thought which has been expressed in the findings of the reports of The Society for the Promotion of Engineering Education, The Carnegie Foundation for the Advancement of

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Teaching, and other bodies or committees, that the normal and advisable college course for the average engineering student is a four year course. The needs of engineering and industry are met in the majority of cases by recruiting, shall we say, three-quarters of the men necessary from those who have secured for themselves a good four year engineering training. The profession and the industry are most vitally concerned, however, with the recruiting of the remaining twenty-five per cent or less who are imperatively needed with a training beyond that which can be secured during a four year period. A training which, depending upon the field of engineeering activity proposed, may consist of any one of an almost endless variety of important combinations, almost any one of which, including actual applied practise, may either precede, or be interspersed with, the usual four year engineering college course or may wholly follow such a course. In general, where they follow after such a course, they are designed for specialized study for definite purposes—mathematics, physics, business, manufacturing, design, production, or various other lines, or through experience in actual applied engineering work along some important line. These are the young men interested in securing the most thorough training for their life work, with whom the colleges, the profession, and the industry are especially concerned, and for whom they are highly responsible.

One of the great difficulties of this problem lies in the suitable selection of the twenty-five per cent, or even a ten per cent, of the students who are so constituted that they can profitably devote one, two, or three years to further training along purely analytic, theoretic, or applied lines, or some advisable combination of them. This selection is attempted in various ways at present by various agencies: Fellowships and scholarships of various sorts by the colleges; grants by various foundations for many purposes; plans for support of graduate study and research, etc., etc. There is not enough of this sort of endeavor and when more is attempted many complications arise. It has been suggested recently* that "perhaps not enough has been done by the cooperation of the several engineering societies standing back of the educational institutions and with the cooperation of the applied engineering industry as a whole." The thought lying back of this suggestion has resulted from personal talks with executives of organizations, particularly with those having to do with the building up of personnel, with recruiting representatives, and with officers of colleges and the professional societies.

Briefly, it is a suggestion that, after suitable study by a properly organized committee of an independent organization such as the American Engineering Council or the Engineering Foundation, with ample representation of engineering industry, and based upon such recommendation as they find advisable, an attempt be made by these several agencies to establish some sort of differential for general and substantial recognition, if not actual agreement, which will provide a sufficiently definite rate to be expected by the young engineer of suitable characteristics for an initial starting salary after one, two, or three years of effective graduate work. What such a differential should be must be a matter for much consideration, and possibly can be decided upon after actual trial. There is sufficient agreement, as matters now stand, so that it does not seem to be too much to hope for a result as tangible as now exists for the initial starting salary at the end of a four year course.

With no thought of final acceptance for such a purpose in the form proposed, but in order to illustrate the purpose of such a plan, let us set up a trial schedule to make such a suggestion a little more definite and to emphasize some of its advantages. Suppose it be assumed that the following schedule is effective as fairly representing effective minimum rates, which may reasonably be expected by the young engineer, it is believed that one of the principal advantages lies merely in the recognition of a more or less substantial understanding of such a schedule of minimum rates.

SCHEDULE

| | Minimum initial starting salary for first year, at end of four year college training or equivalent | Total minimum |
|---|---|---|
| After satisfactory completion of a good four year engineering course or equivalent.....say— | $1750.00 | $1750.00 four years |
| In addition, and after a fifth year of effective graduate work, 5 years training.....say— | 250.00 | 2000.00 five years |
| In addition, and after a sixth year of effective graduate work, 6 years training.....say— | 250.00 | 2250.00 six years |
| In addition, and after a seventh year of effective graduate work, 7 years training.....say— | 250.00 | 2500.00 seven years |

It is found that with every group of students coming to graduation and being interviewed by representatives of the various engineering and industrial organizations, there are several points of view which must be taken into consideration. A not infrequent statement on the part of the interviewer is the interest of his organization in "a few of the best men" of the class. It is probably true that each of the interviewers visiting a given institution will not succeed in picking out and securing the services of all of the "best men." If some such schedule as that proposed is set up by the industry and recognized so far as found practicable, it is believed

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that students themselves will to a large extent pick themselves out for this ten to twenty per cent in which we are all of us so greatly interested. It is also believed that they will "pick themselves" with more accurate judgment on the whole than possible for any one else.

A certain percentage of each graduating class, even though they have profited greatly from their four year training and have good records back of them, have secured this result only at great effort, or, indeed, may have required five years in which to complete the four year training. They have discovered that there are certain types of effort for which they are not well adapted. No one needs to tell them whether to give themselves further advanced study in college or not. They know. And fortunately there is an immediate need and an active need for just this type of man directly following his four year training. Some of them could not be induced to submit themselves to further college training and they readily find the work for which they are well adapted and in which the records show they will prove highly successful.

Then there is a smaller percentage of men who enjoy the college work of analytic and theoretic, or more practical, laboratory or research type and realize themselves that they can profit by further training of this character. They resolve themselves into at least three classes: (a) Those who have financial resources to avail themselves of such training. We sometimes find such men indulging themselves unreasonably and unprofitably in this way. It is the comparatively few of this type who have brought criticism upon themselves and others. (b) Those without financial resources, but who find means to meet their needs through fellowships, scholarships, various funds, etc. (c) Those without financial resources to permit advanced training, but who, themselves, know better than any one else can possibly learn, instructor, recruiting representative or close friend, how definitely they would appreciate and profit from a suitable amount of the type of advanced training for which they are definitely fitted and which they usually definitely crave. It is for the benefit of these men who are of the type that yield us those who go far as the years progress that this proposed plan is presented for consideration. It is also for the benefit of the profession as a whole that it is hoped that some such plan can be established so that we have coming into the profession each year a small well trained group of most able young engineers who will promptly find their places in the inspiring leadership of the profession.

With a reasonably definite differential set up, and under some such sort of an understanding as has been described, these are the men who would, under such an understanding, pick themselves out and under such a plan would find an urge for this training which would enable them, with the differential in mind, to finance themselves. It is believed that the right men would pick themselves out for more advanced training with greater certainty and, on the whole, truer insight into their own qualifications than their instructors or most proficient recruiting representatives could possibly do. The instructor and his advice would not be eliminated. He would still be helpful. They would have to borrow the money for this training, which the differential would permit and would justify them in doing. It would, however, make it their own responsibility to do so and ultimately repay it. They would scrutinize their own inclinations, abilities, and the character of the work they took up with utmost consideration under such conditions. They would, better than any one else, know whether their capacities and urge would justify borrowing for one, two, or three years training. They would, with good advice and better than any one else, know when such training should be interspersed with applied work of a less theoretic character.

The responsibility for the best use of the time, effort, and money for more of advanced training for a comparatively small percentage of men would rest definitely upon those men who elect to secure such training. Industry, the profession, the colleges, by cooperating in setting up some such sufficiently understood and accepted schedule, merely provide a tangible basis upon which the young engineer may understandingly make his decision, at the time when such a decision is necessary for him. It is believed that engineering and industry are prepared to meet the expense involved in such a plan. In fact, such expense is virtually being met at the present time, and more men of the type such a plan would produce are needed. It would be a somewhat gradual development and probably subject to slow modification as time proceeds and as experience dictates. The careful study of such a plan and its possibilities and limitations is recommended.